Low-Cost Rural Surface Alternatives: Literature Review and Recommendations

DECEMBER 2013

Final Report

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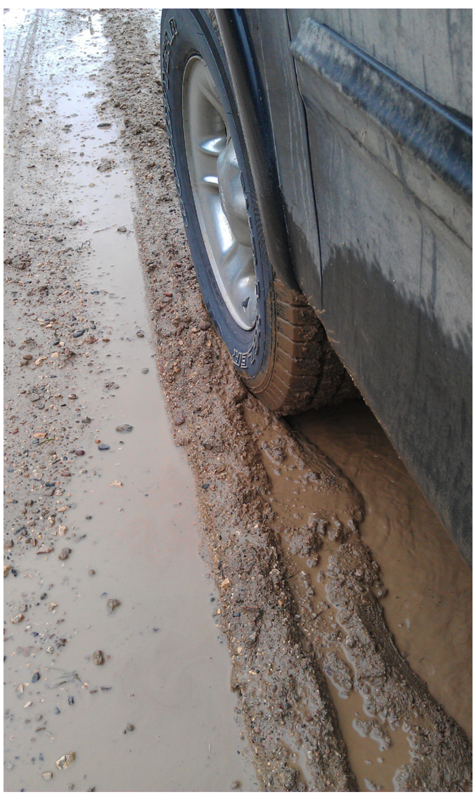


IOWA STATE UNIVERSITY
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Iowa Highway Research Board
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Iowa Department of Transportation
(InTrans Project 11-402)

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The preparation of this report was financed in part through funds provided by the Iowa Department of Transportation through its "Second Revised Agreement for the Management of Research Conducted by Iowa State University for the Iowa Department of Transportation," and its amendments.

Technical Report Documentation Page

1. Report No.	**2. Government Accession No.**	**3. Recipient's Catalog No.**
IHRB Project TR-632		

4. Title and Subtitle	**5. Report Date**
Low-Cost Rural Surface Alternatives: Literature Review and Recommendations	December 2013
	6. Performing Organization Code
7. Author(s)	**8. Performing Organization Report No.**
David White and Pavana Vennapusa	InTrans Project 11-402
9. Performing Organization Name and Address	**10. Work Unit No. (TRAIS)**
Center for Earthworks Engineering Research Iowa State University 2711 South Loop Drive, Suite 4600 Ames, IA 50010-8664	**11. Contract or Grant No.**
12. Sponsoring Organization Name and Address	**13. Type of Report and Period Covered**
Iowa Highway Research Board Iowa Department of Transportation 800 Lincoln Way Ames, IA 50010	Final Report **14. Sponsoring Agency Code**

15. Supplementary Notes

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16. Abstract

Freezing and thawing action induces damage to unbound gravel roads in Iowa resulting in maintenance costs for secondary road departments. Some approaches currently used by County Engineers to deal with this problem include temporarily spreading rock on the affected areas, lowering or improving drainage ditches, tiling, bridging the area with stone and geosynthetic covered by a top course of aggregate or gravel, coring boreholes and filling them with calcium chloride to melt lenses and provide drainage, and re-grading the crown to a slope of 4% to 6% to maximize spring drainage. However, most of these maintenance solutions are aimed at dealing with conditions after they occur. This study was tasked with identifying alternative approaches in the literature to mitigate the problem. An annotated bibliographic record of literature on the topic of frost-heave and thaw-weakening of gravel roads was generated and organized by topic, and all documents were assessed in terms of a suitable rating for mitigating the problem in Iowa. Over 300 technical articles were collected and selected down to about 150 relevant articles for a full assessment. The documents collected have been organized in an electronic database, which can be used as a tool by practitioners to search for information regarding the various repair and mitigation solutions, measurement technologies, and experiences that have been documented by selected domestic and international researchers and practitioners.

Out of the 150+ articles, 71 articles were ranked as highly applicable to conditions in Iowa. The primary mitigation methods identified in this study included chemical and mechanical stabilization; scarification, blending, and recompaction; removal and replacement; separation, and reinforcement; geogrids and cellular confinement; drainage control and capillary barriers, and use of alternative materials. It is recommended that demonstration research projects be established to examine a range of construction methods and materials for treating granular surfaced roadways to mitigate frost-heave and thaw-weakening problems. Preliminary frost-susceptibility test results from ASTM D5916 are included for a range of Iowa materials.

17. Key Words	**18. Distribution Statement**
freeze thaw—frost heave—gravel roads—literature review—low-volume roads—performance—soil stabilization—thaw weakening	No restrictions.

19. Security Classification (of this report)	**20. Security Classification (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified.	Unclassified.	300	NA

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

LOW-COST RURAL SURFACE ALTERNATIVES: LITERATURE REVIEW AND RECOMMENDATIONS

Final Report
December 2013

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Sponsored by
the Iowa Department of Transportation
Iowa Highway Research Board
(IHRB Project TR-632)

Preparation of this report was financed in part
through funds provided by the Iowa Department of Transportation
through its Research Management Agreement with the
Institute for Transportation and the Center for Earthworks Engineering Research
(InTrans Project 11-402)

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ACKNOWLEDGMENTS

The authors would like to thank the Iowa Department of Transportation (DOT) and Iowa Highway Research Board (IHRB) for sponsoring this research (IHRB project TR-632). Peter Becker from Center for Earthworks Engineering Research (CEER) and Daniel Miller (previously with CEER) assisted in organizing the literature database. Their assistance is greatly appreciated.

EXECUTIVE SUMMARY

Problem Statement

Freeze-thaw cycles combined with frost-susceptible soils and inadequate drainage lead to damage in unbound roads and, in severe cases, make them impassable. Intersections and bridge approaches are common trouble locations, but damage due to frost-heave and boils can occur throughout a given roadway depending on variations in drainage, construction quality, and traffic loading. Some approaches currently used by County Engineers to deal with frost boils include temporarily spreading rock on the affected areas, lowering or improving drainage ditches, tiling, bridging the area with stone and geosynthetic covered by a top course of aggregate or gravel, coring boreholes and filling them with calcium chloride to melt lenses and provide drainage, and re-grading the crown to a slope of 4% to 6% to maximize spring drainage. However, most of these maintenance solutions are aimed at dealing with conditions after they occur.

Project Overview and Key Findings

The primary task of this project was to perform a detailed literature review and then conduct a systematic assessment of the documents to identify technologies suitable for future evaluation and implementation in Iowa. An important outcome of this effort is an organized database of literature with 150+ technical articles on this research topic. The literature documents have been organized into an electronic database, which can be shared with other researchers and practitioners. The database will be used as a future resource to search for information regarding the various repair and mitigation solutions, measurement technologies, and experiences that have been documented by selected domestic and international researchers and practitioners. The literature documents have been assessed using eighteen different engineering categories and criteria developed for this project. Each article was rated on a scale of 1 to 4 as it relates to the potential to contribute to solutions to this problem in Iowa (1 – not applicable, 2 – marginally applicable and not considered, 3 – marginally applicable but technically strong, 4 – applicable and technically strong). Engineering judgment was used in rating each article. Out of the 150+ articles assessed, 71 received ratings 3 or 4 and are considered in developing recommendations for future demonstration projects.

Based on the review of literature, stabilization methods and drainage were identified as feasible mitigation solutions to the problems of frost-heave and thaw-weakening. Stabilization works by increasing the shear strength of the surface and/or subgrade layers to resist the actions of freeze-thaw and drainage works by eliminating or reducing water from the freeze-thaw process. Following is a list of different stabilization technologies identified in the literature:

- Chemical stabilization using active chemical agents such as lime, fly ash, and portland cement, or passive chemical agents such as bitumen, foamed asphalt, bio-fuel byproducts, and polymer emulsions.
- Mechanical stabilization by blending coarse-grained and fine-grained materials, using non-biodegradable reinforcements (such as fibers, geotextiles, geogrids, geocells, and geocomposites), using recycled materials (recycled concrete or asphalt and industrial by-

products), and use of macadam base with large particle size to facilitate drainage and stability.

- Bio-stabilization involving biological processes. This process is relatively new with very limited field data and information.

Various damage evaluation techniques involving field and laboratory test methods to evaluate frost-heave and thaw-weakening damage have been documented in the literature. Laboratory evaluations include characterizing soils' frost susceptibility rating based on soil gradation parameters (percent finer than 2 microns) or conducting ASTM D5918 tests to determine frost-susceptibility and thaw-weakening susceptibility rating, heave rates, and thawed California bearing ratio (CBR) values. Preliminary test results for a few Iowa soils are provided in this report. Field testing to evaluate damage during spring thaw includes (a) visual inspection, (b) rut measurement, (c) dynamic cone penetrometer to determine frost depth and CBR profile (during thawing) down to about 3 ft., (d) falling weight deflectometer (FWD) to determine support capacities/ stiffness of the gravel and foundation layers, (e) ground penetrating radar (GPR) survey to determine frost depth and evaluate road conditions, and (f) inground moisture content and temperature monitoring to determine thawing periods.

Recommendations

It is recommended that demonstration research projects be conducted to examine a range of construction methods for building and treating granular surfaced roadways. The primary methods identified in this study include chemical and mechanical stabilization; scarification, blending, and recompaction; removal and replacement; separation, and reinforcement; geogrids and cellular confinement; drainage control and capillary barriers, and use of alternative/ recycled materials. To be effective, stabilization practices must address multiple issues simultaneously, including water migration, durability, cost, performance under loaded vehicles and snow plows/blades, etc. A range of potential stabilization technologies to address these issues are proposed for field evaluation. Demonstration projects could be established to monitor a selected set of these technologies. The test sections of roadway should be monitored year round in terms of performance and maintenance requirements. The objectives of the demonstration projects could be to:

1. Perform laboratory ASTM D5918 tests and field testing on a range of granular surface stabilization technologies.
2. Measure and document the performance of the demonstration roadway sections before, during, and after a seasonal freeze-thaw cycle.
3. Assess the initial cost, relative performance, maintenance requirements, and long-term life-cycle costs of the different stabilization techniques.
4. Identify the most effective and most economical alternatives for minimizing or eliminating frost-heave/boil issues before they occur.

For current monitoring, it is recommended that engineers use GPS enabled cameras and send images of problem areas for compilation on a common ftp site and the results studied to find geographic trends.

CHAPTER 1: INTRODUCTION

This report describes a detailed literature survey on the topic of unbound granular road performance and construction with respect to freeze-thaw damage and resistance. Figure 1 shows typical Iowa gravel roadway conditions during the spring-thaw period. Improvements to reduce rutting and preventing frost-heave are desired. In this report, engineering recommendations are provided for (1) collecting local information to better characterize the extent of the problem and (2) constructing test sections to evaluate freeze-thaw mitigation technologies at a full-scale.

A worldwide literature review was conducted using many sources and the results were assessed in a systematic approach using a rating system developed as part of this project. The results of the literature review are organized by engineering categories. Approximately 300 documents were reviewed and then down selected to about 150 for full assessment and inclusion in the bibliography.

The report is organized into five chapters and an Appendix. Chapter 2 of this report provides an overview of the freeze-thaw mechanism and examples of freeze/thaw problems in unpaved roads. Chapter 3 summarizes the results of the literature review and assessment and Chapter 4 presents key findings from literature on freeze-thaw damage evaluation and mitigation methods. Chapter 5 presents key findings from this study and recommendations for field evaluation studies. An annotated bibliography of the literature categorized into eighteen engineering categories is provided in the Appendix. The literature database is available electronically in EndNote® by request to the authors.

(a) (b)

Figure 1. Examples of spring-thaw rutting in Iowa: (a) from Boone County on March 20, 2013, and (b) from Hamilton County on March 5, 2013

CHAPTER 2: BACKGROUND AND DESCRIPTION OF PROBLEM

Problem Statement

Freezing and thawing action induces physical changes to granular surface road that can negatively impact public users, reduces emergency responder access/time, and results in maintenance costs for secondary road departments. Stabilization can help reduce frost-susceptible conditions for unbound granular roads, but require careful engineering design and controlled construction techniques. The comprehensive literature review conducted for this project categorized technical and some economic aspects of freeze-thaw mitigation for granular surfaced roadways. Figure 2 shows the pervasive extent of this challenging problem globally in freeze-thaw climates.

(a) (b) (c) (d)

Figure 2. Freeze thaw damage on unpaved roadways: (a) potholes during July 2010 thawing season on a gravel road near Boden, Sweden (Christoffersson and Johansson 2011), (b) structural spring thaw damage on a moraine soil in Kemijarvi, Finland (Saarenketo and Aho 2005), (c) rutting damage on a gravel road in Vermont shortly after adding 6 in. of gravel to saturated subgrade in April 2002 (Henry et al. 2005), (d) early phase of surface thaw-weakening on a gravel road in Finland (Saarenketo and Aho (2005))

The European Union established a ROADEX project, which is a transnational technical collaboration to share information on low volume roads (i.e., winter maintenance issues, management, research reports, testing data, etc.) among different European northern periphery countries. The project started in 1998 as a three-year pilot project and then expanded to multiple countries to continue as ROADEX II project. The project goals were to develop models, assessment methods, and tools to improve the road condition management of the low-volume rural road networks in the northern European countries (Munro et al. 2007). Many project reports have been published as part of this effort since 1998 (see www.roadex.org), and references relevant to this research project have been collected and included in the literature review (Aho and Saarenketo 2006, Christoffersson and Johansson 2011, Christoffersson and Johansson 2012, Dawson et al. 2007, Drake 2012, Hyvonen et al. 2012a, 2012b, Munro et al. 2007, Saarenketo and Aho 2005, Salour and Erlingsson 2012).

Freezing and Thawing Process in Soils

In climates with freeze-thaw cycles, damaging heave during frozen conditions and strength loss after the thaw can occur in unbound materials used in unpaved roads. Presence of freezing temperatures, water, and soils that have suitable pore structures (e.g. silts) to facilitate capillary flow, results in freezing and thawing cycles as the temperature fluctuates during the winter.

Heave is primarily caused by the formation of ice lenses, where water is moved to the freezing front in soils via capillary action. The degree of frost-heave is dependent on the soil pore size, the associated capillary stress, and the duration of the freezing period. Capillary stress is caused by surface tension of free water. Frost boils typically become noticeable mid to late winter and grow during the frozen period. Figure 3 shows an example of heaving of the pavement foundation soils.

Figure 3. Frost-heave pavement damage in Norway (Ystenes 2011)

Heave on unpaved roads mostly occurs in the vertical direction because this is the direction of least resistance. Heave pressures can be on the order of 200 psi (Taber 1929), which is equivalent to about 200 ft of overburden pressure. Increasing soil pressure could be beneficial by increasing the consolidation pressure, but as ice lenses grow at pressures larger than the overburden pressure, the stresses between soil particles becomes zero. Then the soil particles move freely with the ice (Miller 1972). The perimeter of the frozen ice lenses is called the frozen fringe and has been described as analogous to "quick sand" indicating water movement and loss of inter-particle soil shear strength. Frost-heave is problematic for unpaved roads, but not as serious generally or costly to repair compared to thaw-weakening problems.

As the temperatures begin to warm, thaw-weakening progresses. The ice lenses that formed during frost penetration eventually thaw from the top down and bottom up. As the frozen soil thaws, its moisture content increases and the shear strength decreases as a result of the soil particles being separated during the ice lens formation process. Because the underlying materials are still frozen, water is trapped in the unbound surface gravel. This leads to rutting under wheel loads. Stability is only regained once the water drains away. During this period of thawing and wet conditions, severe damage occurs. Figure 4 illustrates this damage (VTrans 2005).

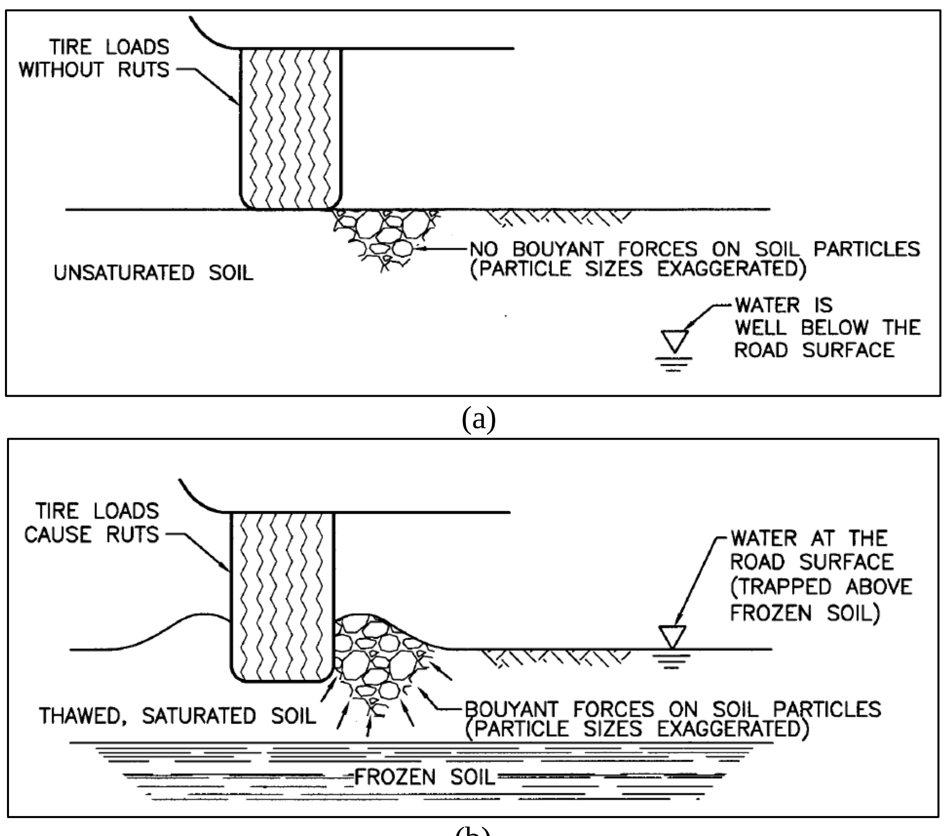

Figure 4. Rutting damage under tires (VTrans 2005): (a) dry conditions during late spring through fall with unsaturated soil and no rutting under tires, and (b) wet conditions during spring-thaw resulting in rutting

CHAPTER 3: LITERATURE REVIEW AND ASSESSMENT

The primary task of this project was to perform a detailed literature review and then conduct a systematic assessment of the documents to identify technologies suitable for future evaluation and implementation in Iowa. An important outcome of this effort is an organized database of literature with 150+ technical articles on this research topic. The literature documents have been organized in an electronic database (EndNote®), which can be shared with other researchers and practitioners. The database can be used as an effective tool to search for information regarding the various repair and mitigation solutions, measurement technologies, and experiences that have been documented by selected domestic and international researchers and practitioners.

Assessment Approach

A worldwide literature review was conducted and assessed in a systematic approach. Literature was obtained from on-line sources and inter library loans. On-line sources included various search engines including: (a) Google, (b) Engineering Village, (c) Web of Knowledge, (d) Swedish Geotechnical Institute, (e) American Society of Civil Engineers (ASCE) library, (f) Transportation Research Information Services Database (TRID), (g) WorldCat, (h) Iowa DOT library, and (i) other state DOT search engines. Peer-reviewed journal (PJ) and conference proceeding (CP) articles, technical reports (TR), agency publications (AP) (e.g., design standards and manuals), text books (B), and thesis/dissertations (T/D) were collected. Literature that was not available for download through these online resources were requested through Iowa State University interlibrary loan for complimentary copies. The literature documents were then organized in to an electronic database to generate an automatic Annotated Bibliography and for being able to share the database electronically with Iowa DOT members and Iowa County Engineers (Figure 5). All of the documents can be provided upon request.

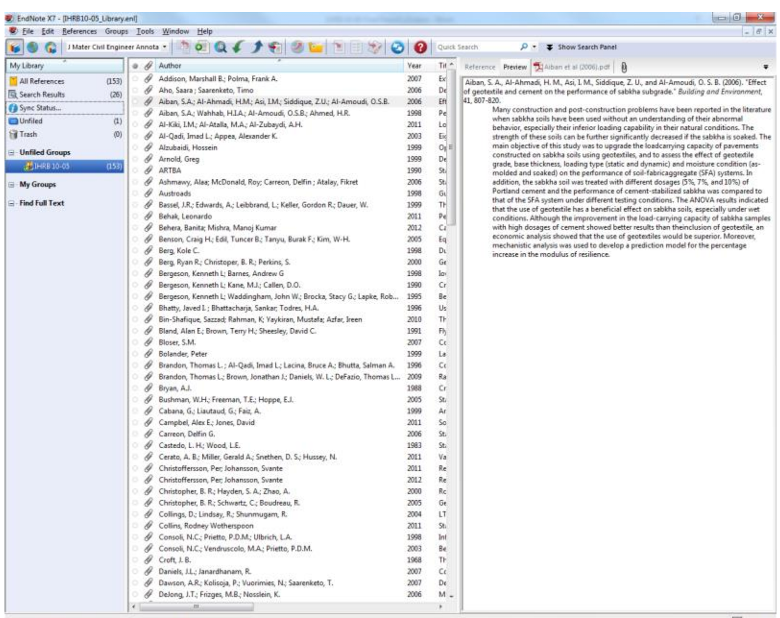

Figure 5. Screenshot of EndNote® literature library software

The literature documents were assessed according the following assessment criteria and engineering categories:

- Stabilization Method
  - Chemical Stabilization (cement, fly ash, bitumen/asphalt emulsion, hydrated fly ash, lime, chlorides, sodium montmorillonite/bentonite, biofuel byproducts)
  - Mechanical Stabilization (blending, geotextiles, geogrids, geocomposites, geocells, macadam base, fibers, recycled materials)
  - Bio Stabilization (microbial/bio-remediation) – This topic is relatively new and has been limited to laboratory trials. Very limited literature has been collected on this topic as part of this project.
- Soil Type
  - Granular Soil
  - Non Granular Soil
  - Other (e.g., hydrated fly ash)
- Freeze-Thaw or Frost-Heave Issues – mechanisms of frost-heave and thaw-weakening, damage during thaw-weakening and frost boils.
- Rehabilitation/Repair Options – use of cold in-place recycling, full depth or partial depth reclamation, grading, and other repair options to fix roadways after thaw damage.
- Stabilization Design Procedures – mix design for chemical stabilization processes and granular layer thickness design for geosynthetic design.
- Durability – results corresponding to freeze-thaw durability aspects.
- Construction Methods/Considerations and Time – construction methods used for stabilization or repair, recommended considerations during construction, and time for stabilization/repair.
- Equipment and Contractors – specialized equipment used corresponding to a stabilization method and Contractor information.
- Specifications – information regarding specifications or contracts that are documented in the literature (actual specification documents are not included in this search).
- Quality Assurance (QA)/Quality Control (QC) Testing Procedures –information on QA/QC testing procedure to assess damage during thawing period on roadways.
- Performance Monitoring Results – long-term monitoring results with rutting or other performance related measurements.
- Limitations – limitations of a particular stabilization method.
- Lab Testing Results – information from lab testing.
- Field Study (Unpaved Roads) – field studies on unpaved roads with test sections.
- Field Study (Unpaved Roads) – field studies on paved roads with test sections.
- Environmental Impacts – information related to environmental impacts of using a particular stabilization method.
- Initial Cost – cost of materials and construction/installation
- Life Cycle Costs – results of life cycle costs based on initial costs and maintenance costs over a long period (including literature with analysis methods).
- Maintenance issues – maintenance aspects of roadways during spring/thawing period.
- Numerical Analysis/Thickness Design Aspects – information regarding gravel layer and pavement layer thickness design, and numerical analysis modelling freeze-thaw damage or rutting.

Each literature document was rated on a scale of 1 to 4 as it relates to the potential to contribute to solutions to this problem in Iowa (1 – not applicable, 2 – marginally applicable and not considered, 3 – marginally applicable but technically strong, 4 – applicable and technically strong). Engineering judgment was used in rating each article. In addition, the publication type of each article is identified, i.e., AP – Agency Publication, B – Book, CP – Conference Proceedings, IP – Industry Publication, NJ – Non Peer-Reviewed Journal, P – Patent, PJ – Peer-Reviewed Journal, T – Thesis (Masters), D – Dissertation (Doctorate), and TR – Technical Report. The number each article was cited is also determined, based on Google Scholar Citations.

Key Outcomes

The key outcomes of the literature review/assessment include an assessment matrix (Table 1) and an Annotated Bibliography included in the Appendix, which is organized by the eighteen engineering categories highlighted in gray in Table 1. A total of 153 technical articles, which included 105 articles from domestic (with in US) and 48 articles from international research (including Canada, South America, Europe, South Asia). The number of references collected based on the stabilization type, soil type, origin of publication, and type of publication are summarized as pie-charts in Figure 6. A pie chart with number of references for each engineering category is shown in Figure 7. Out of the153 references, 10 received rating 1, 70 received rating 2, 65 received rating 3, and 6 received rating 4 (see Figure 8). The literature that reviewed ratings 3 and 4 were considered in developing recommendations for field studies.

The most important aspects of this study is to have field performance measurements on unpaved rural surface roads that have been stabilized and subjected to freeze-thaw cycles over a long period of time. Figure 9 shows a Venn diagram combining the references corresponding to three engineering categories (i.e., field study on unpaved roads, freeze thaw durability aspects, and performance measurements). Only 5 relevant references were found with information from these three categories, although with limited information. Brief overview of these references are as follows:

- Bergeson et al. (1995) — Iowa Highway Research Board (HR 351) project: This research project involved laboratory and field evaluation of sodium montmorillonite clay (Bentonite) for dust reduction on gravel (limestone) roads. The bentonite treatment was found to be effective in dust reduction for two to three seasons, which was higher than chloride based treatments which were only effective for three to four months. Bonding was observed between bentonite and limestone particles, which was recoverable from freeze-thaw and wet/dry cycles. Rutting or other performance measurements were not available from this study.
- Henry et al. (2005) — US Army Corps of Engineers Project: This research project involved evaluating use of a geowrap technique which comprised of clean sand sandwiched by geotextile separators, and a patented geocomposite drainage layer technique to mitigate thaw-weakening at the surface. The study indicated that both these techniques worked well in keep the surface layers dry during the thawing period. Literature on the use of these techniques with long-term performance measurements is limited, however.

- Hoover et al. (1982) — Iowa Highway Research Board (HR 211) project: This research project involved laboratory and field investigation of using randomly oriented fibers for stabilizing base course materials. Although promising results were obtained with increased durability and compressive strengths with certain types of fibers in a laboratory setting, field test results were not conclusive due to the variability. Further, long-term performance results were limited in the study.
- Jobgen et al. (1994) — Iowa Highway Research Board (HR 312) project: This research project evaluated performance of four different stabilization methods on unsurfaced roads including: a) high float emulsion (HFE-300) treated base stone, b) a bio-chemical formula (BIO CAT 300-1) treated base stone with different thicknesses, c) Consolid System treated subgrade, wherein when the soil is dry a combination of two inverted emulsions are used and when the soil is wet a combination of an inverted emulsion and a lime hydrated base powder are used to treat the base stone, and d) 5 in. of macadam base and 2 in. of choke stone along with fabric under one of the sections. All test sections were sealed using a double seal coat and performance evaluation was conducted on these sections using Iowa Road Rater, Roughometer, and visual inspection annually for three years. The results indicated that the macadam base and the HFE-300 treated sections were cost effective treatment options, and all other sections showed deterioration within the evaluation period due to freeze-thaw action.
- Shoop et al. (2003) — US Army Corps of Engineers projects: This paper documented results with different techniques used to stabilize/repair thawing soils. These techniques involved using unit mats (plastic or rubber mats or wood), chunk wood, tire mats, tire chips, geocomposite drainage system, high strength geotextile, pipes, portland cement, rapid set cement, hydrated lime, and quick lime. Results indicated successful short-term treatment, but long-term durability under freeze-thaw cycles was not available.

Table 1. Literature assessment matrix

KEY:
- ✓ = item addressed
- C – Chemical stabilization (cement, fly ash, bitumen/asphalt emulsion, hydrated fly ash, lime, chlorides, sodium montmorillinite/bentonite, combinations, biofuel byproducts)
- M – Mechanical stabilization (blending, geosynthetics, macadam base, fibers, use of recycled products)
- B – Bio-stabilization (microbial)
- G – Granular Soil
- N – Non-Granular Soil
- O – Other (e.g., hydrated fly ash)
- D – Domestic
- I – International
- AP – Agency Publication
- B – Book
- CP – Conference Proceedings
- IP – Industry Publication
- NJ – Non Peer-Reviewed Journal
- P – Patent
- PJ – Peer-Reviewed Journal
- T – Thesis (Masters)
- D – Dissertation (Doctorate)
- TR – Technical Report

Reference	Stabilization Type	Soil Type	Freeze-Thaw or Frost-Heave Issues	Rehabilitation/Repair Options	Stabilization Design Procedure/Typical Values	Durability (Freeze-Thaw Cycles)	Construction Methods/Considerations and Time	Equipment and Contractors	Specifications/Contract Related Aspects	QA/QC Testing Procedures	Performance Monitoring Results	Limitations	Lab Testing Results	Field Study – Unpaved Road	Field Study – Paved Road	Environmental Impacts	Initial Cost	Life Cycle Costs	Maintenance Issues	Numerical Analysis / Thickness Design Aspects	Origin of Reference	Publication Type	Number of Instances Cited[a]	Rating (1 to 4)[b]
Addison and Polma (2007)	C	NG								✓	✓				✓						D	CP	2	2
Aho and Saarenketo (2005)	C/M	G/ NG	✓	✓			✓			✓								✓		✓	I	TR	2	4
Aiban et al. (1998)	C	NG								✓			✓		✓						I	PJ	13	1
Aiban et al. (2006)	C/M	G/ NG											✓								I	PJ	12	2
Al-Kiki et al. (2011)	C	NG				✓							✓								I	PJ	1	2
Al-Qadi and Appea (2003)	M	G/ NG								✓	✓				✓						D	PJ	7	3
Alzubaidi (1999)			✓	✓			✓												✓		I	TR	3	3
Arnold (1999)				✓						✓										✓	I	PJ	1	2
ARTBA (1990)	C/M	G/ NG			✓		✓														I	AP	—	3
Ashmawy et al. (2006)	M											✓				✓					D	TR	1	2
Austroads (1998)	C/M	G/ NG			✓		✓			✓						✓					I	AP	—	3
Bassel et al. (1999)	M	G		✓			✓			✓				✓			✓				D	PJ	0	2
Behak (2011)	C	NG								✓	✓			✓							I	PJ	0	1
Behera and Mishra (2012)	C	O											✓								I	PJ	0	1
Benson et al. (2005)	M	G			✓					✓			✓		✓						D	TR	0	2
Berg (1998)	C	O				✓							✓								D	T	3	3
Berg et al. (2000)	M	G/ NG			✓		✓											✓		✓	D	TR	23	3
Bergeson and Barnes (1998)	C	O													✓					✓	D	PJ	13	2

KEY:
✓ = item addressed
C – Chemical stabilization (cement, fly ash, bitumen/asphalt emulsion, hydrated fly ash, lime, chlorides, sodium montmorillinite/bentonite, combinations, biofuel byproducts)
M – Mechanical stabilization (blending, geosynthetics, macadam base, fibers, use of recycled products)
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NJ – Non Peer-Reviewed Journal
P – Patent
PJ – Peer-Reviewed Journal
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	Stabilization Type	Soil Type	Freeze-Thaw or Frost-Heave Issues	Rehabilitation/Repair Options	Stabilization Design Procedure/Typical Values	Durability (Freeze-Thaw Cycles)	Construction Methods/Considerations and Time	Equipment and Contractors	Specifications/Contract Related Aspects	QA/QC Testing Procedures	Performance Monitoring Results	Limitations	Lab Testing Results	Field Study – Unpaved Road	Field Study – Paved Road	Environmental Impacts	Initial Cost	Life Cycle Costs	Maintenance Issues	Numerical Analysis / Thickness Design Aspects	Origin of Reference	Publication Type	Number of Instances Cited[a]	Rating (1 to 4)[b]
Bergeson et al. (1990)		G		✓			✓			✓	✓		✓	✓					✓		D	TR	1	2
Bergeson et al. (1995)	C	G		✓		✓					✓		✓	✓			✓				D	TR	5	4
Bhatty et al. (1996)	C	NG				✓				✓			✓								D	TR	27	2
Bin-Shafique et al. (2010)	C	NG				✓							✓								D	PJ	14	2
Bland et al. (1991)	C/M										✓		✓	✓		✓					D	TR	0	2
Bloser (2007)							✓				✓			✓					✓		D	PJ	1	2
Bolander (1999)	C	G				✓							✓								D	PJ	18	2
Brandon et al. (1996)	M	G/ NG					✓							✓							D	PJ	40	1
Brandon et al. (2009)	C/M						✓					✓									D	TR	2	3
Bryan (1988)	C	N			✓	✓															I	PJ	18	2
Bushman et al. (2005)	M	G/ NG		✓			✓										✓	✓			D	PJ	6	3
Cabana et al. (1999)									✓												I	PJ	12	1
Campbell and Jones (2011)	C	NG					✓							✓							I	PJ	0	1
Carreon (2006)	M															✓					D	T	1	2
Castedo and Wood (1983)	C	G											✓								D	PJ	25	1
Cerato et al. (2011)	C	NG			✓								✓								D	TR	0	1
Chrisoffersson and Johansson (2011)				✓						✓						✓	✓				I	TR	0	3
Chrisoffersson and Johansson (2012)				✓			✓			✓						✓	✓				I	TR	0	3
Christopher et al. (2000)	M	G/ NG								✓	✓				✓						D	CP	20	3
Christopher et al. (2005)	C/M	G/ NG	✓	✓							✓									✓	D	AP	9	2

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B – Bio-stabilization (microbial)

G – Granular Soil

N – Non-Granular Soil

O – Other (e.g., hydrated fly ash)

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Collings et al. (2004)	C	G								✓	✓				✓						I	CP	7	2
Collins (2011)	C	G/ NG				✓							✓								D	T	4	3
Consoli et al. (1998)	C/M	G											✓								I	PJ	137	2
Consoli et al. (2003)	C/M	G											✓								I	PJ	46	
Croft (1968)	C	NG											✓								I	PJ	20	2
Daniels and Janardhanam (2007)	C	NG											✓								D	CP	3	2
Dawson et al. (2007)																				✓	I	PJ	5	3
DeJong et al. (2006)	B												✓								D	PJ	185	2
DeJong et al. (2010)	B												✓								D	PJ	110	2
Dempsey and Thompson (1972)	C	G/ NG				✓							✓								D	PJ	6	2
DOD (1985)	C/M	G/ NG	✓	✓			✓			✓										✓	D	AP	–	3
Douglas and Valsangkar (1992)	M	G											✓								I	PJ	8	2
Drake (2012)		G								✓	✓			✓							I	TR	0	3
Edil et al. (2002)	C/M	NG								✓	✓				✓						D	PJ	74	3
Embacher (2006)										✓				✓	✓				✓		D	TR	7	3
Fannin and Sigurdsson (1996)	M	NG								✓	✓			✓							I	PJ	65	2
Foye (2011)	M	G							✓						✓						D	PJ	2	2
Ghazavi and Roustaie (2010)	C/M	NG				✓							✓								I	PJ	19	3
Giroud (2009)	M	G/ NG			✓						✓										D	CP	0	2
Giroud and Han (2004a)	M				✓																D	PJ	80	3

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Giroud and Han (2004b)	M				✓																D	PJ	41	3
Glogowski et al. (1992)	C	G/ NG				✓	✓		✓	✓											D	TR	3	3
Gopalakrishnan et al. (2010)	C	NG											✓								D	TR	1	3
Gray and Ohashi (1983)	M	G											✓								D	PJ	455	2
Gullu and Hazirbaba (2010)	C	NG				✓							✓								D	PJ	6	3
Hazirbaba and Gullu (2010)	C	NG				✓							✓								D	PJ	10	3
Heath et al. (1999)	C	O								✓	✓				✓						I	PJ	6	2
Helstrom et al. (2007)	M	G/ NG				✓	✓			✓					✓					✓	D	TR	2	3
Henry (1990)	M					✓							✓								D	TR	2	2
Henry (1996)	M					✓							✓								D	PJ	7	4
Henry et al. (2005)	M	G/ NG	✓			✓	✓			✓	✓			✓			✓	✓	✓		D	TR	2	4
Hicks (2002)	C/M					✓		✓		✓							✓	✓			D	TR	16	4
Holtz and Sivakugan (1987)	M				✓					✓										✓	D	PJ	14	2
Holtz et al. (2008)	M									✓										✓	D	TR	71	2
Hoover (1973)	C	G					✓			✓			✓	✓			✓				D	TR	21	2
Hoover (undated)	C	G				✓							✓								D	TR	0	2
Hoover et al. (1981a)	M					✓				✓	✓			✓			✓				D	PJ	3	4
Hoover et al. (1981b)	C	G				✓							✓	✓			✓				D	TR	0	3
Hoover et al. (1982)	M	G/ NG				✓				✓	✓		✓	✓							D	TR	0	3
Hopkins et al. (1995)	C/M	NG			✓		✓			✓			✓		✓						D	TR	7	3

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Hopkins et al. (2002)	C/M	NG									✓		✓		✓						D	TR	5	3
Houlsby and Burd (1999)	M																			✓	I	CP	6	2
Houlsby and Jewell (1990)	M				✓															✓	I	CP	22	2
Hufenus et al. (2006)	M	G								✓	✓			✓							I	PJ	56	2
Huntington and Ksaibati (2011)																			✓		D	PJ	1	1
Hyvonen et al. (2012a)	M	G	✓							✓	✓			✓				✓			I	TR	0	3
Hyvonen et al. (2012b)	M	G	✓							✓	✓			✓				✓			I	TR	0	3
Jahren et al. (2011)	C	G					✓			✓		✓		✓							D	TR	2	2
Janoo et al. (1997)													✓							✓	D	TR	1	2
Jobgen et al. (1994)	C/M	G				✓	✓	✓		✓	✓	✓		✓			✓				D	AP	NA	3
Johnson (2012)	C	G/ NG	✓			✓							✓								D	T	0	3
Kalkan (2009)	C	NG				✓							✓								I	PJ	14	2
Kaniraj and Havanagi (2001)	C/M	G/ NG											✓								I	PJ	124	2
Keller and Sherar (2003)							✓							✓					✓		D	TR	35	2
Kendall et al. (2001)	C	G					✓			✓	✓				✓		✓				I	CP	1	2
Kestler (2003)						✓				✓											D	PJ	4	3
Kestler (2009)	C/M	G/N G			✓		✓	✓								✓	✓				D	AP	5	3
Kestler et al. (1999)										✓	✓										D	PJ	3	3
Kettle and McCabe (1985)	M	NG				✓							✓								I	PJ	4	3
Khoury and Zaman (2002)	C	G											✓								D	PJ	15	2
Khoury and Zaman (2007a)	C	G											✓								D	PJ	4	2

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Khoury and Zaman (2007b)	C	G				✓							✓								D	PJ	10	3
Koch et al. (2011)	C/M	G					✓				✓			✓							D	PJ	2	2
Latha et al. (2010)	M	G									✓		✓								I	PJ	0	2
Less and Paulson (1977)	M	G				✓	✓				✓				✓		✓				D	TR	0	3
Li et al. (2008)	C	G				✓								✓		✓					D	PJ	10	2
Litzka and Haslehner (1995)	M	G									✓				✓		✓				I	CP	7	2
Lohnes and Coree (2002)	C	G			✓																D	TR	12	2
Lynam and Jones (1979)	M	G						✓		✓	✓				✓						D	TR	0	3
Marti et al. (2003)			✓	✓															✓		D	AP	0	3
Mathur et al. (1999)	C												✓								I	PJ	10	2
Maurer et al. (2007)				✓							✓			✓							D	PJ	5	2
Maxwell et al. (2004)	M	NG			✓										✓						D	TR	0	2
McHattie (2010)	C	G		✓					✓										✓		D	AP	0	3
Mekkawy et al. (2011)	M	G/ NG			✓					✓	✓		✓	✓							D	PJ	2	3
Mhaiskar and Mandal (1992)	M	NG											✓								I	CP	0	2
Monlux (2003)	C	G											✓	✓			✓	✓	✓		D	PJ	11	2
Monlux and Mitchell (2007)	C	G											✓	✓			✓	✓	✓		D	PJ	10	2
Morgan et al. (2005)	C	G												✓			✓				D	TR	0	2
Muench et al. (2007)																					D	PJ	5	1
Munro et al. (2007)		G				✓				✓	✓			✓							I	PJ	2	3
Muthen (1999)	M	G		✓	✓								✓								I	TR	75	2
Newman and White (2008)	M	NG					✓	✓		✓				✓							I	PJ	6	2

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Parsons and Kneebone (2005)	C	NG													✓						D	PJ	14	2
Parsons and Milburn (2003)	C	NG				✓							✓								D	PJ	28	3
PCA (1995)	C	G/ NG			✓	✓															D	AP	21	3
Pinilla et al. (2011)	C	NG											✓								D	PJ	3	2
Powell et al. (1999)	M	G												✓			✓				D	PJ	4	2
Pratico et al. (2011)	C	G/ NG																✓			D	PJ	9	2
Raymond and Bathurst (2000)	M	G				✓								✓							I	CP	2	3
Rollings and Rollings (1996)	M/C	G/ NG			✓			✓		✓				✓							D	B	–	3
Saarenketo and Aho (2005)			✓	✓		✓				✓	✓			✓							I	TR	1	3
Salour and Erlingsson (2012)			✓			✓				✓	✓				✓						I	TR	0	3
Shoop and Henry (1991)	M	G				✓							✓								D	PJ	3	3
Shoop et al. (2003)	M/C	G/ NG				✓	✓			✓	✓			✓			✓				D I	PJ	3	3
Shoop et al. (2005)		G												✓						✓	D	TR	2	3
Shoop et al. (2006)		G												✓						✓	D	TR	14	3
Shoop et al. (2008)		G												✓						✓	D	PJ	10	3
Sigurdsson (1991)	M	G					✓			✓	✓			✓							I	T	7	3
Simonsen et al. (2002)		G/ NG				✓							✓								D	PJ	55	3
Sirivitmaitrie et al. (2011)	C	NG								✓	✓				✓						D	PJ	3	2
Solanki et al. (2013)	C	NG				✓							✓								D	CP	0	3

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Stormont and Stockton (2000)	M	G					✓						✓								D	CP	6	3
Stormont et al. (2001)	M	G					✓						✓								D	PJ	7	3
Terrel et al. (1979)	C/M	G/ NG			✓		✓													✓	D	TR	35	3
Tingle and Webster (2003)	M	G/ NG			✓															✓	D	PJ	6	2
Velasquez et al. (2005)	C	NG											✓								D	TR	4	2
Vennapusa et al. (2013)	C	G								✓				✓							D	TR	0	2
VTrans (2005)	C/M	G/ NG	✓			✓	✓							✓							D	AP	–	3
White et al. (2005a)	C	NG					✓			✓	✓		✓		✓						D	TR	2	3
White et al. (2005b)	C	NG				✓					✓									✓	D	TR	2	3
White et al. (2007)	C/M	G/ NG								✓				✓							D	TR	2	3
White et al. (2008)		G								✓	✓		✓		✓						D	TR	1	3
Yarbasi et al. (2007)	C/M	G				✓							✓								I	PJ	50	2
Zaimoglu (2010)	C/M	G				✓							✓								I	PJ	8	2

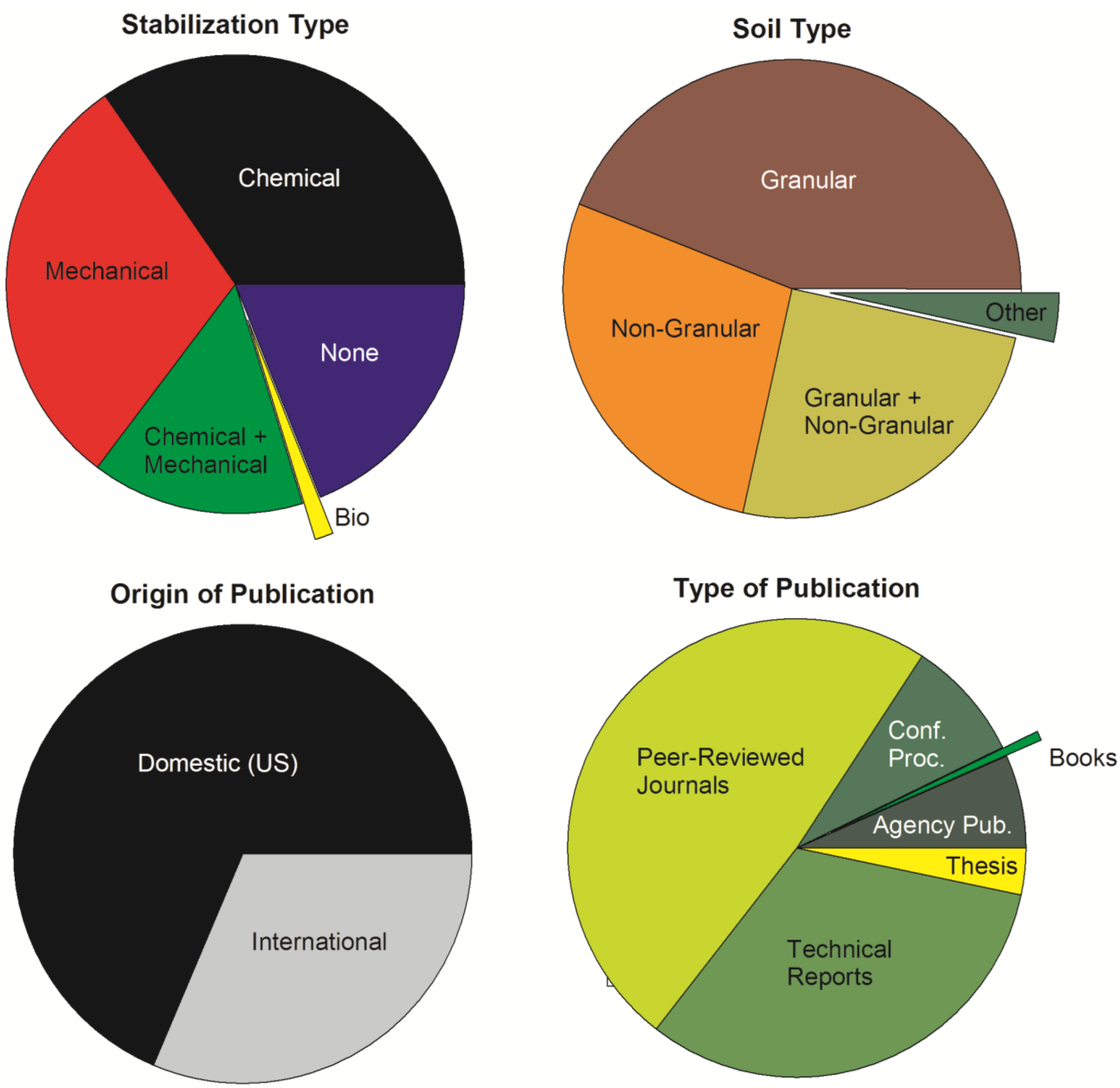

Figure 6. Number of references obtained (# shown in parenthesis) for stabilization type, soil type, origin of publication, and type of publication

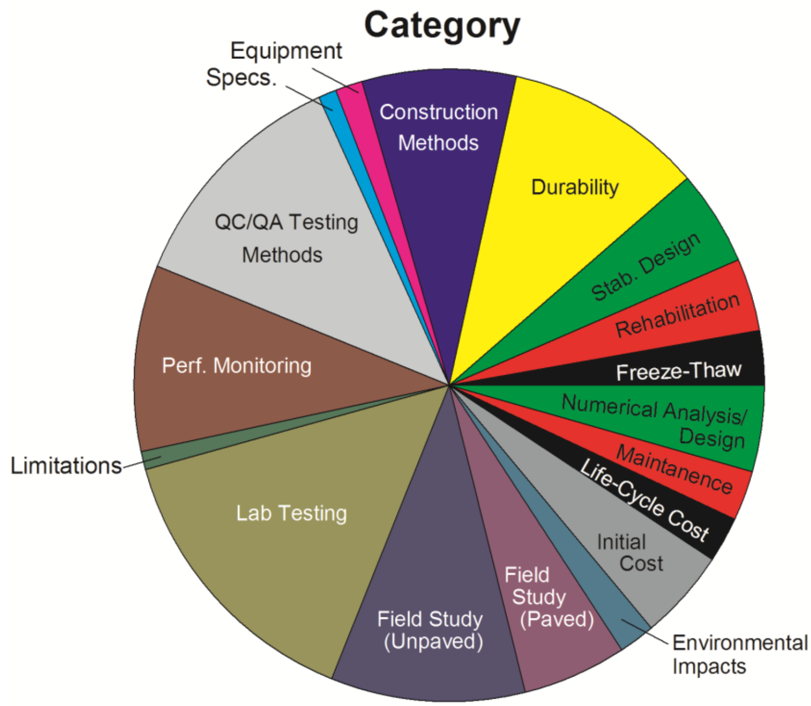

Figure 7. Number of references obtained (# shown in parenthesis) for each category

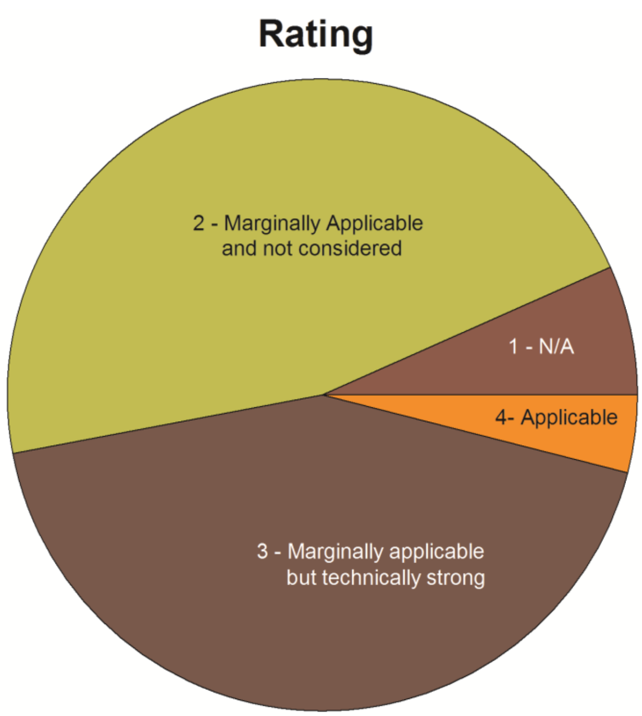

Figure 8. Number of references (# shown in parenthesis) with corresponding rating

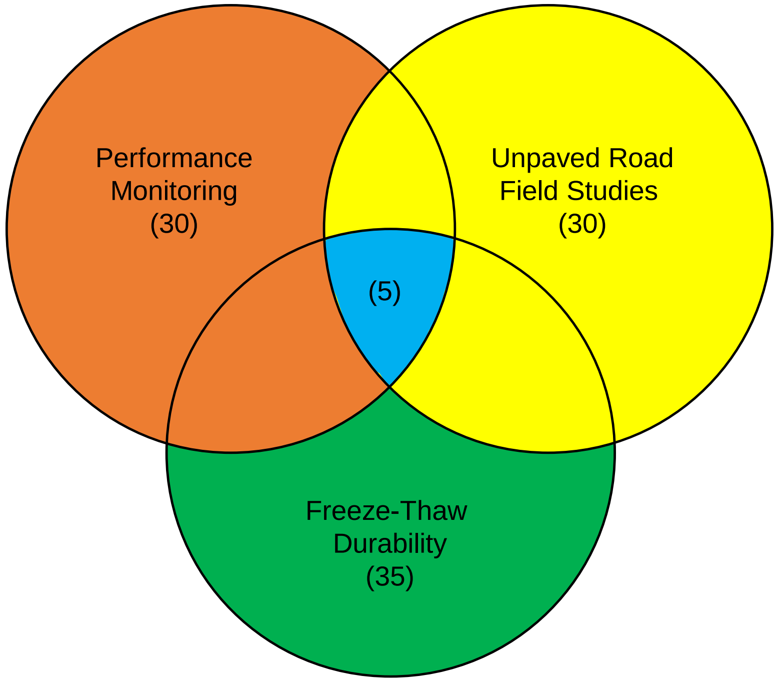

Figure 9. Number of references (# shown in parenthesis) for each category

CHAPTER 4: DAMAGE MITIGATION AND EVALUATION TECHNIQUES

Freeze-thaw cycles combined with frost-susceptible soils and inadequate drainage lead to damage in unbound roads, and in severe cases, make them impassable. Intersections and bridge approaches are common trouble locations, but damage due to frost-heave and boils can occur throughout a given roadway depending on variations in drainage, construction quality, and traffic loading. Some approaches currently used by County Engineers to deal with frost boils include temporarily spreading rock on the affected areas, lowering or improving drainage ditches, tiling, bridging the area with stone and geosynthetic covered by a top course of aggregate or gravel, coring boreholes and filling them with calcium chloride to melt lenses and provide drainage, and re-grading the crown to a slope of 4 to 6% to maximize spring drainage. However, most of these maintenance solutions are aimed at dealing with conditions after they occur.

Based on the review of literature, stabilization and drainage were identified as feasible mitigation solutions to the problems of frost-heave and thaw-weakening. Stabilization works by increasing the shear strength of the surface and/or subgrade layers to resist the actions of freeze-thaw and drainage works by eliminating or reducing water from the freeze-thaw process. Short descriptions of stabilization and improved drainage mitigation approaches are described below. Various damage evaluation techniques involving field and laboratory test methods to evaluate frost-heave and thaw-weakening damage that have been documented in the literature are also summarized below.

Mitigation Solutions

Chemical Stabilization

Numerous studies have been conducted over the past several decades on chemical stabilization process. An extensive review of chemical stabilization process is beyond the scope of this study. However, articles that discussed chemical stabilization in the context of freeze-thaw durability and general design and construction guidelines have been collected. 76 technical articles have been collected on the chemical stabilization topic. Review of literature indicated that admixtures used in the stabilization process are typically either active or passive. Active chemical admixtures that are commonly used include portland cement, fly ash, lime, and passive chemical admixtures include bitumen, plant processed bio-fuel co-products with varying lignin contents and lignosulfates, and polymer emulsions.

General information published in the literature for selecting stabilizer based on soil grain-size characteristics and Atterberg limits are shown in Figure 10 to Figure 12 and Table 2. ASTM class C self-cementing fly ash has been used on a limited scale in Iowa to treat unstable/wet subgrades. Using self-cementing fly ash for soil stabilization provide environmental incentives in terms of using a waste product, cost savings relative to other chemical stabilizers, and availability at several power plants across Iowa (White et al. 2005). The characteristics of fly ash can vary significantly between different plants due to variations in the coal used and various operating conditions in the plant. Laboratory mix design is recommended when using fly ash for stabilization. Chemical stabilization process in the field typically involves application of stabilizer to loose soil, mixing the stabilizer with a soil reclaimer and moisture-conditioning the mixture, and compacting the mixture within a specified time (typically less than 1 to 2 hours). Typical field construction operations are shown in Figure 13. Compaction time is critical and is dependent on the chemical admixture set time and must be determined using laboratory testing.

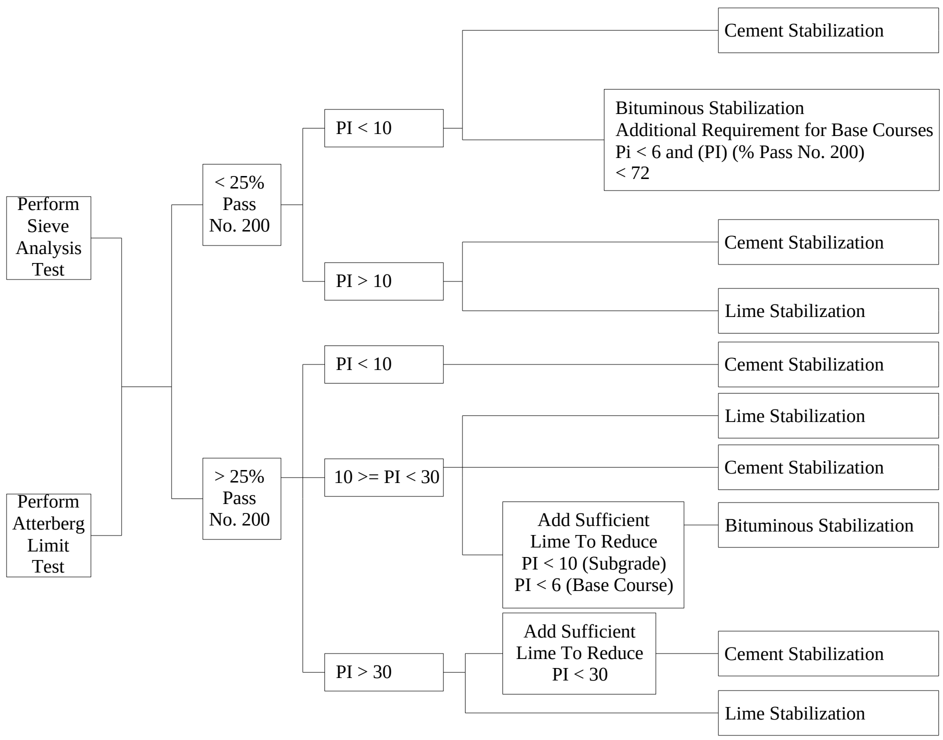

Figure 10. Chart for selection of stabilizer (Chu et al. 1955)

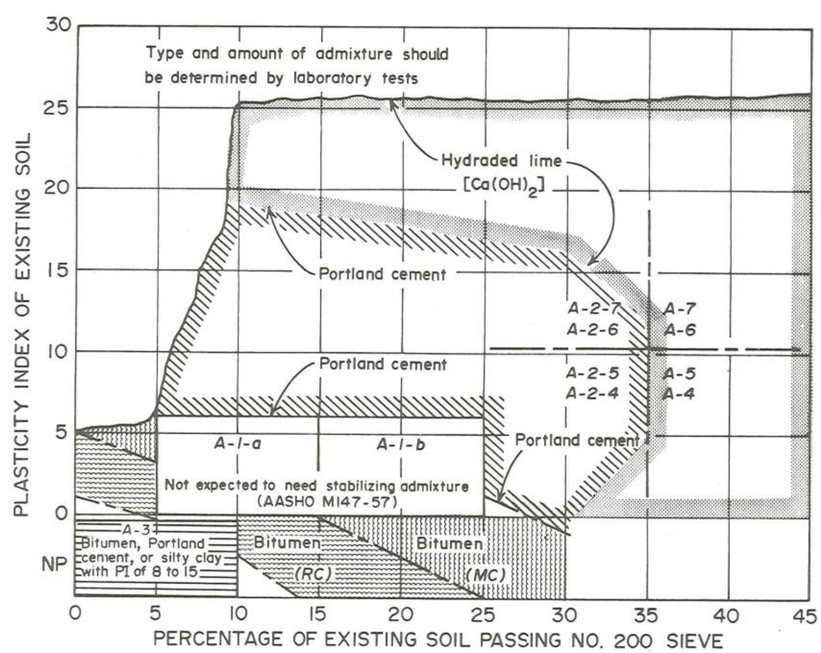

Figure 11. Chart for selection of stabilizer (Terrel et al. 1979)

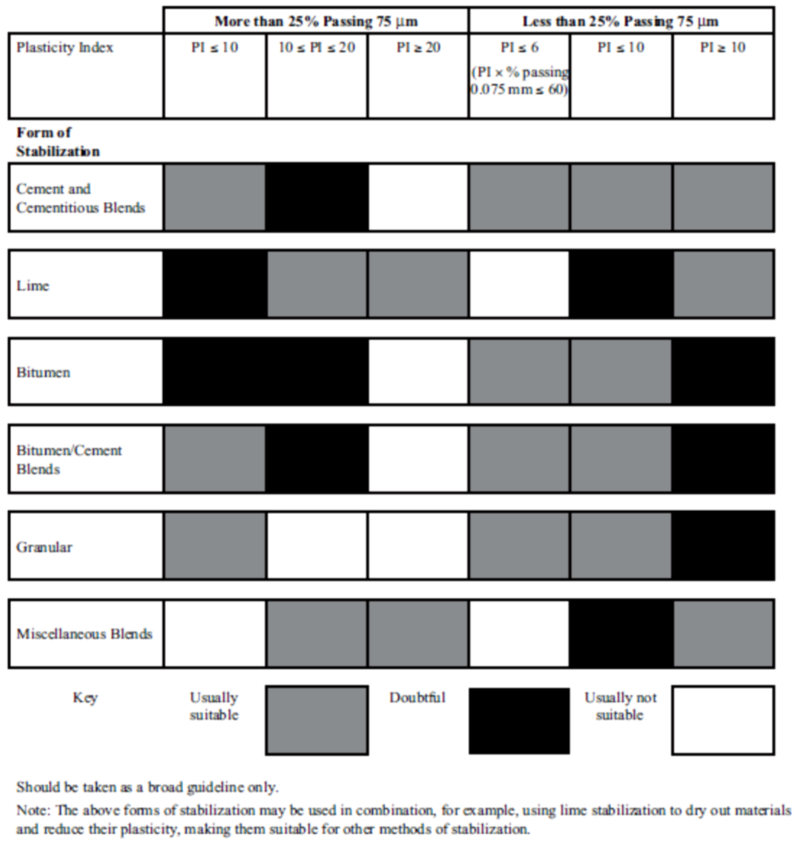

Figure 12. Guide to selecting stabilization method (Originally from Austroads 1998 and modified by Hicks 2002)

Table 2. Recommended cement contents for different soil types (PCA 1995)

AASHTO soil classification	Unified soil classification	Normal range of cement requirements: % by volume	Normal range of cement requirements: % by weight	Cement content for moisture-density test, % by weight	Cement contents for wet-dry and freeze-thaw tests, % by weight
A-1-a	GW, GP, GM, SW, SP, SM	5-7	3-5	5	3-5-7
A-1-b	GM, GP, SM, SP	7-9	5-8	6	6-4-8
A-2	GM, GC, SM, SC	7-10	5-9	7	5-7-9
A-3	SP	8-12	7-11	9	7-9-11
A-4	CL, ML	8-12	7-12	10	8-10-12
A-5	ML, MH, CH	8-12	8-13	10	8-10-12
A-6	CL, CH	10-14	9-15	12	10-12-14
A-7	MH, CH	10-14	10-16	13	11-13-15

(a)

(b)

(c)

Figure 13. Photos showing typical chemical stabilization process: (a) spreading of cement stabilizer on subgrade, (b) mixing cement with subgrade material using a pulverizer, and (c) compaction of the soil-cement mixture using a padfoot roller (pictures from Boone County Expo Site, June 2012)

Durability of chemically stabilized materials to freeze-thaw cycles has been studied by many researchers in laboratory setting. The testing involves either determining loss of material during freeze thaw cycles and/or measuring unconfined compressive strength/California bearing ratio (CBR) after a certain number of freeze thaw cycles. Previous research indicated that portland cement stabilized materials generally show superior performance than any other chemical stabilizer (e.g., Parsons and Milburn 2003, Henry et al. 2005). A picture of a cement stabilized section from Vermont during spring thaw is shown in Figure 14, with no significant damage (Henry et al. 2005). A few studies indicated improvements with non-traditional stabilizers such as Soil-Sement (polymer emulsion) products (e.g., Collins 2011). Mixed information was found with fly ash stabilized fine-grained and coarse-grained soils. For e.g., Berg (1998) studied freeze-thaw performances of reclaimed hydrated fly ash activated aggregate materials, and found that the materials did not survive over ten laboratory freeze-thaw cycles. The percentage fly ash additive levels in these materials varied from about 15% to 20%. However, some field studies documented therein showed that these materials did perform well, even though they break down during the freeze-thaw action. Results presented by Bin-Shafique et al. (2010) were similar to Berg (1998), in terms of performance of fly ash stabilized soils. Bin-Shafique et al. (2010) indicated that fly ash stabilized soils lost up to 40% of the strength due to freeze-thaw cycles, although they did not experience significant strength loss during wet-dry cycles. The swell potential of the stabilized expansive soil was greater due to freeze-thaw cycles. However, even after the strength loss, the fly ash stabilized mixture had about three times more strength than an unstabilized soil. Khoury and Zaman (2007b) investigated the effect of freeze-thaw cycles on cement kiln dust (CKD), class C fly ash, and fluidized bed ash (FBA) stabilized aggregates. Results indicated that the resilient modulus values of these mixtures decreased with increasing freeze thaw cycles. Comparisons with no stabilizer were not provided in this study. It is mentioned therein that CKD stabilized base materials deteriorated faster than fly ash and FBA stabilized base materials.

Figure 14. Cement stabilized section during thawing period from a test site in Vermont (picture from March 17, 2003, Henry et al. 2005)

Stabilization of aggregates, sand, and silt soils using foamed asphalt also showed good performance on unpaved roadways (Castedo and Wood 1983, Collings et al. 2004, Kendall et al. 2001). The foamed asphalt is produced by a process in which water is injected into the hot bitumen resulting in immediate foaming. The foam expands to approximately 15 times its original volume forming foam with high surface area and low viscosity, and is mixed with aggregate in its foamed state (Kendall et al. 2001 and Muthen 1998). Foamed asphalt can offer a cheaper means of mixing asphalt/bitumen into soils compared to emulsified asphalt. Information of freeze-thaw durability of these mixtures is not well documented in the literature. White et al. (2007) conducted field full depth reclamation of granular shoulders with foamed asphalt, which indicated increase in CBR of the stabilized layer shortly after stabilization but started rutting after one year. Freeze-thaw testing indicated that the material can expand by about 18%, but the percent loss during freeze-thaw was however not significant.

A recent Iowa DOT research study (TR-582) by Gopalakrishnan et al. (2010) conducted a laboratory study investigating the use of ethanol based liquid type bio-fuel by-products with high and low lignin contents. Their study results indicated that the by-products are effective in stabilizing Iowa Class 10 soils (CL or A-6(8)) with excellent resistance to moisture degradation. By-products with high lignin content performed better than with low lignin content (Figure 15). The authors of that study indicated that additional research is warranted to evaluate the freeze-thaw durability of the stabilized soils.

Use of lignosulfonates to treated unpaved gravel roads is documented in the literature (Cook 2002 and Bushman et al. 2005). Lignosulfonates are the glue found mainly in trees. During the pulping process, lignosulfonates are removed from the pulp and flushed into tanks or lagoons. The chemicals added during the pulping process determine whether it is a calcium, sodium, or ammonium lignosulfonate. The liquid is typically sold in a 50% suspended solid solution (Cook 2002). Previous research documented mixed performance information on lignosulfonate stabilized granular materials. Cook (2002) reported good performance results based on studies conducted in New York on shoulder material with no signs of erosion or distress after two years. In contrary, Bolander (1999) reported that lignosulfonates have poor durability to wet-dry and freeze-thaw cycle. White et al. (2007) studied performance of stabilized granular shoulders with polymer and soybean oil by-product materials. Results from their study did not show considerable improvement, but recommended needing additional durability testing.

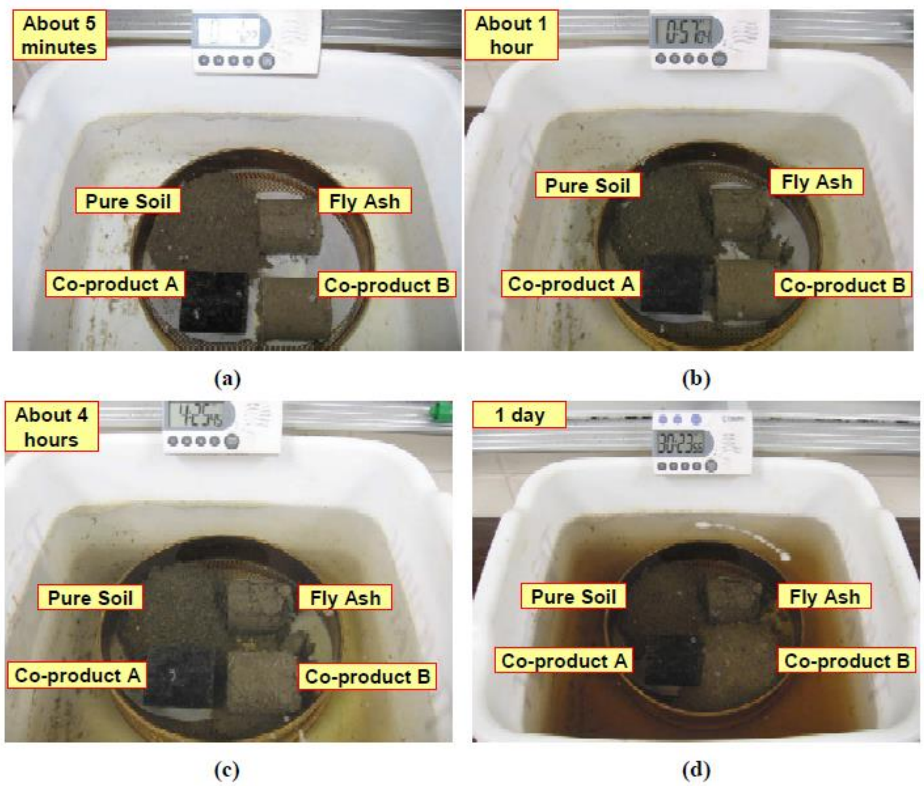

Figure 15. Pictures showing soaking test results of different specimens after: (a) five minutes, (b) one hour, (c) four hours, and (d) one day (Gopalakrishnan et al. 2010)

Mechanical Stabilization

Mechanical stabilization includes using a compacted granular layer blended with fine-grained subgrade materials or a compacted granular layer in conjunction with non-biodegradable reinforcements (e.g., fibers, geotextiles, geogrids or geocomposites) to improve roadway support over soft, wet subgrades and to improve performance of base course materials. Thick granular layers or granular layers with large aggregate particle sizes (e.g., macadam rock) are also used to facilitate drainage and avoid or reduce frost problems by providing a protection to the underlying subgrade layers. Use of recycled or reclaimed materials from pavement rubblization/recycling and use of heavy compaction methods (e.g., high energy impact rollers) to densify existing granular material also fall under the mechanical stabilization category.

A brief overview of the different mechanical stabilization processes is provided below. Numerous studies have been published on this topic and an extensive review of all of these processes is beyond the scope of this study. However, articles that discussed mechanical stabilization in the context of freeze-thaw durability and soft subgrade support, and general design and construction guidelines have been collected. 48 technical articles have been collected on the mechanical stabilization topic.

Blending of Coarse and Fine Grained Soils

Mechanical stabilization by mixing/blending coarse-grained granular materials with wet fine grained subgrade soils (Figure 16) and compaction can provide a stable working platform and foundation layer under pavements (Christopher et al. 2005). The mechanically stabilized layer can potentially exhibit lower plasticity, lower frost-heave potential, and higher drainage characteristics compared to subgrade soils (Kettle and McCabe 1985, Rollings and Rollings 1996). Based on laboratory testing, Kettle and McCabe (1985) found that the magnitude of reduction in frost-heave is related to the coarse-aggregate content and the type of aggregate used in the mechanically stabilized layer. Further, support capacity of a mechanically stabilized layer is influenced by the degree of saturation and the percentage of clay-particles present in the mixture (Hopkins et al. 1995). Therefore, post-construction changes in saturation (in part due to freeze-thaw) must be considered in properly understanding the long-term performance of a mechanically stabilized layer. Hopkins et al. (1995) indicated that a soil-aggregate mixture must be designed to have a Kentucky California bearing ratio ≥ 10 in soaked condition but cautioned that this limiting condition must be viewed as very approximate. Freeze-thaw durability of mechanically stabilized (by blending) materials is not well documented in the literature.

Figure 16. Blending granular material with subgrade using a soil pulverizer (picture from Boone County Expo Site, June 2012)

Macadam Subbase under Surface Gravel

Macadam subbase material with a maximum particle size ranging from 3 to 4 in. have been used under low-volume paved roads and gravel surface layers in Iowa. Figure 17 shows a picture of macadam stone overlaid by 2 in. of choke stone under an asphalt pavement on County Road D20 in Hamilton County, Iowa.

Jobgen et al. (1994) evaluated field performance of a 5 in. macadam base with 2 in. choke stone at the surface, with and without geotextile at the interface of macadam base and subgrade. The performance of this test section was compared with nearby sections built with chemically treated (with high float emulsion and bio-chemical formula) gravel surface layers. Testing conducted using Iowa Road Rater, Roughometer, and visual inspection from 1989 to 1992 indicated that the test section with macadam subbase (with and without geotextile) performed better (with minimal rutting) than all other sections in that study.

Less and Paulson (1977) and Lynam and Jones (1979) evaluated the feasibility and economics of using macadam subbase material with choke stone under paved road sections (with concrete and asphalt surfacing) in Iowa. The macadam subbase material used in these studies consisted of material with maximum particle size of 3 to 4 in and <1% passing the #8 sieve. Both these studies indicated that the macadam subbase material served well as a drainage layer and helped minimize the effects of frost boils, spring thaw, and other subsurface drainage issues. These studies indicated that the quarry supplying the material must be within close proximity to the project, for the use of macadam stone to be economical.

Figure 17. Macadam subbase material (picture from County Road D20 in Hamilton County, April 2012)

Recycled Materials

Recycled materials can be used to replace virgin granular materials. However, the long-term durability of the materials in terms of their ability to retaining resilient modulus and drainage characteristics over the life of the roadway must be carefully considered. Use of recycled asphalt pavement (RAP) materials and portland cement concrete (PCC) materials is gaining increasing popularity. Recently, Foye (2011) published a case history on the use of RAP as part of a parking lot project in Minnesota. He indicated that selection of RAP stabilization method on site resulted in a much cheaper alternative than a traditional excavate and replace method. Although relevant lab or field test results were not presented in the paper, it was indicated therein that as the material drains freely, it was not susceptible to freeze-thaw damage. Koch et al. (2011) documented the performance of RAP in gravel roads in Wyoming. They have conducted field investigations comparing surface distresses and dust losses between virgin aggregate and RAP surfaced gravel roads, and found that RAP sections can perform well in terms of dust control. A recent Iowa DOT Study (TR-544, White et al. 2008) on performance of recycled portland cement concrete (RPCC) aggregate materials under pavements found that RPCC materials setup over time and generally have lower permeability than virgin aggregate materials. Other recycled industrial byproducts such as shingles, foundry sand, bottom ash, fly ash, etc. have also been used as aggregate bases under pavements (Benson et al. 2005, Edil et al. 2002), but information regarding their freeze-thaw durability is limited.

High Energy Impact Roller Compaction

Application of high-energy impact roller (IR) compaction technology to earthwork and stabilization projects in Iowa has been limited primarily to concrete pavement recycling projects, but is recently seeing increased interest. IR is essentially a non-circular-shaped, tow-behind solid steel compactor that typically varies in weight from about 9 to 15 tons (Figure 18). The dynamic impact compaction energy is transferred to the soil by means of the lifting and falling motion of the non-circular rotating mass. The rollers are pulled at relatively high speeds (typically about 6 to 8 mph) to generate a high-impact force that reportedly can densify material to depths greater than 6 ft, which is significantly deeper than conventional static or vibratory rollers (Clegg and Berrangé 1971). Significant improvement of subgrade may not be possible if the subgrade is wet/saturated (White et al. 2013).

Figure 18. High energy impact roller equipment by equipment by Impact Roller Technology, Plattsmouth, Nebraska (picture from Boone County Expo Site, June 2012)

One disadvantage of this technology is that the high-impact forces disturb (i.e., loosen) the top 0.1 to 0.5 m (0.25 to 1.5 ft) of the surface so the top layer needs additional compaction with conventional rollers. The vibrations caused by the impact rollers and their effect on nearby structures (e.g., underground utilities/pipe lines or nearby building structures) are important to consider with this technology. Some case studies indicated that the vibration effect is minimal beyond 9.1 to 13.7 m (30 to 45 ft) from the impact source (Bouazza and Avalle 2006).

No field studies to the authors' knowledge have been published to date about the use of IR technology on low volume roads in the US, although reportedly it has been used to densify gravel roads in Colorado (personal communication with Mr. Scott Roth, President of Impact Roller Technology, Plattsmouth, Nebraska).

Geosynthetics

Geosynthetics have been used in pavement foundation layers for separation, capillary barrier, filtration, lateral drainage, and reinforcement purposes (Berg et al. 2000). Geotextiles and polymer geogrids are common types of geosynthetics. Geotextiles are either woven or non-woven and are primarily used as separation layers between strata to prevent the upward migration of fine-grained particles from the subgrade into subbase layers (Figure 19). Polymer geogrids act primarily as reinforcement by providing lateral restraint or confinement of aggregate layers above subgrade (Figure 19).

(a) (b)

Figure 19. Geotextiles placed at subgrade/aggregate layer interface: (a) woven geotextile, and (b) non-woven geotextile (pictures from Boone County Expo Site, June 2012)

(a) (b)

Figure 20. Polymer geogrids placed at subgrade/aggregate layer interface: (a) triaxial geogrid, and (b) bi axial geogrid (pictures from Boone County Expo Site, June 2012)

Henry (1996) provided a literature review of using geotextiles to mitigate frost effects in soils, by using certain geosynthetics as capillary barriers and drainage layers. It is indicated therein that soil particle size distribution, wettability, and for some products the material thickness influence will influence the performance. Hoover et al. (1981a) evaluated frost-heave properties of geosynthetic (spun-bounded polyethylene and polypropylene material) reinforced silty clay soil. Their results indicated that sample with two layers of geosynthetic heaved much less than sample with one and no geosynthetic. It was hypothesized that capillary barrier and reinforcement are possible reasons for reduced heave. Use of geocomposites (Figure 21), which act as a capillary barrier as well as an active drainage layer, is becoming increasingly popular (Henry et al. 2005, Kestler 2003). Previous studies have shown that by using geocomposite within gravel layer, positive pore pressures can be prevented/reduced and the material can be kept relatively dry in thawing season (Stormont et al. 2001, Stormont and Stockton 2000).

Geocells are another relatively new type of geosynthetics, which are three-dimensional, honeycomb-shaped soil-reinforcing geosynthetics composed of polymeric materials and are primarily used for confinement of granular material (Figure 22). Geocells are placed at grade, in-filled with granular material, and compacted. The cellular structures of the geocells provide lateral and vertical confinement and tensioned membrane effect, thereby increasing the bearing capacity and providing a wider stress distribution (Rea and Mitchell 1978). As a result, rutting or permanent deformations under traffic loading can be reduced. Typically, the geocell-base/subbase system is underlain by a geotextile to separate the infilled base/subbase material from the subgrade. US Army Corps of Engineers first studied the use of geocells to reinforce unpaved roads with poorly graded sand soils in the 1970s (Webster 1979). Yuu et al. (2008) and Pokharel (2010) summarized previous experimental (lab and field) and analytical studies conducted using geocells. Some key aspects of geocell reinforcement that have been studied include (Pokharel 2010): (a) influence of geometric ratio (i.e., height to diameter) of geocell, (b) failure mechanisms, (c) properties of geocell, (d) effectiveness of geocell, (e) loading area, position, and type, (f) infill density, and (h) type and size of geocell. A design methodology to estimate required base layer thickness over unreinforced or geosynthetic-reinforced layers was proposed by Giroud and Han (2004). This design methodology was extended for geocell reinforcement by Pokharel (2010). Freeze-thaw durability performance of geocells will primarily depend on the permeability characteristics of the infill granular material, but studies on the durability performance of geocells are not well documented. Henry et al. (2005) built test sections in Vermont, but conclusive results related to freeze-thaw durability in those sections was not provided.

Figure 21. Geosynthetic capillary barrier drain (GCBD) installed on a test section over the subgrade/base interface in Vermont (Henry et al. 2005)

Figure 22. Geocells placed over non-woven geotextile on a test section in Vermont (Henry et al. 2005)

Fiber Reinforcement of Subbase and Subgrade Materials

Discrete monofilament and defibrillated polypropylene type fibers (Figure 23) have been used in research studies to study their effectiveness when used in subgrade and base materials. Previous research studies (e.g., Gray and Ohashi 1983, Consoli et al. 1998, Santoni and Webster 2001, Kaniraj and Havanagi 2001, Consoli et al. 2003, Newman and White 2008) on discrete fiber reinforced natural and chemically stabilized soils have generally shown improvements in soil shear strength, bearing capacity, ductility, toughness, and resistance to rutting. Gray and Ohashi (1983) reported that the failure mechanism of a fiber-reinforced soil depends on the acting average effective stress. Failure occurs through slippage of fibers up to a critical stress and as the stresses increase, failure is governed by the tensile strength of the fiber element (Consoli et al. 2011). Santoni and Webster (2001) reported that in unconfined compressive strength tests, the fiber reinforced soil yielder higher shear strengths due to development of tension in the fibers with increasing strains. Consoli et al. (2003) indicated that the fiber content, orientation of fibers with respect to the shear surface, and the elastic modulus of the fibers influences the contribution of the reinforcement to the shear strength. In Iowa loess, Hoover et al. (1982) found that inclusion of fibers decreased freeze-thaw volumetric changes on the order of 40% compared to soil with no fibers. Fiber application rates on the order of 1% to 3% have been reported in the literature (Newman and White 2008, Gullu and Hazirbaba 2010, Hazirbaba and Gullu 2010, Ghazavi and Roustaie 2010).

(a) (b)

(c) (d)

Figure 23. (a) Polypropylene monofilament fibers (black), (b) polypropylene defibrillated fibers (white), (c) distribution of fibers using a straw blower on granular material, (d) mixing of fibers with granular material with a reclaimer (pictures from Boone County Expo Site, June 2012)

Bio-Stabilization

The concept of this bio-stabilization technology is that biological processes can change in-situ weak and unstable soils into stronger and more durable soils. DeJong et al. (2010) defined a bio-mediated soil improvement system as a chemical reaction network that is managed and controlled within soil through biological activity and whose byproducts alter the engineering properties of soil. Experiments to date involving biological processes for soil strengthening have been largely confined to laboratory studies of the precipitation of carbonate as a cementation material in sands and as a crack filler. Much more research is needed to fully evaluate the potential for soil stabilization and improvement to levels necessary for their use as a pavement subgrade material, the potential uniformity of the treatment zone in field, and the longevity of the treated soil properties. Nevertheless, recent advances in the understanding of biogeochemical processes suggest that suitable materials and processes may be developed in the future. Figure 24 shows evidence of bio-stabilization of sand using a procedure developed at the laboratory scale at ISU. In this image, there are bio-precipitants attached on the contact points of particles and increased the unconfined compressive strength (Li, 2012).

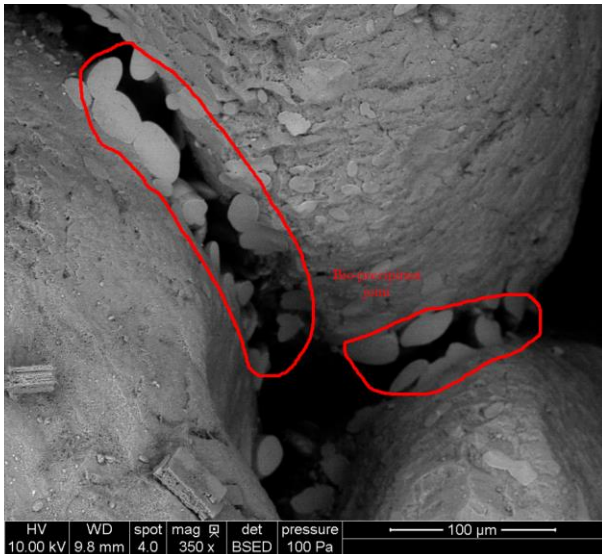

Figure 24. SEM image from bio-treatment of silica sands at ISU (350x) (Li, 2012)

Evaluation Solutions

Marti et al. (2003) developed an example flowchart and worksheet to effectively determine the methods to evaluate and repair frost damaged roadways (Figure 25). Although this does not include all potential mitigation solutions described above, it is provided herein as an example. Evaluation solutions involve laboratory testing to characterize soil frost-heave and thaw-weakening susceptibility, and various field testing methods to evaluate the reduction in the support capacity/bearing strength/stiffness. These methods are described below as addressed in the literature.

Laboratory Testing

Evaluation of frost-heave susceptibility of materials is primarily based on laboratory testing. The particle size distribution of a soil is a controlling factor during freezing. The U.S. Army Cold Regions Research Engineering Laboratory (CRREL) and the U.S. Army Corps of Engineers (USACE) developed a frost susceptibility classification system based on the grain size criteria (Figure 26). The grain size criteria is a commonly used method to determine the frost susceptibility, and is adapted in pavement design procedures (AASHTO 1993). Brandl (2008), however, identified other factors that influence the freeze-thaw behavior of geomaterials:

- grain size distribution,
- mineral composition of the fine grains,
- soil chemistry,
- water content and degree of saturation;

- density,
- groundwater level,
- availability of water (e.g., precipitation, seepage, groundwater),
- temperature, hydraulic gradient, and chemistry of groundwater,
- temperature conditions (e.g., magnitude and duration of freezing temperatures, temperature gradient), and
- local climate, especially freeze-thaw cycles.

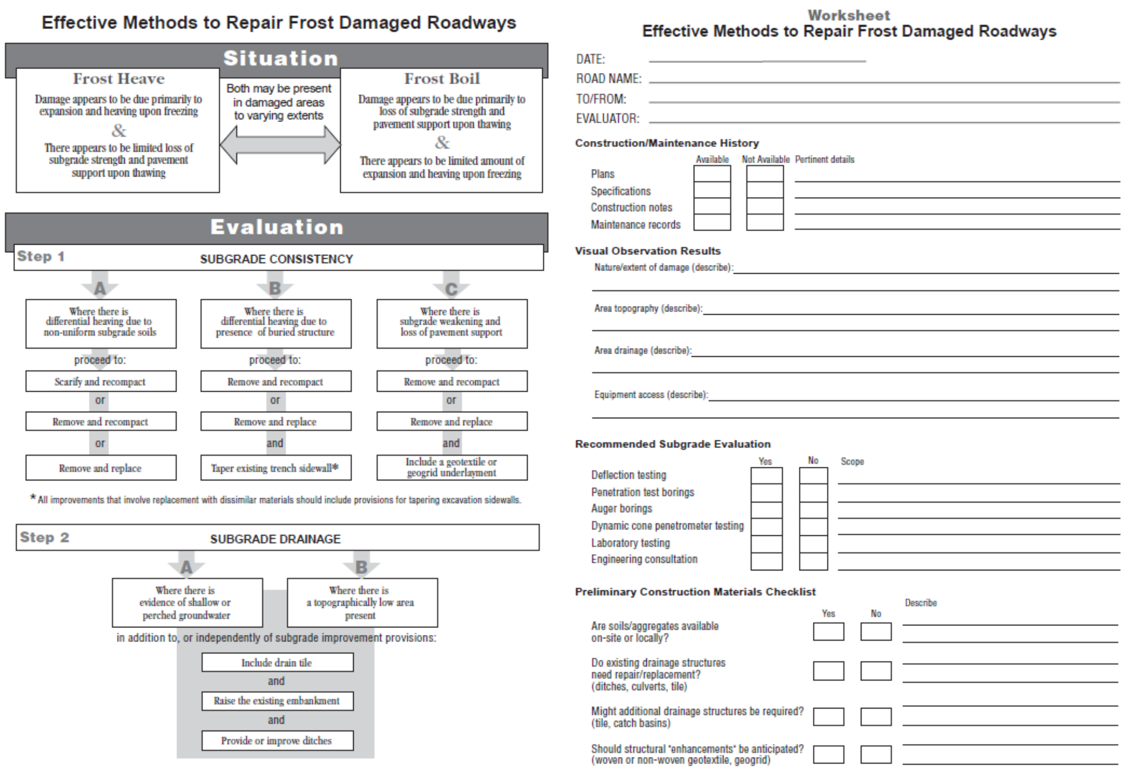

Figure 25. Flowchart and worksheet to determine methods to evaluate and repair frost damaged roadways (Marti et al. 2003)

To directly determine frost susceptibility, heave rates, and CBR after thawing, an ASTM D5918 test must be performed. The frost susceptibility classification resulted from this test is provided in Table 3. The Center for Earthworks Engineering Research (CEER) at Iowa State University recently design and fabricated a freeze-thaw test device meeting the requirements of ASTM D5916. Recently, several samples of road building materials were collected from Iowa to conduct a preliminary assessment of freeze-thaw (F/T) susceptibility and to evaluate the performance of selected stabilizers to mitigate by heave and thaw softening (Johnson 2012 and Zhang 2013). Various combinations of geomaterials and stabilizers were tested to provide the frost susceptibility of the materials. From evaluating the test results, the improvement on the freeze-thaw performance of geomaterials can be determined. The stabilization effects of different types and contents of stabilizers on freeze-thaw were compared based on the frost-heave rates and CBR values. Preliminary frost susceptibility tests results for Iowa soils and gravel materials are summarized in Table 4. Although these tests were not required as part of this project, they are included because they reveal important information about the high frost-susceptibility for many of the materials commonly used in Iowa. Additional ASTM D5918 testing is recommended.

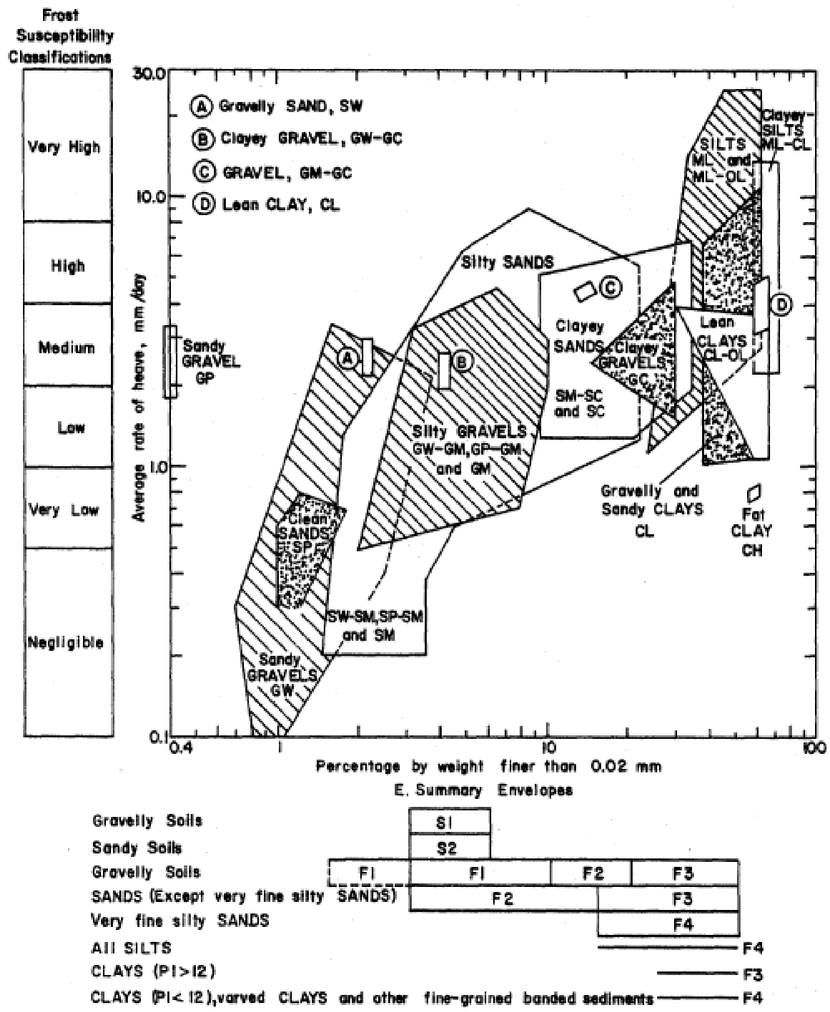

Figure 26. Frost susceptibility classification of soils (Joint Departments of the Army and Air Force 1985)

Table 3. ASTM D5918 frost susceptibility classification

Frost susceptibility classification	2nd 8-hr heave rate (mm/d)	CBR after thaw (%)
Negligible	<1	>20
Very low	1 to 2	20 to 15
Low	2 to 4	15 to 10
Medium	4 to 8	10 to 5
High	8 to 16	5 to 2
Very High	>16	<2

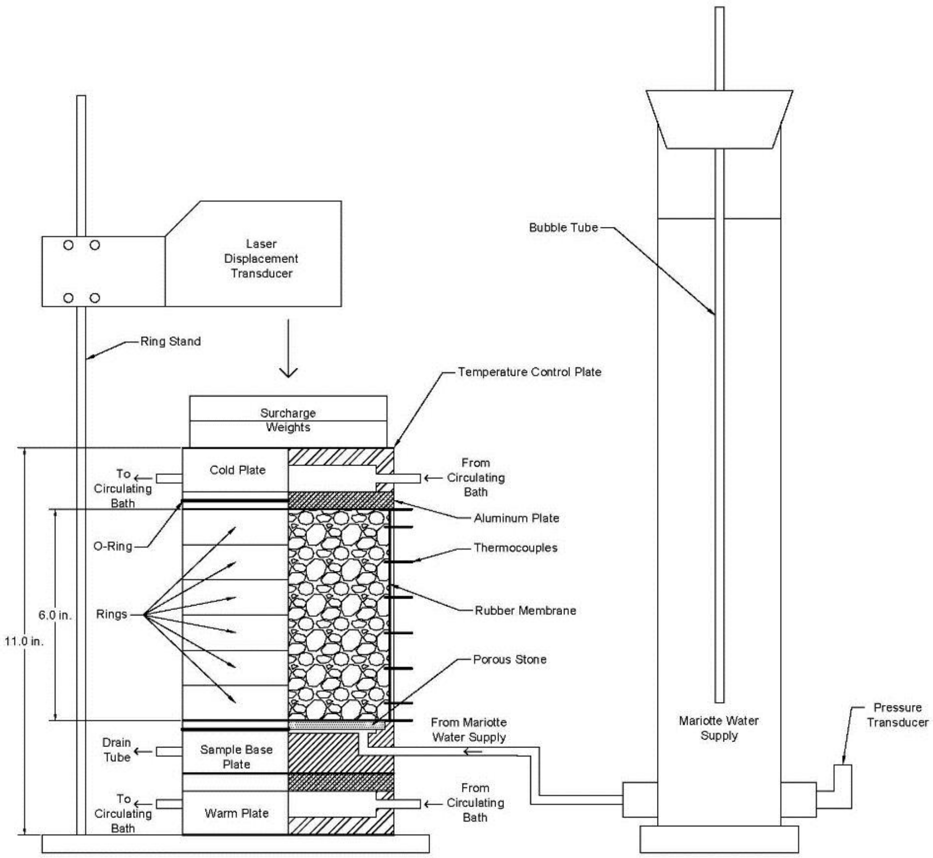

Figure 27. ISU-CEER laboratory frost-heave and thaw-weakening sample assembly (Johnson 2012)

Table 4. Summary of preliminary frost-heave and thaw-weakening tests results performed at ISU 2012-2013 (modified from Johnson 2012 and Zhang 2013)

Material	USCS	Standard CBR (%)	Average CBR (%) after test	Frost-heave rate (mm/day)	Thaw-weakening susceptibility rating	Frost-heave susceptibility rating
IA I-29 lean clay subgrade	CL	21.8	0.7	12.4	Very high	High
PA US-22 sandy lean clay subgrade	CL	21.1	3.0	4.3	High	Medium
WI US-10 sandy lean clay subgrade	CL	25.9	7.2	5.5	Medium	Medium
IA I-29 silt with sand subgrade	ML	21.6	1.4	11.0	Very high	High
IA US-30 clayey sand subgrade	SC	8.4	2.7	7.8	High	Medium
MI I-96 clayey sand subgrade	SC	26.3	5.8	13.1	Medium	High
160th Street poorly graded sand with silt and gravel	SP-SM	65.1	28.9	11.5	Negligible	High
160th Street well graded sand with silt and gravel	SW-SM	39.7	15.0	13.4	Very low	High
Manatts concrete sand subbase	SP	9.4	8.1	0.9	Medium	Negligible
IA US-30 RPCC subbase	GM	70.3	33.3	6.1	Negligible	Medium
IA US-30 RPCC/RAP subbase	GP-GM	40.6	37.6	5.4	Negligible	Medium
IA US-30 limestone subbase	GP-GM	70.5	33.2	6.4	Negligible	Medium
Martin Marietta crushed limestone subbase	GP-GM	87.3	47.5	8.0	Negligible	High
IA US-30 RPCC subbase modified (half fines)	GP	—	39.2	6.1	Negligible	Medium
IA US-30 RPCC subbase modified (no fines)	GP	—	35.5	6.1	Negligible	Medium
Manatts RAP subbase	GW	11.6	8.7	1.8	Medium	Very low
Manatts RPCC/RAP subbase	GW	48.2	33.2	1.9	Negligible	Very low
Loess	ML	10.0	0.5	19.1	Very high	Very high
Loess + 3% PC	—	—	>100	0	Negligible	Negligible
Loess + 5% PC	—	—	>100	0	Negligible	Negligible
Loess + 7% PC	—	—	>100	0	Negligible	Negligible
Loess + 9% PC	—	—	>100	0	Negligible	Negligible
Loess + 11% PC	—	—	>100	0	Negligible	Negligible
Loess + 13% PC	—	—	>100	0	Negligible	Negligible

Material	USCS	Standard CBR (%)	Average CBR (%) after test	Frost-heave rate (mm/day)	Thaw-weakening susceptibility rating	Frost-heave susceptibility rating
Loess + 10% Fly Ash 7 days	—	—	5.0	22.2	High	Very high
Loess + 15% Fly Ash 7 days	—	—	7.1	14.1	Medium	High
Loess + 20% Fly Ash 7 days	—	—	25.5	11.0	Negligible	High
BC Subgrade No stabilizer	CL	2.8	1.4	11.4	Very high	High
BC Subgrade 5% Ames fly ash		15.5	6.6	8.4	Medium	High
BC Subgrade 10% Ames fly ash	—	44.6	9.6	6.6	Medium	Medium
BC Subgrade 15% Ames fly ash	—	73.2	20.1	6.9	Negligible	Medium
BC Subgrade 20% Ames fly ash	—	18.2	10.2	7.8	Low	Medium
BC Subgrade 5% Muscatine fly ash	—	—	2.9	9.9	High	High
BC Subgrade 10% Muscatine fly ash	—	—	2.6	12.3	High	High
BC Subgrade 5% Port Neal fly ash	—	—	5.7	6.6	Medium	Medium
BC Subgrade 10% Port Neal fly ash	—	15.0	11.2	8.2	Low	High
BC Subgrade 15% Port Neal fly ash	—	25.8	16.9	2.0	Very low	Very low
BC Subgrade 20% Port Neal fly ash	—	—	17.9	3.3	Very low	Low
BC Subgrade 5% cement	—	37.3	165.8	<1.0	Negligible	Negligible
BC Subgrade 10% cement	—	94.5	>100	<1.0	Negligible	Negligible
BC Recycled Subbase No stabilizer	SM	4.6	8.8	15.6	Medium	High
BC Recycled Subbase 2.5% cement	—	95.6	12.8	12.7	Low	High
BC Recycled Subbase 3.75% cement	—	127.0	35.1	2.1	Negligible	Low
BC Recycled Subbase 5.0% cement	—	208.9	56.7	3.4	Negligible	Low
BC Recycled Subbase 7.5% cement	—	>100	43.4	1.6	Negligible	Very low
BC Recycled Subbase 0.2% PP	—	4.6	11.4	12.1	Low	High
BC Recycled Subbase 0.4% PP	—	7.3	7.8	12.7	Medium	High

Material	USCS	Standard CBR (%)	Average CBR (%) after test	Frost-heave rate (mm/day)	Thaw-weakening susceptibility rating	Frost-heave susceptibility rating
BC Recycled Subbase 0.6% PP	__	5.8	16.3	6.3	Very low	Medium
BC Recycled Subbase 0.2% MF	__	4.1	12.1	10.3	Low	High
BC Recycled Subbase 0.4% MF	__	7.9	14.8	9.9	Low	High
BC Recycled Subbase 0.6% MF	__	8.6	18.4	6.9	Very low	Medium
BC Recycled Subbase 0.2% PP + 3.75% cement	__	185.5	58.2	1.3	Negligible	Very low
BC Recycled Subbase 0.2% PP + 3.75% cement (12-hr compaction delay)	__	—	20.3	3.8	Negligible	Low
BC Recycled Subbase 0.4% PP + 3.75% cement	__	>100	>100	<1.0	Negligible	Negligible
BC Recycled Subbase 0.4% PP + 3.75% cement (12-hr compaction delay)	__	—	19.8	2.98	Negligible	Low
BC Recycled Subbase 0.6% PP + 3.75% cement	__	>100	>100	1.48	Very low	Very low
BC Recycled Subbase 0.2% MF+ 3.75% cement	__	>100	>100	0.75	Negligible	Negligible
BC Recycled Subbase 0.4% MF+ 3.75% cement	__	>100	>100	1.4	Negligible	Very low
BC Recycled Subbase 0.6% MF+ 3.75% cement	__	>100	>100	1.0	Negligible	Negligible
Loess 15% fly ash 7 days curing	__	—	7.1	14.1	Medium	High
Loess 15% fly ash 90 days curing	__	—	8.7	11.8	Medium	High
Loess 15% fly ash 180 days curing	__	—	32.0	8.3	NG	High

Field Testing

Field testing to evaluate damage during spring thaw include: (a) visual inspection, (b) rut measurement (Figure 28), (c) dynamic cone penetrometer (DCP) measurement (Figure 29) (d) falling weight deflectometer (FWD) measurement (Figure 30 and Figure 31), (e) ground penetrating radar (GPR) survey (Figure 33 and Figure 34), and (f) in-ground moisture content and temperature monitoring (Figure 35).

Figure 28. Rutting during spring-thaw (Henry et al. 2005)

DCP tests can be performed in accordance with ASTM D6951. The tests involve dropping a 17.6 lb hammer from a height of 22.6 in. and measuring the resulting penetration depth. Based on the measurements, CBR or shear strength of soil layers down to about 3 ft can be determined. DCP test can be performed periodically to determine the thawing depth and the thawing period. Embacher (2006) demonstrated the use of DCP on various Minnesota aggregate-surfaced roads.

FWD tests (Figure 30) involve a truck-mounted device dropping a dynamic load (varying from about 5,000 to 15,000 lbs) on a 12 in. diameter plate and measuring deflection at the plate center and up to 6 ft away from the plate center. The load and deflection data can be used to determine composite modulus of the layer as well as the underlying layer modulus. Other deflection basin data can also be computed, which can be useful in comparing FWD measurements over time. Example data from Salour and Erlingsson (2012) are shown in Figure 31, which shows low values during the thawing period and recovery after thawing.

Figure 29. Dynamic cone penetrometer testing

Figure 30. ISU-Kuab Falling weight deflectometer testing on a gravel road

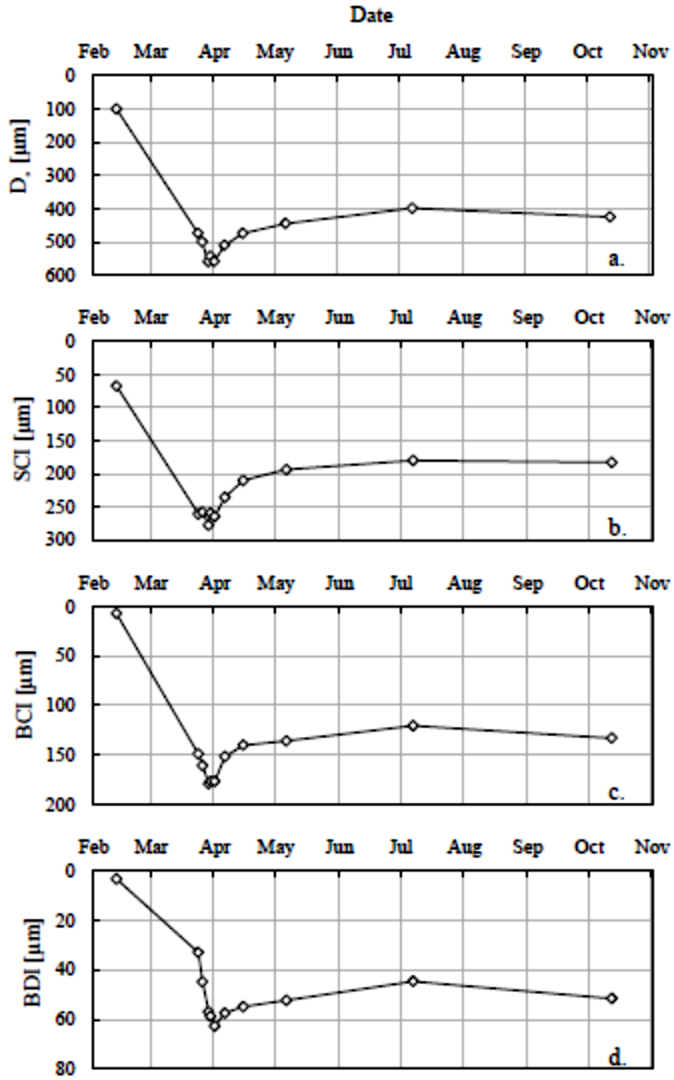

Figure 31. Variation in FWD deflection basin parameters over an year (lowest point in all graphs depicting the thawing time) from a low volume road site in Southern Sweden (Salour and Erlingsson 2012)

GPR survey involves sending a pulse of energy into the ground and recording the strength and time required for the return of any reflected signal. The frequency of the antenna used is a major factor in the depth of penetration into the ground. The higher the frequency of the antenna, the shallower into the ground it will penetrate. GPR scanning can be performed using ground-coupled antennas (Figure 33) or air-borne antennas (Figure 33). GPR scanning using ground-coupled antennas can be performed by pulling the antenna on the ground using a wheel cart or a hand-held survey wheel on paved and unpaved roadways. These antennas can also be mounted to a truck, however, the scans can only be obtained at slow travel speeds (< 5 mph). Air-borne antennas, commonly referred to as horn, are high frequency antennas (2600 MHz) and are suitable for shallow depth applications only (< 1.5 ft), but scanning can be performed at driving speeds. Example GPR data from Saarenketo and Aho (2005) on a gravel road section are shown in Figure 34.

Moisture measurement in combination with temperature measurements can be useful in determining the frost depth and the time of thawing. Saarenketo and Aho (2005) demonstrated the use of moisture and temperature sensors wirelessly transmitting the data to a remote office location, to make informed decisions on testing and load-restrictions. Kestler et al. (1999) used time domain reflectometry and radio frequency soil moisture sensors strategically located in the forest road network to provide a means to determine when to remove load restrictions.

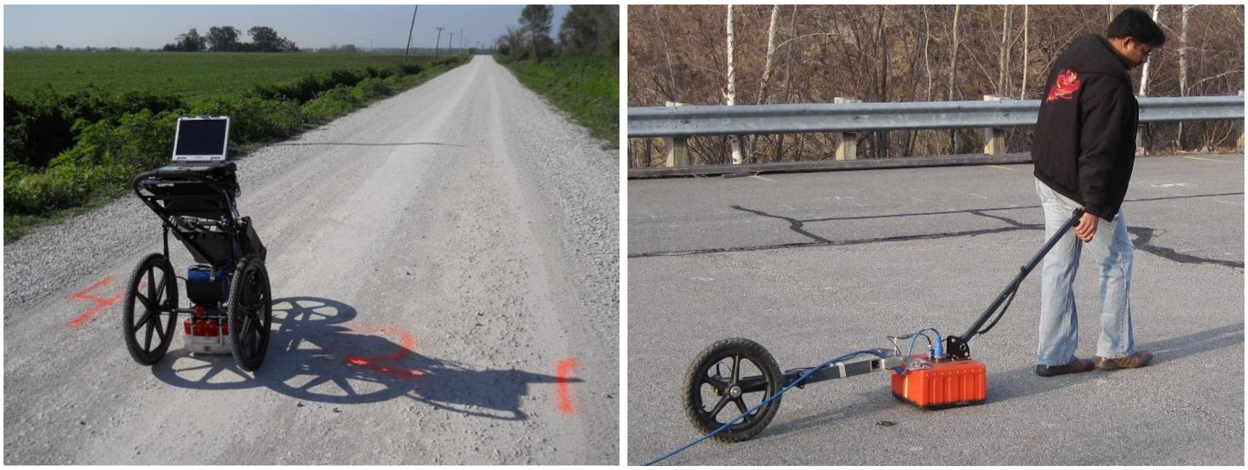

Figure 32. ISU-GPR scanning using ground-coupled antennas

Figure 33. Air borne GPR survey vehicle used for condition assessment on ROADEX projects in Europe (Drake 2012)

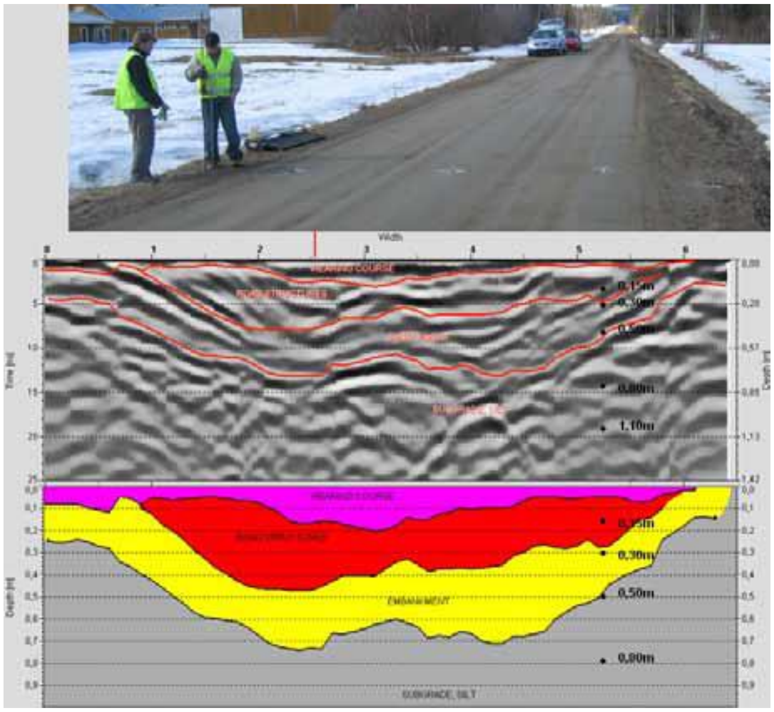

Figure 34. Example results of GPR survey from ROADEX projects in Europe (Saarenketo and Aho 2005)

Figure 35. Moisture probes with wireless data transfer installation at a ROADEX project site in Southern Sweden (Saarenketo and Aho 2005)

CHAPTER 5: SUMMARY OF KEY FINDINGS AND RECOMMENDATIONS

Summary of Key Findings

The physical mechanism of freeze-thaw action is currently well understood and well documented. Freeze-thaw cycles combined with frost-susceptible soils and inadequate drainage lead to damage in unbound roads, and in severe cases, make them impassable. Intersections and bridge approaches are common trouble locations, but damage due to frost-heave and boils can occur throughout a given roadway depending on variations in drainage, construction quality, and traffic loading. Some approaches currently used by County Engineers to deal with frost boils include temporarily spreading rock on the affected areas, lowering or improving drainage ditches, tiling, bridging the area with stone and geosynthetic covered by a top course of aggregate or gravel, coring boreholes and filling them with calcium chloride to melt lenses and provide drainage, and re-grading the crown to a slope of 4 to 6% to maximize spring drainage. However, most of these maintenance solutions are aimed at dealing with conditions after they occur.

The primary task of this project was to perform a detailed literature review and then conduct a systematic assessment of the documents to identify technologies suitable for future evaluation and implementation in Iowa. An important outcome of this effort is an organized database of literature with 150+ technical articles on this research topic. The literature documents has been organized in an electronic database (EndNote®), which can be shared with other researchers and practitioners. The database can be used as an effective tool to search for information regarding the various repair and mitigation solutions, measurement technologies, and experiences that have been documented by various domestic and international researchers and practitioners.

Based on the review of literature, stabilization methods and drainage were identified as feasible mitigation solutions to the problems of frost-heave and thaw-weakening. Stabilization works by increasing the shear strength of the surface and/or subgrade layers to resist the actions of freeze-thaw and drainage works by eliminating or reducing water from the freeze-thaw process. Following is a list of different stabilization technologies identified in the literature:

- Chemical stabilization using active chemical agents such as lime, fly ash, and portland cement, or passive chemical agents such as bitumen, foamed asphalt, bio-fuel byproducts, and polymer emulsions.
- Mechanical stabilization by blending coarse-grained and fine-grained materials, using non-biodegradable reinforcements (such as fibers, geotextiles, geogrids, geocells, and geocomposites), using recycled materials (recycled concrete or asphalt and industrial by-products), and use of macadam base with large particle size to facilitate drainage and stability.
- Bio-stabilization involving biological processes. This process is relatively new with very little field data.

Various damage evaluation techniques involving field and laboratory test methods to evaluate frost-heave and freeze-thaw damage have been documented in the literature. Laboratory evaluations include characterizing soils' frost susceptibility rating based on soil gradation parameters (percent finer than 2 microns) or conducting ASTM D5918 tests to determine frost-susceptibility and thaw-weakening susceptibility rating, heave rates, and thawed California bearing ratio (CBR) values. Preliminary results of laboratory frost-susceptibility testing for Iowa materials is provided herein. Additional testing for various stabilization treatments is recommended.

Field testing to evaluate damage during spring thaw includes: (a) visual inspection, (b) rut measurement, (c) dynamic cone penetrometer to determine frost depth and CBR profile (during thawing) down to about 3 ft., (d) falling weight deflectometer (FWD) to determine support capacities/ stiffness of the gravel and foundation layers, (e) ground penetrating radar (GPR) survey to determine frost depth and evaluate road conditions, and (f) in-ground moisture content and temperature monitoring to determine thawing periods.

Recommendations

To prevent or minimize the occurrence of such freeze-thaw damage related problems in the first place, it is recommended that a demonstration research project examine a range of construction methods for building and treating granular surfaced roadways. The primary methods identified in this study included chemical and mechanical stabilization; scarification, blending, and recompaction; removal and replacement; separation, and reinforcement; geogrids and cellular confinement; drainage control and capillary barriers, and use of alternative materials.

To be effective, stabilization practices must address multiple issues simultaneously, including water migration, durability, cost, performance under loaded vehicles and snow plows/blades, etc. A range of potential stabilization technologies to address these issues are proposed for field evaluation including:

- Macadam base + 2 to 4 inches of unbound aggregate
- Surface treatment with bio-stabilization and calcium chloride
- Subsurface treatment with bio-stabilization + 4 inch wearing surface
- 12 inches of 10% cement stabilization + 2 to 4 inches for wearing surface
- Geo-composite drain (from different manufacturers) at different depths (8 to 12 inches)
- 6 to 8 inch diameter aggregate column drains
- 6 to 8 inch diameter aggregate column drains with geotextile wrap
- High-energy impact compaction + surface compaction
- Geogrid BX
- Geogrid TX
- Heavy non-woven geofarbic at 12 inches – stabilization and drainage
- Heavy woven at 12 inches - stabilization
- 2 inch drainage layer clean aggregate with non-woven above and below at 12 inches
- Base reinforcement with chip seal surface

Demonstration projects could be established to monitor a selected set of these technologies. The test sections of roadway should be monitored year round in terms of performance and maintenance requirements. The objectives of the demonstration projects could be to:

1. Perform field testing of a range of granular surface stabilization technologies.
2. Measure and document the performance of the demonstration roadway sections before, during, and after a seasonal freeze-thaw cycle.
3. Assess the initial cost, relative performance, maintenance requirements, and long-term life-cycle costs of the different stabilization techniques.
4. Identify the most effective and most economical alternatives for minimizing or eliminating frost-heave/boil issues before they occur.

Evaluation of the field performance can be determined from laboratory and field testing. Laboratory testing should involve ASTM D5918 frost susceptibility rating tests as described in Chapter 4. Field testing should capture FWD, DCP, and moisture and temperature data periodically throughout the year capturing freezing, thawing, and summer conditions over several years to obtain performance measurements. Further, visual observations and rutting measurements must be obtained to keep track of performance. For current monitoring, it is recommended that engineers use GPS enabled cameras and send images of problem areas for compilation on a common ftp site and the results studied to find geographic trends.

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APPENDIX: ANNOTATED BIBLIOGRAPHY

Freeze-Thaw and Frost-Heave Issues

Aho, S., and Saarenketo, T. (2006). "Design and repair of roads suffering spring thaw weakening." The Swedish Road Administration, Northern Region, Sweden.

The ROADEX Project is a technical cooperation between roads organizations across northern Europe that aims to share roads related information and research between the partners. The Project was started in 1998 as a 3 year pilot co-operation between the roads districts of Finnish Lapland, Troms County of Norway, the Northern Region of Sweden and The Highland Council of Scotland and this was later followed up with a second project, ROADEX II, from 2002 to 2005. The partners in the ROADEX II Project comprised public road administrations, forestry organizations, forest companies and haulage organizations from regions in the Northern Periphery. These were The Highland Council, Forest Enterprise & The Western Isles Council from Scotland. The Region Nord of The Norwegian Public Roads Administration and The Norwegian Road Haulage Association, The Northern Region of The Swedish Road Administration and The Lappi and Keski-Suomi Regions of The Finnish National Roads Administration. (These latter Finnish Regions also received aid from their local forest industry organizations of Metsähallitus, Lapin Metsäkeskus, Metsäliitto & Stora-Enso.). The goal of the project was to develop ways for interactive and innovative road condition management of low traffic volume roads integrating the needs of local industry, society and roads organizations. 8 formal reports were published together with a project DVD and full copies of all reports are available for download at the ROADEX web site at www.roadex.org. This Executive Summary report is one of 8 summaries that have been prepared under the direction of the ROADEX III project (2006-2007), a new Project where the named project Partners above were joined by the additional Northern Periphery Partners of the Municipality of Sisimiut, Greenland, The Iceland Public Roads Administration and the Finnish Road Administration Region of Savo-Karjala.

Alzubaidi, H. (1999). "Operation and Maintenance of Gravel Roads - A Literature Study." Swedish National Road and Transport Research Institute, Linkoping, Sweden, 231.

Gravel roads form a large percentage of the road network in Sweden. The public road network under the jurisdiction of the Swedish National Road Administration has a total length of some 98,000 kilometers. About 22,000 km of this network consist of gravel roads. In addition, there are about 74,000 kilometers of private road and 210,000 kilometers of forest roads. This report describes the present position in the operation and maintenance of gravel roads. It presents a comprehensive literature survey of current and recent national and international research. It deals only with summer maintenance and focuses primarily on roads surfaced with aggregate. The following aspects are covered in the report: 1. Definitions and terms regarding the operation and maintenance of gravel roads. 2. General description of the Swedish road network. 3. Major factors causing deterioration of gravel roads. 4. Technical requirements for Swedish gravel roads. 5. Factors influencing the operation and maintenance of gravel roads. 6. Operation and maintenance methods. 7. Condition assessment of gravel roads. 8. Planning and evaluation of operation and maintenance measures.

Christopher, B. R., Schwartz, C., and Boudreau, R. (2005). "Geotechnical Aspects of Pavements." FHWA NHI-05-037, National Highway Institute, Federal Highway Administration, U.S. Dept. of Transportation, Washington, D.C.

The manual covers the latest methods and procedures to address the geotechnical issues in pavement design, construction and performance for new construction, reconstruction, and rehabilitation projects. The manual includes details on geotechnical exploration and characterization of in place and constructed subgrades as well as unbound base/subbase materials. The influence and sensitivity of geotechnical inputs are reviewed with respect to the requirements in past and current AASHTO design guidelines and the mechanistic-empirical design approach developed under NCHRP 1-37A, including the three levels of design input quality. Design details for drainage features and base/subbase material requirements are covered along with the evaluation and selection of appropriate remediation measures for unsuitable subgrades. Geotechnical aspects in relation to construction, construction specifications, monitoring, and performance measurements are discussed.

DOD (1985). "Pavement design for seasonal frost conditions." Technical Manual No. 5-818-2, Air Force Manual No. 88-6, Chapter 4, Departments of the Army and Air Force, Washington, D.C.

This manual presents criteria and procedures for the design and construction of pavements placed on subgrade or base course materials subject to seasonal frost action. The criteria are applicable to Air Force and Air National Guard airfields, and to roads. This manual is concerned with modes unique to frost areas. The principal non-traffic-associated distress modes are distortion caused by frost heave and reconsolidation, and cracking caused by low temperatures. The principal traffic-load-associated distress modes are cracking and distortion as affected by the extreme seasonal changes in supporting capacity of subgrades and bases that may take place in frost areas.

Henry, K. S., Olson, J. P., Farrington, S. P., and Lens, J. (2005). "Improved performance of unpaved roads during spring thaw." ERDC/CRREL TR-05-01, Engineer Research and Development Center Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Unpaved roads in Vermont are subject to deterioration from seasonal freezing and thawing, and many towns have roads that suffer chronic serviceability problems during the so-called “spring thaw,” or mud season. Several techniques thought to mitigate deterioration of unpaved roads during spring thaw were constructed on test sections of unpaved roads in two towns. Each potential remedy was aimed at providing some combination of limiting the availability of moisture in the winter, improving drainage during spring, and strengthening the upper portion of the road. Each technique used local and/or commercially available materials, and all were easy to construct, i.e., a town road crew could build them. For two spring thaw seasons, we compared strength estimates based on dynamic cone penetrometer tests and the percentage of the road surface rutted for treated and control sections. Methods that permanently improved the strength of the top 12 inches of the road or decreased the water content of the upper 12 inches of the road resulted in significant performance improvement during spring thaw. Cement and cellular confinement systems worked well by improving the strength of the upper layers of the soil. Two new techniques— geowrap, comprising clean sand sandwiched by geotextile separators placed 12–18 inches deep, and the patented Geosynthetic Capillary Barrier

Drain—provided benefit by keeping the upper layers of the soil relatively dry. Geogrid and geotextile separators placed 12 inch deep and trench drains parallel to the road provided no observable benefit.

Hyvonen, L., Vuorimies, N., and Kolisoja, P. (2012a). "Road 16589 Saalahti - Mode 2 rutting site on a soft subgrade." The ROADEX “Implementing Accessibility” Project, The Swedish Transport Administration, Northern Region, Sweden.

Rutting of the road surface due to the development of permanent deformations, both in the road structure itself and in the underlying subgrade, is in most cases the dominant distress mechanism on low volume roads of the Northern Periphery area. From a road users’ point of view rutting both lowers driving comfort and reduces traffic safety. This is particularly the case when surface water is trapped in ruts, thereby increasing the risk of aquaplaning in summertime and of icing in the wheel path in winter when temperatures fall below 0°C. In addition, rutting can also be very harmful to the structural condition of the road, as it speeds up water infiltration into the road structure, increasing the effects of dynamic wheel loads etc. Rutting can develop in a road for a number of reasons. It may develop in the structural layers due to poor quality material, or as a result of poor drainage making the material more susceptible to permanent deformations. It may also develop in a weak subgrade material if the overall thickness of the structural layers is low. This is a very typical situation on the low volume roads of the Northern Periphery area, particularly during the spring thaw where the subgrade material is frost susceptible. Rutting mechanisms are discussed in greater detail in the ROADEX reports available at www.roadex.org, together with a new method of classifying rutting modes. This report describes a ROADEX demonstration exercise carried out on a low volume road section of Road 16589 Saalahti in Jämsä, Central Finland. A geogrid reinforcement was used in the demonstration to retard the development of permanent deformations of a gravel road section located on a silty subgrade. The demonstration section had been suffering from deformations primarily taking place in the subgrade material that had become very soft during the spring thaw of the seasonal frost. This had also resulted in severe widening of the road cross-section and almost total clogging of the side ditches. According to the GPR profiles the total thickness of the structural layers was much higher in the middle of the road than towards the edges of the road which was a clear indication of Mode 2 rutting. The reinforced structure consisted of two subsections in addition to which there was a reference section. One subsection was constructed with one layer of geogrid, rather than the standard rehabilitation solution of a geotextile. The second subsection was constructed with two layers of reinforcing geogrid 150 mm apart from each other. The standard rehabilitation structure of a geotextile was used in the reference structure. After one year of service it only can be concluded that both of the test structures and the reference structure have been performing equally well, and that the road is still in very good condition. Further monitoring of the settlement tubes installed in six cross sections of the road will reveal any differences in the development rate of permanent deformations between the test structure and reference structure. According to the life cycle analysis performed, the subsection reinforced with one layer of geogrid needs to last at least one year longer and the subsection reinforced with two layers of geogrid at least three years longer to be cost effective in comparison to the reference structure, if that is assumed to have a service life of 10 years. This is slightly longer than the typical assumption of 8 years life as in this case the reference structure was also about 50 mm thicker than would have been the standard solution.

Hyvonen, L., Vuorimies, N., and Kolisoja, P. (2012b). "Road 16583 Ehikki-Juikslahti - Mode 2 rutting site on peat." The ROADEX “Implementing Accessibility” Project, The Swedish Transport Administration, Northern Region, Sweden.

Rutting of the road surface due to the development of permanent deformations, both in the road structure itself and in the underlying subgrade, is in most cases the dominant distress mechanism on low volume roads of the Northern Periphery area. From a road users’ point of view rutting both lowers driving comfort and reduces traffic safety. This is particularly the case when surface water is trapped in ruts, thereby increasing the risk of aquaplaning in summertime and of icing in the wheel path in winter when temperatures fall below 0°C. In addition, rutting can also be very harmful to the structural condition of the road, as it speeds up water infiltration into the road structure, increasing the effects of dynamic wheel loads etc. Rutting can develop in a road for a number of reasons. It may develop in the structural layers due to poor quality material, or as a result of poor drainage making the material more susceptible to permanent deformations. It may also develop in a weak subgrade material if the overall thickness of the structural layers is low. This is a very typical situation on the low volume roads of the Northern Periphery area, particularly during the spring thaw where the subgrade material is frost susceptible. Rutting mechanisms are discussed in greater detail in the ROADEX reports available at www.roadex.org, together with a new method of classifying rutting modes. This report describes a ROADEX demonstration exercise carried out on a low volume road section of Road 16583 from Ehikki to Juokslahti in Jämsä, Central Finland. The section was located on a peat subgrade and was reinforced with a geogrid. The road had been deforming and widening significantly over the section mainly due to clogged side ditches, a low outlet ditch, and settlement of the road structure into the peat subgrade. As it was very difficult in practice to improve the operation of the outlet ditch, it was decided to reduce the further development of permanent deformations on the road by the addition of a new base course layer reinforced with a geogrid. As a reference structure, half of the test section was built with the addition of a new base course layer underlain by a geotextile, which could be considered as a standard solution in this type of problem site. After the first year of service, it only can be concluded that both the test structure and the reference structure have been performing equally well, and that the road is still in very good condition. Further monitoring of the settlement tubes installed in four cross sections of the road will reveal any differences in the development rate of permanent deformations between the test structure and the reference structure. According to the life cycle analysis performed, the section reinforced with geogrid needs to last at least 1.5 years longer to be cost effective in comparison to the reference structure, assuming that the reference structure will have a typical service life of 8 years. This had also resulted in severe widening of the road cross-section and almost total clogging of the side ditches. According to the GPR profiles the total thickness of the structural layers was much higher in the middle of the road than towards the edges of the road which was a clear indication of Mode 2 rutting. The reinforced structure consisted of two subsections in addition to which there was a reference section. One subsection was constructed with one layer of geogrid, rather than the standard rehabilitation solution of a geotextile. The second subsection was constructed with two layers of reinforcing geogrid 150 mm apart from each other. The standard rehabilitation structure of a geotextile was used in the reference structure. After one year of service it only can be concluded that both of the test structures and the reference structure have been performing equally well, and that the road is still in very good condition. Further monitoring of the settlement tubes installed in six cross sections of the road will reveal any differences in the development rate of permanent deformations between the test structure and reference structure. According to the life cycle analysis performed, the subsection reinforced with one layer of geogrid needs to last at least one year longer and the subsection reinforced with two layers of geogrid at least three years longer to be cost effective in comparison to the reference structure, if that is assumed to have a service life of 10 years. This is slightly longer than the typical assumption of 8 years life as in this case the reference structure was also about 50 mm thicker than would have been the standard solution.

Johnson, A. (2012). "Freeze-thaw performance of pavement foundation materials." M.S. Thesis, Dept. of Civil Construction and Environmental Engineering, Iowa State University, Ames, Iowa.

Freezing and thawing processes damage pavement foundation systems; increase pavement and vehicle maintenance costs; reduce traveler comfort and safety; decrease fuel economy; and decrease pavement life spans. Current pavement design methods provide limited guidance characterizing frost-susceptible materials. A laboratory frost-heave and thaw-weakening test could be used to differentiate frost-susceptible materials from non-frost susceptible materials to reduce the effects of frost action. The goal of this research was to provide guidance for the selection of pavement foundation materials based on their freeze-thaw durability. The objectives of this study are to determine the effectiveness of ASTM D5918 Standard Test Methods for Frost Heave and Thaw Weakening Susceptibility of Soils by testing various soil types; study the effects of stabilizers on reducing frost-susceptibility; and determine seasonal changes of in situ pavement support conditions. The important outcomes of this research are that it is difficult to predict frost-heave susceptibility from USCS classifications; when stabilizing loess with cement, increased cement content decreased the range of initial moisture contents that will result in maximum compressive strength; compared to unstabilized loess, cement-stabilized loess was found to be non-frost-susceptible, but fly ash-stabilized loess showed only slight improvement; and the coefficients of variation for ASTM D5918 test results were similar to published results. This research shows that using a test such as ASTM D5918 in the design phase to determine the relative frost-susceptibility of pavement foundation materials may ameliorate the effects of frost action.

Marti, M. M., Mielke, A. J., and Hubbard, C. D. (2003). "Effective Methods to Repair Frost Damaged Roadways." Research Implementation Series Number 27, Minnesota Local Road Research Board, Minnesota Department of Transportation, St. Paul, Minnesota.

This report describes common causes for frost-related damage (non-uniform subgrades, shallow ground water table, low lying areas), means to evaluating prospective repair alternatives, methods to improve subgrade uniformity, and strategies to reduce/limit subgrade moisture.

Saarenketo, T., and Aho, S. (2005). "Managing Spring Thaw Weakening on Low Volume Roads - Problem Description, Load Restriction Policies, Monitoring and Rehabilitation." The ROADEXII Project, The Swedish Road Administration, Northern Region, Sweden.

This is a final report from the Phase II subproject 2_3 survey of the Roadex II project, a technical transnational cooperation project between the Highland Council, the Western Isles Council, and Forest Enterprise from Scotland; the Northern Region (formerly Troms district) of the Norwegian Public Roads Administration and the Norwegian Road Haulage Association; the Northern Region of the Swedish National Road Administration; and from Finland the Regions of Central Finland and Lapland of the Finnish Road Administration, as well as Metsähallitus Region of Eastern Lapland, the Forestry Centre of Lapland (Lapin Metsäkeskus), Stora Enso

Metsä, and Metsäliitto, Procurement Area of Northern Finland. The Roadex project is partly financed by the ERDF IIIB Northern Periphery Programme. The lead partner in the project is the Highland Council from Scotland and project consultant is Roadscanners Oy from Finland. Roadex II project Chairman is Ron Munro from the Highland Council and project manager is Timo Saarenketo from Roadscanners. The report summarizes the work done on Task 2_3 “Spring Thaw Weakening” of the Roadex II project. The report will describe the theory behind spring thaw weakening and different load restriction policies used in the cold climate areas. It will also report the results of the field tests done in Scotland, Sweden and Norway and present some new structural solutions which have been found to work well at spring thaw weakening sites. Finally, new technologies for both road owners and/or road users that could be used in more effective spring thaw weakening management will be revealed.

Salour, F., and Erlingsson, S. (2012). "Pavement Structural Behavior during Spring Thaw - Interpretation of FWD measurements by monitoring environmental data from county road 126 at Torpsbruk." 2009/0572-29, Swedish National Road and Transport Research Institute (VTI), Linkoping, Sweden.

The present research report has been carried out based on the environmental data and Falling Weight Deflectometer (FWD) measurements from the county road Lv 126 in Southern Sweden during the year 2010. The Lv 126 county road has a relatively thin flexible pavement structure with unbound aggregate base and subbase layers. The major intention of this study was to investigate the behaviour of the pavement structure during spring thaw. Temperature and moisture content of the pavement structure profile were continuously monitored throughout the year 2010. Layer moduli backcalculation as well as deflection basin analyses were performed using the FWD measurements data. A comprehensive study on the effect of environmental factor variations and pavement structural capacity were carried out during the spring thaw and recovery period. The result showed a considerable decrease in the bearing capacity of the pavement structure during the spring thaw period when the highest annual moisture content was also registered. Both deflection basin indices and backcalculated layer modulus indicated that the pavement was weakest during the subgrade thawing phase. Backcalculation on the FWD measurements showed a 63% loss in stiffness of the subgrade soil and 48% in the granular base and subbase course during the spring thaw compared to the summer values. In addition, the compatibility of the analysis with a predictive stiffness moduli- moisture content model for unbound materials was studied. The measured field data from the test road pavement in Torpsbruk showed promising agreement with the resilient modulus predictive model, both for the granular layer and subgrade material. Similar models could be developed or calibrated for other soils and granular materials if sufficient data become available in the future.

VTrans (2005). "Preventing Muddy Roads: A Road Commissioner's Tool Box." Vermont Agency of Transportation (VTrans), Prepared by The University of Vermont in Association with US Army Engineer Research and Development Center, Inc., and Geo Design, Inc., ed. Vermont.

This technology transfer document was prepared for VTrans, and includes details of test sections constructed in Westford and Windsor, Vermont. The test sections were monitored during the 2001 through 2003 freeze-thaw seasons using temperature sensors in the roadways, along with visual monitoring and field measurements of road strength and surface distress during the thaw periods. Test sections with wrapped geotextile (called as "geowrap), geocells,

geosynthetic capillary barrier drain system (patented) showed noticeable improvements due to improved drainage during the thawing period.

Rehabilitation/Repair Solutions

Aho, S., and Saarenketo, T. (2006). "Design and repair of roads suffering spring thaw weakening." The Swedish Road Administration, Northern Region, Sweden.

The ROADEX Project is a technical cooperation between roads organizations across northern Europe that aims to share roads related information and research between the partners. The Project was started in 1998 as a 3 year pilot co-operation between the roads districts of Finnish Lapland, Troms County of Norway, the Northern Region of Sweden and The Highland Council of Scotland and this was later followed up with a second project, ROADEX II, from 2002 to 2005. The partners in the ROADEX II Project comprised public road administrations, forestry organizations, forest companies and haulage organizations from regions in the Northern Periphery. These were The Highland Council, Forest Enterprise & The Western Isles Council from Scotland. The Region Nord of The Norwegian Public Roads Administration and The Norwegian Road Haulage Association, The Northern Region of The Swedish Road Administration and The Lappi and Keski-Suomi Regions of The Finnish National Roads Administration. (These latter Finnish Regions also received aid from their local forest industry organizations of Metsähallitus, Lapin Metsäkeskus, Metsäliitto & Stora-Enso.). The goal of the project was to develop ways for interactive and innovative road condition management of low traffic volume roads integrating the needs of local industry, society and roads organizations. 8 formal reports were published together with a project DVD and full copies of all reports are available for download at the ROADEX web site at www.roadex.org. This Executive Summary report is one of 8 summaries that have been prepared under the direction of the ROADEX III project (2006-2007), a new Project where the named project Partners above were joined by the additional Northern Periphery Partners of the Municipality of Sisimiut, Greenland, The Iceland Public Roads Administration and the Finnish Road Administration Region of Savo-Karjala.

Alzubaidi, H. (1999). "Operation and Maintenance of Gravel Roads - A Literature Study." Swedish National Road and Transport Research Institute, Linkoping, Sweden, 231.

Gravel roads form a large percentage of the road network in Sweden. The public road network under the jurisdiction of the Swedish National Road Administration has a total length of some 98,000 kilometers. About 22,000 km of this network consist of gravel roads. In addition, there are about 74,000 kilometers of private road and 210,000 kilometers of forest roads. This report describes the present position in the operation and maintenance of gravel roads. It presents a comprehensive literature survey of current and recent national and international research. It deals only with summer maintenance and focuses primarily on roads surfaced with aggregate. The following aspects are covered in the report: 1. Definitions and terms regarding the operation and maintenance of gravel roads. 2. General description of the Swedish road network. 3. Major factors causing deterioration of gravel roads. 4. Technical requirements for Swedish gravel roads. 5. Factors influencing the operation and maintenance of gravel roads. 6. Operation and maintenance methods. 7. Condition assessment of gravel roads. 8. Planning and evaluation of operation and maintenance measures.

Arnold, G. (1999). "Design of Rehabilitation Treatments for New Zealand's Thin-Surfaced Unbound Granular Pavements." Transportation Research Record: Journal of the Transportation Research Board, 1652, 42-50.

Most thin-surfaced unbound granular pavements are rehabilitated by overlaying with an unbound granular material and surfaced with a chip seal (thin-surfacing). The unbound granular overlay thickness is the difference between the total granular thickness required for future traffic and the granular thickness required for past traffic as determined from the design chart. However, where there are signs of shoving or other indications of a weak and degraded aggregate base layer then a smoothing treatment will not be adequate. For this situation the appropriate rehabilitation is either in situ stabilization (to improve the strength of the aggregate base material) or to cover with a minimum thickness of unbound granular material (determined from the thickness design chart by assuming the existing pavement acts as a subbase). This method of unbound granular overlay design has resulted in significant cost savings over the past 20 years in rehabilitation treatments for New Zealand roads, as the existing pavement has been fully utilized. In 1995 New Zealand adopted the Austroads (the Association of State, Territory and Federal Road and Traffic Authorities in Australia) procedures for pavement design. The Austroads procedures encourage the use of mechanistic procedures for pavement design. By using the same assumptions as the design chart method for determination of granular overlay depths, a mechanistic design procedure for rehabilitation treatments was developed. This method produces comparable results and has the advantage of being able to design a range of rehabilitation treatments.

Bassel, J. R., Edwards, A., Leibbrand, L., Keller, G. R., and Dauer, W. (1999). "Three road-crushing demonstration projects." Transportation Research Record: Journal of the Transportation Research Board, 1652.

At the Sixth International Conference on Low-Volume Roads Yves Provencher, Forest Engineering Research Institute of Canada, presented a paper on the F.A.H.R. rock crusher mounted to a front-end loader. At the same time the Coronado National Forest in Arizona was renting a F.A.H.R. rock crusher for an in-place road-crushing project. In 1997 San Dimas Technology and Development Center, in partnership with the Coronado National Forest, sponsored two demonstration projects to further test the crusher at unique locations to gain additional information from actual field trials. These projects were located on the Rio Grande National Forest in Colorado and the Plumas National Forest in California. The three projects are described here, with results and conclusions gained from the demonstration projects. The concentration is on the characteristics of the processed material. Samples taken from windrows during the crushing operation were tested to determine hardness and gradations before and after crushing. Cost varied from $8 to $26 per m3 including roadbed preparation, crushing, and blading. Rocks and boulders to 405-mm maximum size were crushed. The processed material has a maximum size of 50 to 75 mm. The product produced by the crusher offers a viable alternative for aggregate on a road surface, particularly as a road surface cushion material, where the quality and expense of standard crushed aggregate, such as base course material, are not needed on low-volume roads.

Bergeson, K. L., Kane, M. J., and Callen, D. O. (1990). "Crushed stone granular surfacing materials." Sponsored by the Iowa Limestone Produces Association and National Stone

Association Research Program, Report by Engineering Research Institute, Iowa State University, Ames, Iowa.

The results of this research project indicate that crushed stone surfacing material graded on the fine side of IDOT Class A surfacing specifications provides lower roughness and better rideability; better braking and handling characteristics; and less dust generation than the coarser gradations. This is believed to be because there is sufficient fines (-#40 to - #200) available to act as a binder for the coarser material, which in turn promotes the formation of tight surface crust. This crust acts to provide a smooth riding surface, reduces dust generation, and improves vehicle braking and handling characteristics.

Bergeson, K. L., Waddingham, J. W., Brocka, S. G., and Lapke, R. K. (1995). "Bentonite treatment for economical dust reduction on limestone surface secondary roads." Iowa DOT Project HR-351, Engineering Research Institute, Iowa State University, Ames, Iowa.

This research project was directed at laboratory and field evaluation of sodium montmorillonite clay (Bentonite) as a dust palliative for limestone surfaced secondary roads. It was postulated that the electrically charged surfaces (negative) of the clay particles could interact with the charged surfaces (positive) of the limestone and act as a bonding agent to agglomerate fine (- #200) particulates, and also to bond the fine particulates to larger (+ #200) limestone panicles. One mile test roads were constructed in Tama, Appanoose, and Hancock counties in Iowa using Bentonite treatment levels (by weight of aggregate) ranging from 3.0 to 12.0 percent. Construction was accomplished by adding dry Bentonite to the surfacing material and then dry road mixing. The soda ash water solution (dispersing agent) was spray applied and the treated surfacing material wet mixed by motor graders to a consistency of 2 to 3 inch slump concrete. Two motor graders working in tandem provided rapid mixing. Following wet mixing the material was surface spread and compacted by local traffic. Quantitative and qualitative periodic evaluations and testing of the test roads was conducted with respect to dust generation, crust development, roughness, and braking characteristics. As the Bentonite treatment level increased dust generation decreased. From a cost benefit standpoint, an optimum level of treatment is about 8 percent (by weight of aggregate). For roads with light traffic, one application at this treatment level resulted in a 60-70 percent average dust reduction in the first season, 40-50 percent in the second season, and 20-30 percent in the third season. Crust development was rated at two times better than untreated control sections. No discernible trend was evident with respect to roughness. There was no evident difference in any of the test sections with respect to braking distance and braking handling characteristics, under wet surface conditions compared to the control sections. Chloride treatments are more effective in dust reduction in the short term (3-4 months). Bentonite treatment is capable dust reduction over the lone: term (2-3 seasons). Normal maintenance blading operations can be used on Bentonite treated areas. Soda ash dispersed Bentonite treatment is conservatively estimated to be more than twice as cost effective per percent dust reduction than conventional chloride treatments, with respect to time. However, the disadvantage is that there is not the initial dramatic reduction in dust generation as with the chloride treatment. Although dust is reduced significantly after treatment there is still dust being generated. Video evidence indicates that the dust cloud in the Bentonite treated sections does not rise as high, or spread as wide as the cloud in the untreated section. It also settles faster than the cloud in the untreated section. This is considered important for driving safety of following traffic, and for nuisance dust invasion of residences and residential areas. The Bentonite appears to be functioning as a bonding agent to bind small limestone particulates to larger particles and is acting to agglomerate fine particles of limestone as evidenced by laboratory sieve analysis data, and by SEM micrographs. This bonding capability appears recoverable from environmental effects of winter, and from alternating wet and dry periods. The Bentonite is able to interact with new applications of limestone maintenance material and maintains a dust reduction capability.

Bushman, W. H., Freeman, T. E., and Hoppe, E. J. (2005). "Stabilization techniques for unpaved roads." Transportation Research Record: Journal of the Transportation Research Board, 1936, 26-33.

An amendment to Virginia House Bill 1400, Item 490, No. 1h, calls for the Virginia Transportation Research Council to “continue its evaluation of soil stabilizers as an alternative to paving low-volume secondary roads.” In response, promising soil stabilization products were evaluated with the relatively new technique of deeply mixing chemical additives into unpaved roadbeds. This work is based on the construction of a 1.75-m-long trial installation on Old Wheatland Road in Loudoun County, where seven commercially available stabilization products were applied to the unpaved road. A rigorous evaluation of treatment performance will provide the basis for recommendations to the Virginia Department of Transportation’s operating divisions regarding improvements to the maintenance practices for gravel roads. Results thus far indicate that the introduction of soil stabilizers through deep mixing is a promising technique. The life-cycle cost analysis indicates that constructing a standard bituminous surface-treated roadway and maintaining it as such is much more cost-effective than using any of the products in this trial. Further, the analysis indicates that using the bituminous surface treatment alternative is also much more cost-effective than maintaining an unpaved road.

Christoffersson, P., and Johansson, S. (2011). "Rehabilitation of the Forest Road Timmerleden." A ROADEX demonstration report, The Swedish Transport Administration, Northern Region, Sweden.

The European Union ROADEX Project 1998 – 2012 was a trans-national roads cooperation that aimed at developing ways for interactive and innovative management of low volume roads across the European Northern Periphery. Its main goals were to facilitate co-operation and research into the common problems of constructing and maintaining low volume roads in harsh climates. This report gives a summary of a local demonstration of ROADEX methods for assessing forest roads for heavy timber traffic and based on the results making a rehabilitation design proposal. Using the ROADEX-method the road was first surveyed using the modern non-destructive road survey techniques of video, ground penetrating radar and falling weight deflectometer. Three samples were also taken to check the grading and to verify the GPR-results. Following this an integrated analysis was carried out using Road Doctor software to produce a strength assessment of the road. The results were then used to do an analytical design of the strengthening measures needed to carry the load from the timber trucks. The ROADEX method was compared to regular road condition assessments and rehabilitation proposals from the project partners: The Swedish Forest Agency and the forest companies Sveaskog and SCA Forest. The partners used their normal procedures for field surveys, analyses and design. The comparison included: (1) Design, (2) Volumes of road materials used, (3) Environmental influence, (4) costs for design, materials, construction, and environmental impacts. The results demonstrate that making a more careful road condition investigation and an analytical road rehabilitation design based on the road condition analyses, can reduce the overall rehabilitation costs.

Christoffersson, P., and Johansson, S. (2012). "Rehabilitation of the Timmerleden Forest Road - Condition Survey, Design Proposals, Construction and Quality Control." A ROADEX demonstration report, The Swedish Transport Administration, Northern Region, Sweden.

The European Union ROADEX Project 1998 – 2012 was a trans-national roads cooperation that aimed at developing ways for interactive and innovative management of low volume roads across the European Northern Periphery. Its main goals were to facilitate co-operation and research into the common problems of constructing and maintaining low volume roads in harsh climates. This report gives a summary of a local demonstration of ROADEX methods for assessing forest roads for heavy timber traffic and based on the results making a rehabilitation design proposal. The report also gives a short description of the construction of the rehabilitation and the quality control. Using the ROADEX-method the road was first surveyed using the modern non-destructive road survey techniques of video, ground penetrating radar and falling weight deflectometer. Three samples were also taken to check the grading and to verify the GPR-results. Following this an integrated analysis was carried out using Road Doctor software to produce a strength assessment of the road. The results were then used to do an analytical design of the strengthening measures needed to carry the load from the timber trucks. The ROADEX method was compared to regular road condition assessments and rehabilitation proposals from the project partners: The Swedish Forest Agency and the forest companies Sveaskog and SCA Forest. The partners used their normal procedures for field surveys, analyses and design. The comparison included: (1) Design, (2) Volumes of road materials used, (3) Environmental influence, (4) costs for design, materials, construction, and environmental impacts. To make the ROADEX forest road rehabilitation package complete a quality control was carried out to check if the measures were done right in place, if the layer thicknesses were constructed in accordance with the design and if the bearing capacity target was reached. New GPR- and FWD surveys were carried out about a month after the rehabilitation work was finished. It was found from the GPR survey that measures were very well in place but in some places the base course was a little thinner than the design thickness. A new calculation in accordance with the Odemark method based on the new survey results showed that 98 % of the road length met the bearing capacity target of 90 MPa. The results demonstrate that making a more careful road condition investigation and an analytical road rehabilitation design based on the road condition analyses, can reduce the overall rehabilitation costs and the environmental impacts significantly. The demonstration project has shown that the use of the ROADEX method in this case reduced the costs between 15 and 50%.

Christopher, B. R., Schwartz, C., and Boudreau, R. (2005). "Geotechnical Aspects of Pavements." FHWA NHI-05-037, National Highway Institute, Federal Highway Administration, U.S. Dept. of Transportation, Washington, D.C.

The manual covers the latest methods and procedures to address the geotechnical issues in pavement design, construction and performance for new construction, reconstruction, and rehabilitation projects. The manual includes details on geotechnical exploration and characterization of in place and constructed subgrades as well as unbound base/subbase materials. The influence and sensitivity of geotechnical inputs are reviewed with respect to the requirements in past and current AASHTO design guidelines and the mechanistic-empirical design approach developed under NCHRP 1-37A, including the three levels of design input quality. Design details for drainage features and base/subbase material requirements are covered along with the evaluation and selection of appropriate remediation measures for unsuitable

subgrades. Geotechnical aspects in relation to construction, construction specifications, monitoring, and performance measurements are discussed.

DOD (1985). "Pavement design for seasonal frost conditions." Technical Manual No. 5-818-2, Air Force Manual No. 88-6, Chapter 4, Departments of the Army and Air Force, Washington, D.C.

This manual presents criteria and procedures for the design and construction of pavements placed on subgrade or base course materials subject to seasonal frost action. The criteria are applicable to Air Force and Air National Guard airfields, and to roads. This manual is concerned with modes unique to frost areas. The principal non-traffic-associated distress modes are distortion caused by frost heave and reconsolidation, and cracking caused by low temperatures. The principal traffic-load-associated distress modes are cracking and distortion as affected by the extreme seasonal changes in supporting capacity of subgrades and bases that may take place in frost areas.

Marti, M. M., Mielke, A. J., and Hubbard, C. D. (2003). "Effective Methods to Repair Frost Damaged Roadways." Research Implementation Series Number 27, Minnesota Local Road Research Board, Minnesota Department of Transportation, St. Paul, Minnesota.

This report describes common causes for frost-related damage (non-uniform subgrades, shallow ground water table, low lying areas), means to evaluating prospective repair alternatives, methods to improve subgrade uniformity, and strategies to reduce/limit subgrade moisture.

Maurer, G., Bemanian, S., and Polish, P. (2007). "Alternative Strategies for Rehabilitation of Low-Volume Roads in Neveda." Transportation Research Record: Journal of the Transportation Research Board, 1989, 309-320.

An overview of the attempt by the Nevada Department of Transportation (NDOT) to find alternative rehabilitation strategies to rehabilitate its low-volume road network effectively is provided. Because of Nevada's continuing growth, NDOT is faced with the challenge of how to balance its available funding between pavement preservation and capacity improvement projects. NDOT is responsible for 13,000 lane miles of roadway, of which 3,385 lane miles (26%) qualify as low-volume roads. The low-volume roads have a two-directional average daily traffic of 400 or less. Five roadway projects with a combined total of 111 centerline miles were rehabilitated with 29 combinations of structural and surface strategies. The rehabilitation strategies investigated included full-depth reclamation with lime, cement, asphalts, and foamed asphalt. Various cold-mix, cold-in-place recycling with millings and different rejuvenating agents, and surface treatment test sections were constructed. The constructability issues that were reported during construction are discussed. In addition, pavement condition is examined and laboratory testing is reviewed. Results suggest that NDOT can use alternative rehabilitation strategies in place of its conventional method of 2-in. plant-mix bituminous surface overlay and chip seal to rejuvenate its low-volume roadway network. A cost saving of approximately $100,000 per centerline mile is anticipated.

McHattie, R. L. (2010). "Evaluating & Upgrading Gravel Roads For Paving." Alaska Department of Transportation.

Scenario: The Matanuska-Susitna Borough wants to consider paving an existing gravel road. As a Borough engineer you are assigned to develop and/or manage such a project. The road must handle only light, local traffic, and you would therefore like to pave it at the lowest possible cost. As an engineer you need a comfortable degree of confidence that you can properly design the new pavement, and that it can be justified, economically and otherwise. Is it possible to simply go ahead and apply new hot mix asphalt concrete or an asphalt surface treatment (AST) pavement to that old gravel road surface? For a number of good reasons that would not be prudent. As the engineer assigned to the project, your involvement begins with a couple of basic questions: (a) Is the Borough committed to a road management program, including new maintenance and load restriction policies that will sustain the service life of the new pavement? (b) Have you considered the public's opinions, user costs, and safety issues? You must answer these questions before this engineering guide will be of use. Then, in order to provide Borough management with realistic estimates of economic feasibility, and design requirements, you must answer these questions: (a) Do predicted traffic levels confirm that asphalt concrete pavement is appropriate? (b) What kind of asphalt pavement is best? (c) Are you prepared, in terms of engineering time and resources, to evaluate and upgrade the existing gravel road, as necessary, to obtain a predictable service life? (d) Is the candidate gravel road in nearly good enough condition to receive pavement? (e) Does the existing road need to be significantly upgraded prior to paving? (f) If upgrading is needed, what type and how much is necessary? These latter questions are directly related to evaluating the existing gravel road and designing for a new asphalt pavement surface — the subject of this guide.

Muthen, K. M. (1999). "Foamed Asphalt Mixes - Mix Design Procedure." CR-98/077, CSIR Transportek, Pretoria, South Africa.

Foamed asphalt epitomizes the asphalt industry's drive towards energy efficient, environmentally friendly and cost-effective solutions for road-building. Foamed asphalt refers to a bituminous mixture of road-building aggregates and foamed bitumen, produced by a cold mix process. Although the foamed bitumen process was developed more than 40 years ago and lauded by researchers the world over, it is believed that the lack of standardized design procedures has contributed to the limited implementation of the technology in South Africa, with practitioners favouring more familiar and well documented products. Recently there has been significant interest in the product, especially in the in-situ method of construction, and hence the need for a standard mix design procedure has now become essential. One element of foamed asphalt technology which may prove to be an impediment to standardization is the emergence of various proprietary bitumen foaming techniques. This report focusses on the development of a mix design method for foamed asphalt mixes, based on research work conducted at CSIR Transportek on behalf of SABITA. An extensive survey was undertaken of the worldwide practice with regard to foamed asphalt mix design, which included literature surveys and liaison with recognized experts. A mix design procedure was developed, encompassing all the necessary elements from the selection of aggregates and binder to the determination of the optimum engineering properties of the mix. This was followed by a laboratory program designed to verify the proposed mix design procedure. It is believed that the proposed mix design procedure is independent of the type of bitumen foaming process used and should, therefore, be acceptable to practitioners.

Saarenketo, T., and Aho, S. (2005). "Managing Spring Thaw Weakening on Low Volume Roads - Problem Description, Load Restriction Policies, Monitoring and Rehabilitation." The ROADEXII Project, The Swedish Road Administration, Northern Region, Sweden.

This is a final report from the Phase II subproject 2_3 survey of the Roadex II project, a technical transnational cooperation project between the Highland Council, the Western Isles Council, and Forest Enterprise from Scotland; the Northern Region (formerly Troms district) of the Norwegian Public Roads Administration and the Norwegian Road Haulage Association; the Northern Region of the Swedish National Road Administration; and from Finland the Regions of Central Finland and Lapland of the Finnish Road Administration, as well as Metsähallitus Region of Eastern Lapland, the Forestry Centre of Lapland (Lapin Metsäkeskus), Stora Enso Metsä, and Metsäliitto, Procurement Area of Northern Finland. The Roadex project is partly financed by the ERDF IIIB Northern Periphery Programme. The lead partner in the project is the Highland Council from Scotland and project consultant is Roadscanners Oy from Finland. Roadex II project Chairman is Ron Munro from the Highland Council and project manager is Timo Saarenketo from Roadscanners. The report summarizes the work done on Task 2_3 "Spring Thaw Weakening" of the Roadex II project. The report will describe the theory behind spring thaw weakening and different load restriction policies used in the cold climate areas. It will also report the results of the field tests done in Scotland, Sweden and Norway and present some new structural solutions which have been found to work well at spring thaw weakening sites. Finally, new technologies for both road owners and/or road users that could be used in more effective spring thaw weakening management will be revealed.

Stabilization Design Procedures

ARTBA (1990). "Stabilization and Pavement Recycling." Stabilization, Rehabilitation, and Recycling Committee, American Road and Transportation Builders Association (ARTBA), Washington, D.C.

This report contains an overview of (1) stabilization and recycling, (2) asphalt stabilization, (3) asphalt emulsion for dust control, (4) dust control and stabilization with calcium chloride, (5) cement stabilization, (6) fly ash stabilization, (7) lime stabilization, (8) sodium chloride stabilization, and (9) pavement recycling, along with key references.

Austroads (1998). "Guide to stabilisation in roadworks." Austroads, Sydney, A4, New Zealand.

This Guide provides systematic guidance to practitioners for the selection, design and construction of stabilised pavement layers for use in the construction of new road pavements and the maintenance, rehabilitation and recycling of existing road pavements. It replaces the 1986 NAASRA Guide to Stabilisation in Roadworks. Since the NAASRA Guide was published, there have been substantial improvements in many aspects of stabilisation technology including: (1) improved pavement design procedures; (2) improved materials characterisation procedures; (3) higher capacity plant and equipment; (4) wider range of stabilisation agents with greater effectiveness; and (5) increased environmental awareness of the benefits of stabilisation. Guidance is given to assist the practitioner to select the appropriate type of stabilisation for a particular application as well as materials and pavement design guidance for the following broad types of stabilisation techniques: cementitious stabilisation, lime stabilisation, bituminous stabilisation, granular stabilisation, and other forms of stabilisation. Construction and quality management issues are also addressed. While there have been significant advances in stabilisation technology in the past decade, there are still a number of areas in need of greater understanding including: materials mix design and characterisation, erosion mechanisms, long term strength gains, and stabilisation under traffic. While the information given in the Guide is

considered to represent best practice at the time of publication, with the current rate of change of stabilisation technology, it will continue to improve in the future.

Benson, C. H., Edil, T. B., Tanyu, B. F., and Kim, W.-H. (2005). "Equivalency of Crushed Rock with Industrial By-Products and Geosynthetic-Reinforced Aggregates Used for Working Platforms during Pavement Construction." WHRP Final Report No. 0092-00-12, Department of Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, WI.

A study was conducted to define an equivalency criterion for five materials used for working platforms during pavement construction on a poor subgrade: conventional crushed rock (referred to as “breaker run”) and four alternatives (i.e. Grade 2 granular backfill (referred to as “Grade 2”), foundry slag, bottom ash, and foundry sand). Total deflection data for the equivalency assessment were obtained from a large-scale model experiment (LSME) simulating a prototype-scale pavement structure and in the field using a rolling wheel deflectometer (RWD). Design charts were developed for selecting the equivalent thickness of alternative working platform materials so that the alternative provides equal deflection as a layer of breaker run. Another phase of the study was conducted to determine the equivalency of geosynthetic reinforced aggregate working platforms in providing support during pavement construction over soft subgrade. Four reinforcing geosynthetics (a geogrid, a woven geotextile, a non-woven geotextile, and drainage geocomposite) incorporated into two granular materials: Grade 2 and breaker run were used in this study. Design charts were developed for selecting the equivalent thickness of an alternative geosynthetic-reinforced working platform material so that the alternative provides equal deflection as a layer of breaker run.

Berg, R. R., Christoper, B. R., and Perkins, S. (2000). "Geosynthetic Reinforcement of the Aggregate Base/Subbase Courses of Pavement Structures." Geosynthetic Materials Association, Roseville, MN.

Geosynthetic reinforcement of the base, or subbase, course of pavement structures is addressed. The value added with reinforcement, design criteria/protocols, and practices for design and for material specifications are presented. Base, or subbase, reinforcement is defined within as the use of geosynthetic reinforcement in flexible pavements to support vehicular traffic over the life of a pavement structure. Primary base reinforcement benefits are to improve the service life and/or obtain equivalent performance with a reduced structural section. Substantial life-cycle cost savings are possible with base reinforcement. Cost saving benefits should be quantified using life-cycle analyses, and on an agency specific basis due to the many input variables. Recommended design procedure and material specifications are presented. It is recommended that specification with an approved products list be utilized, as the mechanisms of reinforcement are not fully understood and the geosynthetic performance should be considered product, and test conditions, specific. Equivalent materials must demonstrate equivalent performance in test structures and/or possess equivalent material properties, as defined by the specifier. The use of geosynthetic reinforcement to aid in construction over low strength subgrades, termed subgrade restraint within, is also addressed. Geosynthetic reinforcement is used to increase the support equipment during construction of a roadway. Subgrade restraint design procedures are based upon either (i) generic material properties, wherein a generic specification can be prepared based upon those design property requirements; or (ii) product-specific, empirically derived design methods, wherein an approved products list specification approach may be used. Geogrid, geotextile, and geogrid-geotextile composite materials are addressed within. This paper provides government agencies with current, logical recommended practice for the systematic use of geosynthetic reinforcement of pavement base courses. Refined guidance should be developed as the use of base reinforcement increases and additional long-term performance data becomes available.

Bryan, A. J. (1988). "Criteria for the suitability of soil for cement stabilization." Building and Environment, 23(4), 309-319.

A major problem prior to the decision to use soil/cement as the walling material on a construction project is to identify a sufficient supply of soil suitable for economic stabilization. There is now reasonable guidance on both the important soil characteristics and possible limits for satisfactory cement stabilization. This paper summarized these characteristics and compares limits that have been suggested from previous studies. Results from a laboratory programme on 15 soils from the South West of England are presented to identify textural and plasticity characteristics which may offer further guidance for the identification of soils with the potential for stabilization with cement.

Cerato, A. B., Miller, G. A., Snethen, D. S., and Hussey, N. (2011). "Validation and Refinement of Chemical Stabilization Procedures for Pavement Subgrade Soils in Oklahoma - Volume 1." FHWA-OK-11-02, School of Civil Engineering and Environmental Science, University of Oklahoma, Normal, OK.

Additions of byproduct chemicals, such as fly ash or cement kiln dust, have been shown to increase the unconfined compression strength (UCS) of soils. To be considered effective, the soil must exhibit a strength increase of at least 50 psi. Many current design methods base chemical additive percentage recommendations on the results of Atterberg Limit tests which do not always properly characterize the soil stabilization response. For example, Atterberg limit tests may reveal the same AASHTO classification of soil at two different sites, but one site may require more than twice the additive percentage of a chemical to achieve the desired UCS increase. This study examined the relationship between soil physico-chemical parameters and unconfined compression strength in various fine-grained soils to determine if other soil parameters have significant effects on predicting the strength of a soil treated with a given additive and additive content. The results of this study suggest that the surface area and shrinkage properties of the soil, combined with the Atterberg limit results, present a better picture of a given soil and will allow for better predictions of the amount of chemical stabilizer needed to adequately stabilize the soil.

Giroud, J. P. "An assessment of the use of geogrids in unpaved roads and unpaved areas." Proc., Jubilee Symposium on Polymer Geogrid Reinforcement, ARRB Group Limited, Vermonth South, Victoria.

This paper presents an assessment of the use of geogrids in unpaved roads and unpaved areas. Unpaved areas comprise working platforms, storage areas, parking lots, log yards, etc. The phrase “unpaved roads and trafficked areas”, sometimes used, is not used herein because it may be confusing (as it may imply that the areas are trafficked and the roads are not, and that the areas are not unpaved). The term “stabilisation structures” will be used to encompass these two types of structures; and the term “subgrade stabilisation” will refer to this application in general. This paper includes two main parts. In the first part, a technical analysis is presented where the relevant properties of geogrids in unpaved roads and unpaved areas are discussed. In the second

part, the state of practice is reviewed and factors that have an impact on the use of geogrids in unpaved roads and unpaved areas are discussed, such as: the cost of geosynthetics and aggregate, competition with geotextiles, and experience of decision-makers. The paper ends with a discussion of challenges for the future, including research needs. This paper is written for readers who have a good knowledge of geotechnical engineering and geosynthetics and their applications. In particular, the readers are assumed to be knowledgeable about unpaved roads and unpaved areas, and to be familiar with the related terminology. Intentionally, the paper does not include any illustration in order to focus the attention of the readers on the analyses and discussions. The purpose of this paper is not to explain how to design and construct unpaved roads and unpaved areas, but to assess the use of geogrids in these structures.

Giroud, J. P., and Han, J. (2004a). "Design Method for Geogrid-Reinforced Unpaved Roads. I. Development of Design Method." Journal of Geotechnical and Geoenvironmental Engineering, 130(8), 775-786.

A theoretically based design method for the thickness of the base course of unpaved roads is developed in this paper, which considers distribution of stress, strength of base course material, interlock between geosynthetic and base course material, and geosynthetic stiffness in addition to the conditions considered in earlier methods: traffic volume, wheel loads, tire pressure, subgrade strength, rut depth, and influence of the presence of a reinforcing geosynthetic, geotextile or geogrid on the failure mode of the unpaved road or area. In this method, the required base course thickness for a reinforced unpaved road is calculated using a unique equation, whereas more than one equation was needed with earlier methods. This design method was developed for geogrid-reinforced unpaved roads. However, it can be used for geotextile-reinforced unpaved roads and for unreinforced roads with appropriate values of relevant parameters. The calibration of this design method using data from field wheel load tests and laboratory cyclic plate loading tests on unreinforced and reinforced base courses is presented in the companion paper by the authors.

Giroud, J. P., and Han, J. (2004b). "Design Method for Geogrid-Reinforced Unpaved Roads. II. Calibration and Applications." Journal of Geotechnical and Geoenvironmental Engineering, 130(8), 787-797.

A theoretically based base course thickness design method for unpaved roads was developed in the companion paper. This paper presents a calibration of the design method using data from field wheel load tests and laboratory cyclic plate loading tests on unreinforced and reinforced base courses. The constants in the design method are determined during the calibration. The calibrated design method is used for analyzing the test data through three case studies. In addition, the design procedures and a design example are provided in this paper to demonstrate the use of the design method.

Holtz, R. D., and Sivakugan, N. (1987). "Design charts for roads with geotextiles." Geotextiles and Geomembranes, 5, 191-199.

Design charts have been developed to determine the required aggregate thickness for geotextile-reinforced roads using the Giroud and Noiray procedure. The charts are for rut depths of 75, 100, 150, 200, and 300 mm, with tire pressures of 480 and 620 kPa for a standard design axle load of 80 kN. The charts can be used for the design of geotextile-reinforced unpaved roads,

roadway stabilization aggregate, and for the first construction lift for embankments on very soft foundations.

Hopkins, T. C., Beckham, T. L., and Hunsucker, D. Q. (1995). "Modification of highway soil subgrades." Report KTC 94-11, Kentucky Transportation Center, University of Kentucky, Lexington, KY.
Major study objectives were to develop highway pavement subgrade stabilization guidelines, examine long-term benefits of chemical stabilizers, such as cement, hydrated lime, and two byproducts from industrial processes, and to establish a subgrade stabilization program in Kentucky. In developing a program, a number of design and construction issues had to be resolved. Factors affecting subgrade behavior are examined. Changes in moisture content and CBR strengths of untreated and chemically treated subgrades at three experimental highway routes were monitored over a 7-year period. CBR strengths of the untreated subgrades decreased dramatically while moisture contents increased. CBR strengths of subgrade sections treated with hydrated lime, cement and multicone kiln dust generally exceeded 12 and increased over the study period. At four other highway routs ranging in ages from 10 to 30 years, CBR strengths of soil-cement subgrades exceed 90. Knowing when subgrade stabilization is needed is critical to the development of an economical design and to insure the efficient construction of pavements. Bearing capacity analyses using a newly developed, stability model based on limit equilibrium and assuming a tire constant stress of 552 kPa show that stabilization should be considered when the CBR strength is less than 6.5. For other tire contact stresses, relationships corresponding to factors of safety of 1 and 1.5 are presented. Stability analysis of the first lifts of the paving materials showed that CBR strengths of untreated subgrade should be > 9. Guidelines for using geogrids as subgrade reinforcement are presented. Factors of safety of geogrid reinforced granular bases are approximately 10 to 25 percent larger than granular bases without reinforcement. As shown by strength tests and stability analysis, when the percent finer than the 0.002mm particle size of a soil increases to a value greater than about 15%, the factor of safety decreases significantly. Guidelines are also presented for this selection of the design strengths of untreated and treated subgrades with hydrated lime and cement. Based on a number of stabilization projects, recommended design undrained shear strengths of hydrated lime- and cement-treated subgrades are about 300 and 690 kPa, respectively. A laboratory testing procedure for determining the optimum percentage of chemical admixture is described. Correlations of dynamic cone penetrometer and Clegg impact hammer and in situ CBR strengths and unconfined compressive strengths are presented.

Houlsby, G. T., and Jewell, R. A. (1990). "Design of reinforced unpaved roads for small rut depths." 4th International Conference on Geotextiles Geomembranes and Related Products, D. Hoedt, ed., Balkema, Rotterdam, Netherlands.
Current design methods for reinforced unpaved roads on soft ground are based on the concept that the principal function of the reinforcement is to act as a tensioned membrane. This is usually combined with an empirical increase of the allowable bearing capacity factor for the subgrade in the case of a reinforced road. A new analysis of unpaved roads is presented in which the tensioned membrane effect, which is any case insignificant at small rut depths, is not considered, and a rational calculation is made to determine the appropriate bearing capacity factor for the subgrade. The role of shear stresses on the reinforcement surface becomes of

primary importance. Design charts are presented which allow the necessary depth of granular fill, and the required reinforcement tension to be determined.

Kestler, M. A. (2009). "Stabilization selection guide for aggregate and native-surfaced low-volume roads." National Technology and Development Program, Forest Service, U.S. Department of Agriculture, Washington, D.C.

The purpose of this guide is to facilitate the selection of modification/stabilization agents and techniques for aggregate surfaced and native/unsurfaced LVRs. The objective is to provide low-cost alternatives that reduce aggregate wear and loss, reduce road-surface maintenance (i.e., blading out ruts), and reduce the time period between major rehabilitation (i.e., between adding new aggregate and the total reconditioning of the road pavement). This guide provides information on available stabilizing agents, appropriate conditions for use, selection procedures, quantity determination, and contact information for manufacturers/suppliers. Emphasis is on the modification/stabilization of existing in-place road surface materials, but many of the methods can be used in the construction of new roads. Construction procedures for application are also presented. The intended audience includes road managers, engineers, and technicians involved in road maintenance, construction, and reconstruction. Those involved in trail maintenance and construction also may find the guide beneficial, as stabilizers used on trails, particularly accessible trails, help provide a smooth, durable surface.

Lohnes, R. A., and Coree, B. J. (2002). "Determination and evaluation of alternative methods for managing and controlling highway-related dust." Iowa DOT Project TR449, Iowa State University, Ames, Iowa.

Road dust is caused by wind entraining fine material from the roadway surface and the main source of Iowa road dust is attrition of carbonate rock used as aggregate. The mechanisms of dust suppression can be considered as two processes: increasing particle size of the surface fines by agglomeration and inhibiting degradation of the coarse material. Agglomeration may occur by capillary tension in the pore water, surfactants that increase bonding between clay particles, and cements that bind the mineral matter together. Hygroscopic dust suppressants such as calcium chloride have short durations of effectiveness because capillary tension is the primary agglomeration mechanism. Somewhat more permanent methods of agglomeration result from chemicals that cement smaller particles into a mat or larger particles. The cements include lignosulfonates, resins, and asphalt products. The duration of the cements depend on their solubility and the climate. The only dust palliative that decreases aggregate degradation is shredded shingles that act as cushions between aggregate particles. It is likely that synthetic polymers also provide some protection against coarse aggregate attrition. Calcium chloride and lignosulfonates are widely used in Iowa. Both palliatives have a useful duration of about 6 months. Calcium chloride is effective with surface soils of moderate fine content and plasticity whereas lignin works best with materials that have high fine content and high plasticity indices. Bentonite appears to be effective for up to two years and works well with surface materials having low fines and plasticity and works well with limestone aggregate. Selection of appropriate dust suppressants should be based on characterization of the road surface material. Estimation of dosage rates for potential palliatives can be based on data from this report, from technical reports, information from reliable vendors, or laboratory screening tests. The selection should include economic analysis of construction and maintenance costs. The effectiveness of the treatment should be evaluated by any of the field performance measuring techniques

discussed in this report. Novel dust control agents that need research for potential application in Iowa include; acidulated soybean oil (soapstock), soybean oil, ground up asphalt shingles, and foamed asphalt. New laboratory evaluation protocols to screen additives for potential effectiveness and determine dosage are needed. A modification of ASTM D 560 to estimate the freeze-thaw and wet-dry durability of Portland cement stabilized soils would be a starting point for improved laboratory testing of dust palliatives.

Maxwell, S., Kim, W.-H., Edil, T. B., and Benson, C. H. (2004). "Geosynthetics in Stabilizing Soft Subgrade with Breaker Run." Report No. 0092-45-15, Department of Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, WI.

This report introduced the research begun in 1999 at the University of Wisconsin-Madison to further understand aspects of geosynthetic-reinforced subbases in a pavement system. To learn more about how the performance of highway pavement is improved with geosynthetics, a field demonstration was conducted using a 21-m section along a Wisconsin highway (USH 45) near Antigo, Wisconsin, that incorporated three test sub-sections. Three different geosynthetics including a woven geotextile and two different types of geogrids were evaluated for stabilization. The same pavement structure was used for all test sections except for the geosynthetics. Observations made during and after construction indicate that all sections provided adequate support for the construction equipment and that no distress is evident in any part of the highway. Much has been learned about instrumentation of geosynthetics with foil-type strain gages. The installation procedures and weatherization techniques used during this demonstration project appeared to be a success. Additionally, better strain gage results are possible for a geotextile when a longer (25 mm) strain gage is used. The falling weight deflectometer did not provide sufficient resolution to differentiate between different types of geosynthetic test sections especially in a field environment where there's heterogeneity of natural soils. However, a greater seasonal variability of the subgrade was noted. A control section without reinforcement was not constructed at this time that would have allowed for comparison and assessment of the geosynthetic addition.

Mekkawy, M. M., White, D. J., Suleiman, M. T., and Jahren, C. T. (2011). "Mechanically reinforced granular shoulders on soft subgrade: Laboratory and full scale studies." Geotextiles and Geomembranes, 29, 149-160.

A recently completed field study in Iowa showed that many granular shoulders overlie clayey subgrade layer with California Bearing Ratio (CBR) value of 10 or less. When subjected to repeated traffic loads, some of these sections develop considerable rutting. Due to costly recurring maintenance and safety concerns, the authors evaluated the use of biaxial geogrids in stabilizing a severely rutted 310 m tests section supported on soft subgrade soils. Monitoring the test section for about one year, demonstrated the application of geogrid as a relatively simple method for improving the shoulder performance. The field test was supplemented with a laboratory testing program, where cyclic loading was used to study the performance of nine granular shoulder models. Each laboratory model simulated a granular shoulder supported on soft subgrade with geogrid reinforcement at the interface between both layers. Based on the research findings, a design chart correlating rut depth and number of load cycles to subgrade CBR was developed. The chart was verified by field and laboratory measurements and used to optimize the granular shoulder design parameters and better predict the performance of granular shoulders.

Muthen, K. M. (1999). "Foamed Asphalt Mixes - Mix Design Procedure." CR-98/077, CSIR Transportek, Pretoria, South Africa.

Foamed asphalt epitomizes the asphalt industry's drive towards energy efficient, environmentally friendly and cost-effective solutions for road-building. Foamed asphalt refers to a bituminous mixture of road-building aggregates and foamed bitumen, produced by a cold mix process. Although the foamed bitumen process was developed more than 40 years ago and lauded by researchers the world over, it is believed that the lack of standardized design procedures has contributed to the limited implementation of the technology in South Africa, with practitioners favouring more familiar and well documented products. Recently there has been significant interest in the product, especially in the in-situ method of construction, and hence the need for a standard mix design procedure has now become essential. One element of foamed asphalt technology which may prove to be an impediment to standardization is the emergence of various proprietary bitumen foaming techniques. This report focusses on the development of a mix design method for foamed asphalt mixes, based on research work conducted at CSIR Transportek on behalf of SABITA. An extensive survey was undertaken of the worldwide practice with regard to foamed asphalt mix design, which included literature surveys and liaison with recognized experts. A mix design procedure was developed, encompassing all the necessary elements from the selection of aggregates and binder to the determination of the optimum engineering properties of the mix. This was followed by a laboratory program designed to verify the proposed mix design procedure. It is believed that the proposed mix design procedure is independent of the type of bitumen foaming process used and should, therefore, be acceptable to practitioners.

PCA (1995). "Soil-Cement Construction Handbook." Portland Cement Association, Skokie, Illinois.

This guide describes procedures for constructing, under a wide variety of conditions, high quality soil-cement base courses for roads, streets, airports, and parking and storage areas. Includes inspection and field control, recycling flexible pavement, and a discussion of cement-modified soils.

Rollings, M. P., and Rollings, R. S. (1996). Geotechnical Materials in Construction, McGraw-Hill, New York, NY.

Chapter 6 of this book provides information on Stabilization: Seldom does nature provide the ideal soil or aggregate for construction. To overcome deficiencies in soil or aggregate properties such as poor grading, excess plasticity, or inadequate strength, we may blend two or more soils together, or we may add stabilizing admixtures such as lime, portland cement, or bituminous materials to the soil or aggregates. These techniques are effective if we can readily mix the materials. Other techniques for improving soil conditions at depth will be covered in Chap. 7. We often think of stabilization as a method of providing structural strength, but it can have a number of other construction and behavioral effects that are equally beneficial. These might include improved soil workability, an all-weather construction platform, or reduced swelling of expansive materials. Stabilization may improve the properties of an on-site or local material to allow its use rather than incurring the cost of importing a better material from a distant source. In the following sections we will examine the effects of blending and stabilizing with lime, portland cement, bituminous materials, pozzolanic and slag materials, and specialty admixtures.

Terrel, R. L., Epps, J. A., Barenberg, E. J., Mitchell, J. K., and Thompson, M. R. (1979). "Soil Stabilization in Pavement Structures - A User's Manual." COT-FH-11-9406, Federal Highway Administration, Department of Transportation, Washington D.C.

This manual contains two volumes. Volume 1 covers the pavement design and construction considerations of soil stabilization, while Volume 2 covers the mix design considerations. The primary purpose of this manual is to provide background information for those engineers responsible for utilizing soil stabilization as an integral part of a pavement structure. Information is included which will allow the pavement design engineer to determine the thickness of stabilized layer(s) for a pavement in a specific climate and subjected to definable highway traffic. The construction engineer will find information on quality control, specifications and construction sequences. The materials engineer has been provided with information that will allow the determination of the type and amount of stabilizers that are suitable for a particular soil. The manual has not been written to endorse one type of a chemical stabilizer over another. Nor is it intended to provide the specific features of one manufacturer's products. Rather, it explains the general characteristics of chemical soil stabilization and offers a method for evaluating the benefits of chemical stabilization versus the conventional mechanical stabilization operations. A thorough study of the manual should enable the engineer to recommend where, when and how soil stabilization should be used. It may also act as an aid in solving problems that may arise on soil stabilization projects.

Tingle, J. S., and Webster, S. L. (2003). "Corps of Engineers design of geosynthetic-reinforced unpaved roads." Transportation Research Record: Journal of the Transportation Research Board, 1849, 193-201.

U.S. Army Corps of Engineers design procedure was reviewed to validate the existing criteria for geotextile-reinforced unpaved roads and to modify the criteria for the addition of stiff biaxial geogrids. Geogrid stiffness here refers to products demonstrating good torsional rigidity and aperture stability. The theoretical basis for the existing design procedure was reviewed to ensure that appropriate assumptions were used to derive the current design method. Historical test section results were used to validate the empirical bearing-capacity factors, Nc, used for unreinforced and geotextile-reinforced base materials. In addition, an empirical bearing-capacity factor for geogrid reinforcement was derived to modify the existing design procedure for both geotextile and geogrid use. The relevant theory used in the development of the existing design method to establish the basis for the analyses is described. Previously unpublished test section results are presented and used to calculate experimental bearing-capacity factors, and the calculated factors are compared with the theoretical values used in the existing procedure. The results of the analyses support the use of the existing design procedure’s bearing-capacity factor for unreinforced sections; the existing bearing-capacity factor for geotextile-reinforced unpaved roads appears to be unconservative for the conditions of the full-scale test section presented. Finally, a bearing-capacity factor for the use of a geogrid and geotextile combination is recommended for modification of the existing Corps of Engineers design procedure.

Freeze-Thaw Durability Aspects

Al-Kiki, I. M., Al-Atalla, M. A., and Al-Zubaydi, A. H. (2011). "Long Term Strength and Durability of Clayey Soil Stabilized With Lime." Engineering and Technology Journal, 29(4), 725-735.

This study deals with durability characteristics and unconfined compressive strength of clayey soil stabilized with lime. The tests comprises of unconfined compressive strength for samples stabilized with the optimum lime percent (4%), and subjected to cycles of the wet-dry, dry-wet and freeze-thaw durability tests as well as, long-term soaking and slake tests. The results indicated that, the efficiency of the lime in the improvement of unconfined compressive strength of clayey soil is of negative effect in the long term durability periods The wetting-drying cycles showed greater reduction in unconfined compressive strength than drying-wetting cycles, while the volume change of samples which subjected to drying at first, was greater than those conducted with wetting. On the other hand, freezing-thawing cycles causes a decreasing in the unconfined compressive strength values, and the reduction ratio was greater than wetting and drying cases. But, during soaking tests it was found that at early soaking periods, the lime stabilized samples continuously gaining strength, but beyond this the strength decreased with increasing soaking period. Finally, the stabilized samples with (4 and 6%) lime becomes more durable against the cycles of wetting and drying.

Berg, K. C. (1998). "Durability and strength of activated reclaimed Iowa Class C fly ash aggregate in road bases." M.S. Thesis, Department of Civil Engineering, Iowa State University, Ames, Iowa.

The development of high-volume uses for coal-fired power plant waste creates both economic and environmental benefits. Approximately 90 million tons of coal combustion by-products are produced each year in the United States, including 70 to 80 million tons of fly ash. Only about 25% of the fly ash produced is utilized by other industries. Power plant waste such as fly ash, if not utilized in industrial or construction projects, must be disposed of in landfills or sluice ponds. Fly ash is commonly used as a partial replacement for Portland cement in concrete, where it has been shown to provide comparable strength for a significantly lower cost. A growing application for fly ash use is for the stabilization of soils that would otherwise be unsuitable construction materials. Fly ash has been economically used to increase strength, lower plasticity, and reduce the moisture content of soils that would have otherwise required Portland cement or lime stabilization. While both of these fly ash utilization methods provide clear economic and engineering benefits, only a relatively small portion of the fly ash produced can be utilized. Fly ash is usually limited to 15% replacement of Portland cement in concrete, and typical addition rates for soil stabilization are 5% to 15% by dry weight of soil. Higher volume uses for coal combustion products are necessary to significantly reduce the amount of waste that must be landfilled. The development of high-volume construction uses for a significant portion of this waste can reduce the landfilling costs as well as produce revenue from sale of the materials. A promising high-volume application of hydrated reclaimed Class C fly ash is as a replacement for aggregate in flexible pavement base courses. The focus of this research is to evaluate the properties of hydrated Iowa Class C fly ash aggregates reclaimed from sluice pond disposal sites. Bergeson and Barnes have recently developed a pavement thickness design method for the use of these aggregates in flexible pavement base courses based on the California Bearing Ratio (CBR) and unconfined compressive strength. To reinforce this strength-based pavement design, this research focuses on the freeze-thaw durability, volumetric stability, and long-term strength gain of hydrated reclaimed fly ash aggregate with different chemical activators. The main consideration for the prediction of the durability, strength, and volumetric stability of activator/reclaimed fly ash aggregate mixtures is the manner in which they will perform in field applications. The results of freeze-thaw durability testing, ASTM C 593 vacuum-saturated compressive strength testing, and unconfined compressive strength testing indicate that the untreated materials act as a granular material, while the lime-treated material develops higher strengths associated with a pozzolanic base material. The use of CKD, which is highly effective as an activator, was discontinued due to lowered availability and environmental concerns. CKD can contain high levels of lead, and changes in the manufacture of Portland cement have rendered it nearly unavailable in Iowa. Raw fly ash is somewhat effective as an activator, but fly ash/reclaimed fly ash aggregate mixtures break down when subjected to multiple freeze-thaw cycles. This may not be a large problem if high strengths are not required, because the base will probably function in a similar manner to a crushed stone base. This is evidenced by the good performance of the AFBC/reclaimed fly ash aggregate sections of the Ottumwa-Midland and Sutherland access roads. The surface courses of both roads remain intact and serviceable despite the deterioration of base into rough, angular aggregate-sized pieces. Although cores can no longer be extracted from these sections, aggregate interlock forces appear to provide adequate strength to the pavements. The use of fly ash aggregate without an activator is the obvious choice for low cost applications where high strengths are not required. The addition of 2.5% lime by dry weight of reclaimed ash aggregate provides significant gains in strength and durability for all the reclaimed fly ash aggregate sources tested in this project. The use of fly ash as an activator is preferred by vendors of reclaimed fly ash aggregate because they already possess it and do not need to purchase it from another source. This would not be the case with lime. The effectiveness of fly ash as an activator for reclaimed fly ash aggregate is definite, but it is not nearly as pronounced as the effect of lime activator. The addition of fly ash activator definitely results in a strength and durability increase, but as Barnes (11) has indicated, magnitude of this strength gain is questionable and the fast setting tendency of fly ash may raise concerns for road base construction. The additive level of 10% fly ash by dry weight of aggregate was selected as optimum. This level reduces keeps the workability concerns to a minimum, and 15% and 20% fly ash addition rates did not provide significantly different strength or durability than 10% fly ash in any of the materials tested for this project.

Bergeson, K. L., Waddingham, J. W., Brocka, S. G., and Lapke, R. K. (1995). "Bentonite treatment for economical dust reduction on limestone surface secondary roads." Iowa DOT Project HR-351, Engineering Research Institute, Iowa State University, Ames, Iowa.

This research project was directed at laboratory and field evaluation of sodium montmorillonite clay (Bentonite) as a dust palliative for limestone surfaced secondary roads. It was postulated that the electrically charged surfaces (negative) of the clay particles could interact with the charged surfaces (positive) of the limestone and act as a bonding agent to agglomerate fine (- #200) particulates, and also to bond the fine particulates to larger (+ #200) limestone panicles. One mile test roads were constructed in Tama, Appanoose, and Hancock counties in Iowa using Bentonite treatment levels (by weight of aggregate) ranging from 3.0 to 12.0 percent. Construction was accomplished by adding dry Bentonite to the surfacing material and then dry road mixing. The soda ash water solution (dispersing agent) was spray applied and the treated surfacing material wet mixed by motor graders to a consistency of 2 to 3 inch slump concrete. Two motor graders working in tandem provided rapid mixing. Following wet mixing the material was surface spread and compacted by local traffic. Quantitative and qualitative periodic evaluations and testing of the test roads was conducted with respect to dust generation, crust development, roughness, and braking characteristics. As the Bentonite treatment level increased dust generation decreased. From a cost benefit standpoint, an optimum level of treatment is about 8 percent (by weight of aggregate). For roads with light traffic, one application at this treatment level resulted in a 60-70 percent average dust reduction in the first season, 40-50 percent in the second season, and 20-30 percent in the third season. Crust development was rated at two times better than untreated control sections. No discernible trend was evident with respect to roughness. There was no evident difference in any of the test sections with respect to braking distance and braking handling characteristics, under wet surface conditions compared to the control sections. Chloride treatments are more effective in dust reduction in the short term (3-4 months). Bentonite treatment is capable dust reduction over the lone: term (2-3 seasons). Normal maintenance blading operations can be used on Bentonite treated areas. Soda ash dispersed Bentonite treatment is conservatively estimated to be more than twice as cost effective per percent dust reduction than conventional chloride treatments, with respect to time. However, the disadvantage is that there is not the initial dramatic reduction in dust generation as with the chloride treatment. Although dust is reduced significantly after treatment there is still dust being generated. Video evidence indicates that the dust cloud in the Bentonite treated sections does not rise as high, or spread as wide as the cloud in the untreated section. It also settles faster than the cloud in the untreated section. This is considered important for driving safety of following traffic, and for nuisance dust invasion of residences and residential areas. The Bentonite appears to be functioning as a bonding agent to bind small limestone particulates to larger particles and is acting to agglomerate fine particles of limestone as evidenced by laboratory sieve analysis data, and by SEM micrographs. This bonding capability appears recoverable from environmental effects of winter, and from alternating wet and dry periods. The Bentonite is able to interact with new applications of limestone maintenance material and maintains a dust reduction capability.

Bhatty, J. I., Bhattacharja, S., and Todres, H. A. (1996). "Use of cement kiln dust in stabilizing clay soils." Portland Cement Association, Skokie, Illinois.

This report is part of an overall Portland Cement Association (PCA) project on the role of cement kiln dust (CKD), portland cement, and lime in the stabilization of clay soils. In this report, the term "clay soils" means soils having a variable clay content which normally manifests itself by causing the soil to have undesirable properties from an engineering point of view. The effect of the clay can thus be considered to be due to a combination of the clay's activity (plasticity, volume change, etc.) and its proportion of the whole. In a few special cases, non-clay soils have been stabilized using CKDs; clearly the mechanism of the stabilization is different for these soils. These cases are referenced in this report for completeness, and are differentiated from clay soils. Because of the (sometimes) high lime content and the fineness of CKD particles, the use of dust in stabilizing highly expansive clay soils for subbase and related applications is getting increased attention. Literature suggests that CKD enhances many of the engineering properties of the sub grade soils, and reduces the swelling potential of expansive clays. However, available information on the use of CKD for such applications is preliminary, isolated, and lacks quantitative data, as most of the work has been done only on selected soils and selected CKDs. It has been suggested that in order to have an insight on the stabilization potential of CKD and a complete understanding of the underlying mechanism, comprehensive and systematic studies on CKD-soil stabilization are needed. This would require a selection of CKDs from different plant operations, and a selection of sub grade soils and expansive clays. The effect of CKD on the engineering properties needs to be optimized and compared with traditionally used stabilizing agents such as hydrated lime, fly ash, and portland cement.

Bin-Shafique, S., Rahman, K., Yaykiran, M., and Azfar, I. (2010). "The long-term performance of two fly ash stabilized fine-grained soil subbases." Resources, Conservation and Recycling, 54, 666-672.

An experimental study was conducted to investigate the long-term performance of fly ash stabilized two fine-grained soil subbases. One low plasticity clay soil and one high plasticity expansive clay soil were stabilized with a Class C fly ash with fly ash contents of 0%, 5%, 10%, and 20%, and compacted statically at the maximum dry density (standard Proctor) and at the optimum moisture content of the corresponding soil to prepare ten sets of replicates from each of the combinations. After curing all specimens for 7 days, the first set was subjected to plasticity index tests, unconfined compression tests, and vertical swell tests to estimate the improvement due to stabilization. Similar tests were also conducted on another nine sets of replicates in which six sets were subjected to 12 wet–dry cycles (three sets with tap water and the other three sets with saline water), and the other three sets were subjected to 12 freeze–thaw cycles in a laboratory controlled environment to simulate the weathering action. The effect of wet–dry cycles on stabilized soils was essentially insignificant; however, the fly ash stabilized soils lost up to 40% of the strength due to freeze–thaw cycles. Even after losing the strength significantly, the strength of stabilized soils was at least three times higher than that of the unstabilized soils. The swell potential of stabilized expansive soils also increased due to freeze–thaw cycles. The vertical swell increases rapidly for first four to five cycles and then increases very slowly.

Bolander, P. (1999). "Laboratory Testing of Nontraditional Additives for Stabilization of Roads and Trail Surfaces." Transportation Research Record: Journal of the Transportation Research Board, 1652, 24-31.

Recently the Pacific Northwest Region of the U.S. Department of Agriculture Forest Service conducted laboratory tests evaluating the expected field performance of various additives on dense-graded aggregate. Additives used in the laboratory analysis included chlorides, clay, enzymes, lignin sulfonate, synthetic polymer emulsions, and tall oil emulsions. Laboratory analysis included indirect tensile strength and durability testing on AASHTO T 99 fabricated samples. Durability was evaluated after a number of wet-dry and freeze-thaw cycles. Other variables in the study included the amount of additive and the cure (temperature and time) before testing. Findings and observations include the following: (a) Untreated dense-graded aggregate provides little tensile strength in warm dry climates. (b) Chlorides, clay additives, enzymes, and sulfonate provide some tensile strength in warm dry climates. With increasing moisture contents they lose their tensile strength. (c) Once cured, synthetic polymer and tall oil emulsions provide significant tensile strength in warm dry climates. In wet climates these additives would tend to break down with increased exposure to moisture or freezing. (d) Increasing the percent residual (solids) of the synthetic polymer emulsions and tall oil emulsions increases the tensile strength and durability of the treated material. (e) Cure temperature has a dramatic impact on tall oil emulsions' tensile strength and durability resistance. (f) The use of nontraditional additives can be cost-effective depending on the projects' objective, the type of in-place material, and the cost of the additive.

Bryan, A. J. (1988). "Criteria for the suitability of soil for cement stabilization." Building and Environment, 23(4), 309-319.

A major problem prior to the decision to use soil/cement as the walling material on a construction project is to identify a sufficient supply of soil suitable for economic stabilization. There is now reasonable guidance on both the important soil characteristics and possible limits for satisfactory cement stabilization. This paper summarized these characteristics and compares limits that have been suggested from previous studies. Results from a laboratory programme on 15 soils from the South West of England are presented to identify textural and plasticity characteristics which may offer further guidance for the identification of soils with the potential for stabilization with cement.

Collins, R. W. (2011). "Stabilization of marginal soils using geofibers and nontraditional additives." MS Thesis, University of Alaska, Fairbanks, Alaska.

Western Alaska lacks gravel suitable for construction of roads and airports. As a result, gravel is imported, at a cost of between $200 and $600 per cubic yard, to fill transportation construction needs. In an effort to reduce these costs, the Alaska University Transportation Center (AUTC) began searching for methods to use local materials in lieu of imported gravel. The approach discussed in this thesis uses geofibers and chemical additives to achieve soil stabilization. Geofibers and chemical additives are commercially available products. The goal of the research presented in this thesis is to test the impact of addition of two geofiber types, six chemical additives, and combinations of geofibers with chemical additives on a wide variety of soil types. California Bearing Ratio (CBR) testing was used to measure the effectiveness of the treatments. Soils ranging from poorly graded sand (SP) to low plasticity silt (ML) were all effectively stabilized using geofibers, chemical additives, or a combination of the two. Through the research conducted a new method of soil stabilization was developed which makes use of curing accelerators in combination with chemical additives. This method produced CBR values above 300 for poorly graded sand after a seven day cure.

Dempsey, B. J., and Thompson, M. R. (1972). "Effects of freeze-thaw parameters on the durability of stabilized materials." Highway Research Record, 379, 10-18.

A study was conducted to evaluate the effects of various frost-action parameters on the freeze-thaw durability of stabilized materials and to determine which parameters could be modified so that a characteristic freeze-thaw cycle could be adapted to laboratory use. The parameters studied were cooling rate, freezing temperature, length of freezing period, and thawing temperature. The cooling rate was found to be an important factor affecting the freeze-thaw durability of stabilized soils. Lower cooling rates (0. 2 to 2. 0 F/hr) that correlated best with quantitative field data were generally the most detrimental to durability. A sustained freezing study revealed that the length of the freezing period did not have to be greater than that required to accomplish complete freezing of the test specimen. The study further indicated that freezing and thawing temperatures should be representative of those for in-service pavement systems. Thawing temperatures for some stabilized materials are important because strength increase caused by a pozzolanic reaction is possible at high temperatures. The number of cycles used in a laboratory freeze-thaw test should be related to geographical location, climatic conditions, and position of the stabilized layer in the pavement system. For Illinois climatic conditions, a laboratory freeze-thaw cycle representative of field conditions would require a completion period of 48 hours.

Ghazavi, M., and Roustaie, M. (2010). "The influence of freeze–thaw cycles on the unconfined compressive strength of fiber-reinforced clay." Cold Regions Science and Technology, 61, 125-131.

Freeze–thaw cycling is a weathering process that frequently occurs in cold climates. In the freeze state, thermodynamic conditions at temperatures just below 0 °C result in the translocation of water and ice. Consequently, the engineering properties of soils such as permeability, water content, stress–strain behavior, failure strength, elastic modulus, cohesion, and friction angle may be changed. Former studies have been focused on changes in physical and mechanical properties of soil due to freeze–thaw cycles. In this paper, the effect of freeze–thaw cycles on the compressive strength of fiber-reinforced clay is investigated. For this purpose, kaolinite clay reinforced by steel and polypropylene fibers is compacted in a laboratory and exposed to a maximum of 10 closed-system freezing and thawing cycles. The unconfined compressive strength of reinforced and unreinforced specimens is then determined. The results of the study show that for the soil investigated, the increase in the number of freeze–thaw cycles results in the decrease of unconfined compressive strength of clay samples by 20–25%. Moreover, inclusion of fiber in clay samples increases the unconfined compressive strength of soil and decreases the frost heave. Furthermore, the results of the study indicate that fiber addition does not decrease the soil strength against freeze–thaw cycles. Moreover, the study shows that the addition of 3% polypropylene fibers results in the increase of unconfined compressive strength of the soil before and after applying freeze–thaw cycles by 60% to 160% and decrease of frost heave by 70%.

Glogowski, P. E., Kelly, J. M., McLaren, R. J., and Burns, D. L. (1992). "Fly Ash Design Manual for Road and Site Applications - Volume 1: Dry or Conditioned Placement." TR-100472, GAI Consultants, Inc., Palo Alto, California.

This design manual describes the use of fly ash as a construction material for use as structural and nonstructural fills, backfills, embankments, base courses, and roller compacted concrete dams and pavements, soil stabilization, land reclamation and other high volume uses. The manual details the physical, engineering and chemical properties of bituminous, subbituminous and lignite fly ash. Included are field and laboratory testing methods, design data, procedures and examples, specifications, quality control, and pre- and post-construction monitoring. Volume 1 describes uses where fly ash is used dry or conditioned with small amounts of moisture. Volume 2 describes uses where fly ash is placed as a slurry with relatively large amounts of water. The manual is primarily the result of editing and updating previous publications. High volume ash utilization has been documented in various manuals. These publications have been produced by several agencies including EPRI, Federal Highway Administration (FHWA), American Coal Ash Association (ACAA) and others. However, many of these publications were produced several years ago and are not readily available. Also, the information was published by several sources at various times. Therefore, these earlier publications are summarized and updated in this manual with state-of-practice design methods for use by design engineers. References to additional sources of information are provided.

Gullu, H., and Hazirbaba, K. (2010). "Unconfined compressive strength and post-freeze–thaw behavior of fine-grained soils treated with geofiber and synthetic fluid." Cold Regions Science and Technology, 62, 142-150.

This study focuses on a relatively new non-traditional stabilizer (synthetic fluid) used in conjunction with geofiber to improve the strength characteristics of a low-plasticity fine-grained soil. The investigation is based on unconfined compressive strength (UCS) tests. An efficient geofiber dosage was determined for the soil; treating it with geofiber only for the dosage rates varying from 0.2% to 1% by weight of dry soil. The individual contribution of the geofiber and synthetic fluid to the UCS gain was studied through testing each additive independently with the soil. Additionally, UCS tests were conducted on soil samples treated with geofiber and synthetic fluid together. All experiments were conducted for both unsoaked and soaked sample conditions. Strength developments were also investigated under freezing and thawing conditions. The treatment results are discussed in detail in terms of UCS and stress–strain response of the UCS test. The results demonstrate that the use of geofiber with synthetic fluid provided the highest UCS improvement (170% relative gain) in unsoaked samples when compared with the other treatment configurations. On the other hand, the synthetic fluid, when used alone, caused a relative decrease of 21% in the UCS of untreated soil in soaked conditions. The use of geofiber with synthetic fluid performed better in terms of the UCS under freezing and thawing conditions, while the synthetic fluid alone under the same conditions performed inadequately. The stress–strain responses of the soil treated with geofiber and synthetic fluid in terms of post-peak strength, strain hardening, and ductility were better than that of treated with synthetic fluid alone. Finally, the resilient modulus for the various treatment configurations was estimated from the UCS results. The findings indicate that the investigated soil stabilization technology appears to be promising for sites that can be represented by unsoaked conditions (i.e., where adequate drainage and unsaturated conditions can be ensured).

Hazirbaba, K., and Gullu, H. (2010). "California Bearing Ratio improvement and freeze–thaw performance of fine-grained soils treated with geofiber and synthetic fluid." Cold Regions Science and Technology, 63, 50-60.

This paper presents experimental results on the improvement of the California Bearing Ratio (CBR) performance of fine-grained soils by the addition of geofiber and synthetic fluid. CBR tests were conducted for freezing and thawing conditions in addition to non-freezing conditions. The improvement of soil was tested with the inclusion of: i) geofiber only, ii) synthetic fluid only, and iii) synthetic fluid and geofiber together. To represent unsaturated and saturated soil conditions for various field applications, both unsoaked and soaked samples were investigated. The results for unsoaked conditions indicated significant improvement in the CBR performance, particularly in samples treated with geofiber and synthetic together. For soaked conditions, the best performance was obtained from the samples treated with geofiber only. The CBR performance of samples subjected to a freeze–thaw cycle was also tested. Freezing and thawing tests on unsoaked samples showed that the addition of geofiber together with synthetic fluid was generally successful in providing resistance against freeze–thaw weakening, and that the addition of synthetic fluid alone was not very effective against the detrimental impact of freeze–thaw. The results from soaked samples subjected to a freeze–thaw cycle showed poor CBR performance for treatments involving synthetic fluid while samples improved with geofibers alone generally produced better performance.

Helstrom, C. L., Humphrey, D. N., and Labbe, J. M. (2007). "Performance and Effectiveness of a Thin Pavement Section Using Geogrids and Drainage Geocomposites in a Cold Region." NETCR60, Department of Civil and Environmental Engineering, University of Maine, Orono, Maine.

Test sections were constructed in two portions of Maine Route 9 to investigate the use of geosynthetics for reinforcement and drainage for subbase courses that were 300 mm (12 in.) and 600 mm (24 in.) thick with 150 mm (6-in.) of flexible pavement. Four types of test sections were constructed: geogrid reinforcement, drainage geocomposite, drainage geocomposite with geogrid reinforcement, and control. Test sections using reinforcement geogrid have strain gages attached to the geogrid to measure induced forces. Some of the reinforcement sections have geogrid on subgrade whereas some have geogrid in the center of the subbase to evaluate the effects of geogrid location. Drainage geocomposite and control sections have vibrating wire piezometers to monitor porewater pressure in the subgrade and subbase course. Thermocouples were used to measure the depth of frost penetration. The results of falling weight deflectometer tests were used to backcalculate the effective structural number for each section. Reinforcement geogrid and drainage geocomposite increased the effective structural number by between 5% and 17% for sections with 300 mm (12 in.) subbase. However, they had no apparent effect for sections with 600 mm (24 in.) of subbase. The increase in backcalculated effective structural number that was produced by geogrid and/or drainage geocomposite in the 300-mm (12-in.) subbase sections could also be obtained by adding between 25 and 75 mm (1 and 3 in.) of subbase aggregate to an unreinforced section.

Henry, K. S. (1990). "Laboratory investigation of the use of geotextiles to mitigate frost heave." CREEL Report 90-6, Cold Regions Research and Engineering Laboratory (CRREL), U.S. Army Corps of Engineers, Hanover, New Hampshire.

Frost action beneath pavements can lead to several problems, including thaw weakening, which leads to cracking and subsequent pumping of fine soil particles onto the surface, as well as hazardous conditions caused by differential heaving. This study utilized data and frost-susceptible soil collected at Ravalli County Airport, Hamilton, Montana, to study the use of geotextiles to mitigate frost heave. The ability of geotextiles to reduce frost heave in subgrade material by creating a capillary break was assessed by inserting disks of fabric in soil samples and subjecting them to laboratory frost heave tests. Frost heave tests were also conducted to classify the frost susceptibilities of soils at the airport. Soil moisture characteristics and unsaturated hydraulic conductivities were determined for soils tested as well as for one of the geotextiles used. Results of the laboratory investigation indicate that certain geotextiles show promise for use as capillary breaks. In laboratory tests, the presence of geotextiles led to the reduction of frost heave by amounts up to about 60%. It is speculated that the capillary break action provided by the geotextile is attributable to the pore size and structure of the material and the surface properties of the fibers.

Henry, K. S. (1996). "Geotextiles to mitigate frost effects in soils: A critical review." Transportation Research Record: Journal of the Transportation Research Board, 1534, 5-11.

The use of geotextiles to mitigate frost effects in soils has been studied, but few techniques have been developed. Guidelines developed for the placement of granular capillary barriers are presented to serve as preliminary guidelines for geotextile capillary barriers. Laboratory research shows that pore size distribution, wettability, and, for some geotextiles,

thickness influence capillary barrier performance in a given soil. Geotextiles that easily wet do not reduce frost heave and may even exacerbate it. On the basis of the literature reviewed, guidance for selection of geotextile capillary barriers in field trials is given. If geotextiles function as capillary barriers during freezing and reinforce or separate and filter the subgrade at the base course interface during thaw, then the potential exists for their use in a combination of functions to reduce frost-related damage in geotechnical structures. It was found that properly designed geotextiles have the potential to reduce frost heave by functioning as capillary barriers, they can be filters for capillary barriers, and they can provide reinforcement or separation or filtration (or all of these) of the subgrade soil to reduce thaw-related damage.

Henry, K. S., Olson, J. P., Farrington, S. P., and Lens, J. (2005). "Improved performance of unpaved roads during spring thaw." ERDC/CRREL TR-05-01, Engineer Research and Development Center Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Unpaved roads in Vermont are subject to deterioration from seasonal freezing and thawing, and many towns have roads that suffer chronic serviceability problems during the so-called “spring thaw,” or mud season. Several techniques thought to mitigate deterioration of unpaved roads during spring thaw were constructed on test sections of unpaved roads in two towns. Each potential remedy was aimed at providing some combination of limiting the availability of moisture in the winter, improving drainage during spring, and strengthening the upper portion of the road. Each technique used local and/or commercially available materials, and all were easy to construct, i.e., a town road crew could build them. For two spring thaw seasons, we compared strength estimates based on dynamic cone penetrometer tests and the percentage of the road surface rutted for treated and control sections. Methods that permanently improved the strength of the top 12 inches of the road or decreased the water content of the upper 12 inches of the road resulted in significant performance improvement during spring thaw. Cement and cellular confinement systems worked well by improving the strength of the upper layers of the soil. Two new techniques— geowrap, comprising clean sand sandwiched by geotextile separators placed 12–18 inches deep, and the patented Geosynthetic Capillary Barrier Drain—provided benefit by keeping the upper layers of the soil relatively dry. Geogrid and geotextile separators placed 12 inch deep and trench drains parallel to the road provided no observable benefit.

Hicks, R. G. (2002). "Alaska soil stabilization design guide." FHWA-AK-RD-01-6B, State of Alaska Department of Transportation and Public Facilities, Fairbanks, Alaska.

This guide presents information on the types of soil stabilization techniques that have or can be used in the state of Alaska. It covers techniques including asphalt, cement, lime, mechanical, chemical, and other methods. For each method there is a discussion on materials and design considerations, construction issues, and expected performance and costs. The appendices include a glossary of terms, a reading list on prior stabilization used in Alaska, a discussion on the soils in Alaska, and a slide presentation summarizing the highlights of the guide.

Hoover, J. M. (1973). "Surface improvements and dust palliation of unpaved secondary roads and streets." Iowa Highway Research Board Project HR-151, Engineering Research Institute, Iowa State University, Ames, Iowa.

The report contains five parts:

(I) Project Summary by Hoover, J. M. - As of December 31, 1970 there were 57,270 miles of Local Secondary roads and 32,958 miles of Farm to Market roads in the Iowa secondary road system. The Local Secondary system carried a traffic load of 2,714,180 daily vehicle miles, accounting for 32% of all traffic in secondary system. For all Local Secondary roads having some form of surfacing, 98% were surfaced with gravel or crushed stone. During the 1970 construction year, 335 miles of surfaced roads were constructed in the Local Secondary system with 78% being surfaced with gravel or crushed stone. The total maintenance expenditure for all secondary roads in Iowa during 1970 amounted to $40,086,091. Of this, 42%, or $17,020,332, was spent for aggregate replacement on existing gravel or crushed stone roads with an additional 31% ($12,604,456) being spent on maintenance other than resurfacing. This amounts to 73% of the total maintenance budget and are the largest two maintenance expenditure items out of a list of 10 ranging from bridges to drainage assessments. The next largest item was 7%, for maintenance of existing flexible bases. Present costs of high-type flexible or rigid pavements range from $40,000 per mile up. Because of high cost, budget limitations, and low mileage of high traffic volume on Local Secondary roads, most Iowa counties are severely restricted as to the number of miles of roads that may be paved each year. Present design and construction standards provide adequate means for improvement of grade and cross section of secondary roads followed by: (a) immediate road metal surfacing, or (b) eventual high-type surfacing. There are, at present, no formal provisions for an intermediate type surfacing between these two extremes. Therefore, nearly all Iowa counties are in a situation in which they have only a few miles of high-type pavements with the bulk being surfaced with gravel or crushed stone. From the maintenance expenditures for 1970, it can be seen that the primary method of maintaining aggregate surfaced secondary roads remains, as it has in the past, as aggregate replacement. Roads continue to rut, washboard, ravel, pothole, and become the source for billowing clouds of dust. Loose aggregate makes driving hazardous, and results in cases of vehicle damage including cracked windshields, chipped paint, and dents, as well as increased fatalities. During the spring thaw and subsequent rains, many roads become extremely soft, slippery, and heavily rutted. As aggregate supplies decrease, inferior quality soft limestones and gravels are being used, resulting in faster degradation contributing to the dusting problem. Dust creates a safety hazard to both passing and oncoming traffic. It is also a definite household nuisance in rural areas, especially in heavily populated regions surrounding larger towns and cities where traffic on unpaved roads may range as high as 500 vehicles per day. The severity of these problems continues to increase as: (a) traffic volume increases, (b) more people move to rural areas surrounding larger towns and cities, and (c) the current concern over air pollution increases. The Iowa Air Pollution Control Commission has drafted guidelines with respect to "fugitive" dust, which ultimately will affect all unpaved state, county, and city roads and streets. Besides the above problems, most counties are faced with (a) rising costs of high-type pavement, (b) rising costs of maintenance, and (c) rising costs of replacement aggregates. The foregoing considerations dictated the need for finding a means to provide for low-cost surface improvement and dust control, using existing in-place materials, for immediate (and intermediate) use as a treated surface course on unpaved secondary roads - the objective of this research project. Three concurrent phases of study were included in the project: (1) laboratory screenings studies of various additives thought to have potential for long-lasting dust palliation, soil additive strength, durability, and additive retention potential; (2) test road construction using those additives that indicated promise for performance-serviceability usage; and (3) observations and tests of constructed sections for evaluation of the additive's contribution to performance and serviceability as well as the relationship to initial costs.

(II) Asphaltic products and elastometers as dust palliatives and surface improvement agents for unpaved secondary roads, by Bergeson, K. H. and Hoover, J. M.: Bituminous materials have long been used, with varying degrees of success, as soil stabilizers and waterproofing agents. With advancing technological developments many new asphaltic products, whose properties have been altered and supposedly enhanced by the addition of chemicals and selected emulsifying agents, are being marketed. Elastomers, which contain rubber in a modified form, have also been introduced. The beneficial effects of these products, as soil stabilizers and dust palliatives, can only be determined by laboratory evaluation and field trials. This investigation was conducted essentially as a three phase project consisting of (a) laboratory screenings of various asphaltic products and elastomers to evaluate their effectiveness as soil stabilizers and dust palliatives, (b) construction of a test road, based on the results of the laboratory screening phase, using those additives that appeared to be the most effective and economical, and (c) observation and tests of the various sections of the test road for evaluation of the additives' performance and serviceability with respect to dust palliation and surface improvement. The primary purpose of this study is to present the results of each of the above phases. The test road was constructed in September 1971 and had been in service only one year and three months at the time of termination of research. Therefore, phase 3 analyses are somewhat limited due to the period of time covered.

(III) Ammonium lignosulfonates as dust palliatives and surface improvement agents for unpaved secondary roads, by Fox, D. E., and Hoover, J. M.: At the time the research project was initiated in mid-1970, county engineer offices in Iowa were requested to propose locations for test roads within their respective counties. It was explained that all men, material, and equipment would be furnished by the individual counties. Laboratory screenings of additives and field testing of experimental roads would be carried out by the researchers, who would also be present to observe construction and provide technical assistance when and where needed. Four counties responded with interest in lignosulfonate stabilization. Lignosulfonates are available in almost unlimited quantities from paper mills. Ten years ago, lignosulfonates cost 6 cents per gallon at the mill and the price has not increased, although production has. Due to different pulping processes, the cation associated with lignosulfonate varies. Sodium, calcium, and ammonium lignosulfonates have all been used in soil stabilization and prices are similar. The study reported here utilized commercially-available lignosulfonate with ammonium as the associated cation. The following paragraphs explain the participation offered for lignosulfonate research by the corresponding county. The county engineer's office of Clinton County, Iowa made available a section of road 2620 ft long to which crushed limestone had been added at a rate of 2000 tons per mile. This length was naturally divided into three approximately equal sections, a flat upland location, a curve on a hill of about 6% grade, and a level bottomland section on a backwater area of the Mississippi River. The road was located between, and connected with, paved roads terminating at the Clinton and Camanche city limits. Two nearby industries contributed to a 1967 ADT (average daily traffic) of 500 vehicles per day, and maintenance was a problem. The researchers were invited to perform field tests on several roads within Floyd County, both prior to and following treatment with lignosulfonate. Construction was done by county personnel under the supervision of the lignosulfonate supplier. A dirt road near Marion, Linn County, was made available by the county engineer for research. Of 6000 ft length, the 1968 traffic survey showed an ADT of 44 vehicles. Prior to treatment, the grade was built up and improved by the ditch clean-out method typical of much secondary road construction. Using lignosulfonate from a local source, stabilization of nearly 150 miles of roads was begun in Lee County in the late 1950s and early 1960s. Treatment consisted of only light surface blading and occasional application of aggregate coupled with a lignosulfonate surface spray application. Over the years, an in-depth treatment was produced. Extensive cost and maintenance records on treated roads were kept and made available to the researchers.

(IV) Soil-chemical additives as surface improvement agents for unpaved roads, by Denny, C. K., and Hoover, J. M.: The use of polyester and plastic resins as soil stabilizers is relatively new and untried. The objective of this research was to investigate the capabilities of these resins and several other chemicals and commercial dust palliatives as potential low-cost dust palliatives and surface improvement agents. The investigation was conducted entirely in the laboratory but care was taken to approximate field conditions as accurately as possible. Various soil-chemical additives were evaluated on the basis of the following tests: (1) unconfined compressive strength, (2) durability and erosibility, (3) trafficability, (4) resistance to freezing and thawing, and (5) moisture retention and density. Some of the tests were standard while others were specifically modified, but in every case the treated specimens were compared with untreated control specimens.

(V) Appendix: Mineralogical analyses of dust samples, by Handy, R. L.: This part contains results of differential thermal-thermogravimetric analysis and petrographic analysis. Thermogravimetric analysis offers a rapid, accurate method for the measurement of carbonates and organic matter in 50 mg dust samples, and gives a reliable semi-quantitative indication of the amount of clay minerals. Analysis by petrographic microscope is less accurate but requires less sample, and therefore is a valuable supplemental technique for very small samples. Dust analyses show conclusively that selective sorting is operative, calcium carbonate dominating in dust samples collected near the road, and gradually decreasing to near zero several hundred feet away from the road. Simultaneously, the contents of clay and organic matter increase with distance from the road. The efficiency of the sorting indicates that it is size-selective rather than specific gravity-selective (i.e., carbonate contents are higher close to the road because the grains are larger and settle faster). Lignin treatment will drastically reduce the carbonate percentage in road dust, by more than a factor of 10, provided the added rock amount does not exceed 1000 T/mile. The total amount of dust is less drastically reduced, and the amount roughly coincides with the amounts of noncarbonate components in dusts from untreated roads. This suggests that lignin and clay build up a protective patina at the road surface, by migration upward due to evaporation. This patina protects the limestone and is worn off by traffic; however, it should renew so long as sufficient lignin remains in the road. (Alternatively, it probably can be renewed by surface treatments.) The existence of such a coating, while greatly reducing the limestone aggregate loss from the dry road, also may contribute some slipperiness on a wet road, and probably acts to reduce bonding between the road metal and a bituminous overlay. Rock added in excess of about 1000 T/mile is not effectively protected by a 1% lignin treatment, or lignin plus lime. In addition, at the higher rock application levels, added Ca(OH)* lime tends to further reduce the protective effect on carbonates, probably by flocculating the clay and reducing migration and development of a film.

Hoover, J. M. (Undated). "Factors influencing stability of granular base course mixes." Iowa Highway Research Board Project HR-99, Engineering Research Institute, Iowa State University, Ames, Iowa.

To evaluate the various factors influencing the stability of granular base course mixes, three primary goals were included in the project: (1) determination of a suitable and realistic laboratory method of compaction; (2) effect of gradation, density and mineralogy of the fines on shearing strength; and (3) possible improvement of the shear strength with organic and inorganic chemical stabilization additives.

Hoover, J. M., Moeller, D. T., Pitt, J. M., Smith, S. G., and Wainaina, N. W. (1982). "Performance of randomly oriented, fiber-reinforced roadway soils: A laboratory and field investigation." Iowa Highway Research Board Project HR-211, Engineering Research Institute, Iowa State University, Ames, Iowa.

The purpose of the study was to conduct a laboratory and field investigation into the potential of improving (a) soil-aggregate surfaced and subgrade materials, including those that are frost-prone and/or highly moisture susceptible, and (b) localized base course materials, by uniting such materials through fibrous reinforcement. The envisioned objective of the project was the development of a simple construction technique(s) that could be (a) applied on a selective basis to specific areas having a history of poor performance, or (b) used for improvement of potential base materials prior to surfacing. Little background information on such purpose and objective was available. Though the envisioned process had similarities to fibrous reinforced concrete, and to fibrous reinforced resin composites, the process was devoid of a cementitious binder matrix and thus highly dependent on the cohesive and frictional interlocking processes of a soil and/or aggregate with the fibrous reinforcement; a condition not unlike the introduction of reinforcing bars into a concrete sand/aggregate mixture without benefit of portland cement. Thus the study was also directed to answering some fundamental questions: (1) would the technique work; (2) what type or types of fibers are effective; (3) are workable fibers commercially available; and (4) can such fibers be effectively incorporated with conventional construction equipment, and employed in practical field applications? The approach to obtaining answers to these questions, was guided by the philosophy that an understanding of basic fundamentals was essential to developing a body of engineering knowledge that would serve as the basis for eventual development of design procedures with fibrous products for the applications previously noted.

Hoover, J. M., Pitt, J. M., Handfelt, L. D., and Stanley, R. L. (1981a). "Performance of soil-aggregate-fabric systems in frost-susceptible roads, Linn County, Iowa." Transportation Research Record: Journal of the Transportation Research Board, 827, 6-14.

Geotechnical construction fabric applied in soil-aggregate and granular-surfaced low-volume roadways indicate that fabric systems can, under certain circumstances, reduce thaw-induced deformations and improve field performance. Eleven test sections that involved different soil-aggregate-fabric systems were constructed on subgrades that displayed varying degrees of frost-related performance. Field evaluations were conducted over three cycles of spring thaw plus summer healing. Laboratory simulation of freeze-thaw action along with strength and deformation parameters obtained through the Iowa K-test were used on a fabric-reinforced, frost-susceptible soil to provide insight into soil fabric mechanisms and the potential for predicting field performance. Variation in the constructed soil-aggregate-fabric systems was achieved by

locating fabric at different positions relative to layers of soil-aggregate or existing roadway materials, a choked macadam base course, and a thick granular backfill. Improvement was most noticeable where fabric was used as a reinforcement between a soil-aggregate surface and a frost-prone subgrade. Fabric used in conjunction with granular backfill, macadam base, and non-frost-susceptible subgrade did not appear justifiable.

Hoover, J. M., Pitt, J. M., Lusting, M. T., and Fox, D. E. (1981b). "Mission-oriented dust control and surface improvement processes for unpaved roads." Iowa DOT Project HR-194, Engineering Research Institute, Iowa State University, Ames, Iowa.

The study documented herein was implemented as a mission-oriented project designed to quantify and evaluate dust control and surface improvement processes for unpaved roads. In order to accomplish this mission, three levels of processing and treatment were established for comparison with untreated soil aggregate-surfaced roads utilizing only the existing in-place roadway materials: Category 1, surface applied dust palliation; Category 2, mixed-in-place dust palliation and surface improvement, without additional surfacing; and Category 3, mixed-in-place base stabilization with seal coat surfacing. Demonstration sections were developed in several representative geographic/geologic regions of the state including Plymouth, Pottawattamie, Story, Franklin, and Marion counties. Samples from these, as well as other possible sites, were subjected to laboratory tests including unconfined compression, freeze-thaw durability, Iowa K-Test, and trafficability testing, in both the untreated and treated conditions, as well as under varying forms of curing. The purpose of the laboratory testing was for evaluation of the subject material for potential use in one or more of the three categories of dust control and/or surface improvement processing. Field studies were initiated in each potential demonstration site for measurement of dust fall within, as well as to the exterior of the ROW. Such measurements were continued following Category 1 applications of selected palliation treatments. In-situ pre- and post-construction tests were conducted within each Category 3 demonstration section, including periodic plate-bearing, Benkelman beam, and moisture-density tests. During Category 3 construction, assistance was provided each county in construction coordination and moisture-density control. Specimens were field molded from each Category 3 mix prior to field compaction and returned to the laboratory for periodic testing of moisture-density and K-Test parameters. Dust fall testing included both quantity and particle-size distribution versus distance from roadway centerline. Through regression analyses of dust fall data, predictions were developed for quantity of dust at the ROW, as well as distance from roadway centerline at which ambient levels of dusting might be anticipated. Through such analyses, two potential control criteria for dust fall were developed. Based on comparison of pre- and post-Category 1 treatment applications, dust reduction effectiveness of several palliatives was evaluated. Such evaluations were coupled with estimated costs of each treatment as an approach to respective cost-benefits. Based on comparison of laboratory tests, pre- and post-construction in-situ tests, and visual examinations, each Category 3 stabilized base demonstration section was evaluated for structural integrity. The following generalized conclusions are thus founded on the various tests, investigations, and analyses presented within this report: (1) Unconfined compression tests of 2-in. by 2-in. cylindrical specimens can provide an initial method of trial mix suitability of various products for possible use as dust palliatives and/or surface improvement agents. Such trial mix testing should be followed by more refined testing on selected mixes. (2) Stability of various product and soil mixtures can be evaluated with freeze-thaw durability, trafficability, and the Iowa K-Test. Freeze-thaw elongation provides an indication of climatic stability as well as susceptibility to capillary moisture increases and heave potential. Trafficability tests provide a quantitative measure of waterproofing and resistance to an adverse traffic loading and environmental condition. The Iowa K-Test provides a quick measure of the undrained shear parameters: cohesion and angle of internal friction. In addition, the K-Test provides a qualitative measure of rutting potential of a mixture through the lateral stress ratio K and a measure of stress-strain relations through the vertical deformation modulus Ev. (3) Of the products evaluated through the various laboratory tests, only the combined Portland cement and fly ash appeared effective as a Category 3 stabilization process with most soil-aggregate classifications, though optimum quantities of the two products varied with each material. Variation of CSS asphalt emulsion zeta potential exhibited pronounced effects on mixture compatibility and required asphalt content, regardless of consideration of categorical usage. In a similar manner, the laboratory tests indicated categorical usage of ammonium lignosulfonate, Coherex, Polybind Acrylic DLR 81-03, and Amsco Res AB 1881 varied from negative to potentially effective depending on soil-aggregate type. (4) All demonstration sections, regardless of category level of processing, were constructed with conventional equipment. (5) Utilizing the measurement and analytical techniques described in this study, two recommendations of minimal roadway dust fall criteria were subjectively quantified. First, an ambient level should be achieved within a distance of 100 to 150 ft or less of an unpaved roadway centerline. Second, a quantity of 15 lbs/acre/day/100 vehicles, or less, should be achieved at the ROW. Such criteria should be considered as a reasonable starting point, with possible refinement with time. (6) Effective dust abatement as well as structural improvement may be obtained through Category 3 construction processing of an unpaved road using cement and fly ash or emulsified asphalt. (7) Only limited Category 1 dust palliation and cost effectiveness were obtained with Amsco Res AB 1881, Polybind Acrylic DLR 81-03, and cationic asphalt emulsion. Coherex appeared very effective as a dust palliative so long as it was not used with an absorptive aggregate. However, the cost of Coherex would limit its usage in Iowa. Calcium chloride and ammonium lignosulfonate appeared comparatively cost-effective as dust palliatives. Effectiveness of both the chloride and lignosulfonates might be enhanced if incorporated with a soil-aggregate surface using methods and/or specifications cited in preceding sections of this report.

Jobgen, M. C., Callahan, M., Harris, G., and Tymkowicz, S. (1994). "Low cost techniques of base stabilization." Project HR-312, Iowa Department of Transportation, Ames, Iowa.

The IHRB HR-312 research project (Jobgen et al. 1994) evaluated performance of four different stabilization methods for on unsurfaced roads. These stabilization methods included using: a) high float emulsion (HFE-300) to treat top 3 in. of base stone, b) a bio-chemical formula called as BIO CAT 300-1 to treat the base stone for different thicknesses (6 in., 8in., and 10 in.), c) Consolid System method in the top 10 in. of subgrade soil, wherein when the soil is dry a combination of two inverted emulsions are used and when the soil is wet a combination of an inverted emulsion and a lime hydrated base powder are used to treat the base stone, and d) 5 in. of macadam base and 2 in. of choke stone along with fabric under one of the sections. All test sections were sealed using a double seal coat and performance evaluation was conducted on these sections using Iowa Road Rater, Roughometer, and visual inspection annually from 1989 to 1992. Some key findings from the field testing were as follows: (a) Test sections stabilized with BIO CAT300-1 and Consolid system showed the highest average k-value (207 pci to 225+ pci) four years after construction. HFE-300 stabilized section showed an average k-value of 181 pci, macadam subbase section showed an average k-value of 172 pci, and macadam subbase with fabric section showed an average k-value of 116 pci, four years after construction. (b) Although the BIO CAT 300-1 and Consolid System stabilized sections showed high k-values, they showed poor performance with alligator cracking and rutting under traffic, and continued deterioration every year. It is speculated in the report that these failures could have been due to freeze-thaw cycles in the stabilized layers. (c) HFE-300 treated test sections showed some deterioration with alligator cracking. Macadam subbase test sections (with and without fabric) experienced minor rutting and showed the best overall performance than all other sections. The use of fabric did not show noticeable improvement. (d) Use of macadam base and HFE-300 treatment showed cost effectiveness than other treatment options evaluated in this study.

Johnson, A. (2012). "Freeze-thaw performance of pavement foundation materials." M.S. Thesis, Dept. of Civil Construction and Environmental Engineering, Iowa State University, Ames, Iowa.

Freezing and thawing processes damage pavement foundation systems; increase pavement and vehicle maintenance costs; reduce traveler comfort and safety; decrease fuel economy; and decrease pavement life spans. Current pavement design methods provide limited guidance characterizing frost-susceptible materials. A laboratory frost-heave and thaw-weakening test could be used to differentiate frost-susceptible materials from non-frost susceptible materials to reduce the effects of frost action. The goal of this research was to provide guidance for the selection of pavement foundation materials based on their freeze-thaw durability. The objectives of this study are to determine the effectiveness of ASTM D5918 Standard Test Methods for Frost Heave and Thaw Weakening Susceptibility of Soils by testing various soil types; study the effects of stabilizers on reducing frost-susceptibility; and determine seasonal changes of in situ pavement support conditions. The important outcomes of this research are that it is difficult to predict frost-heave susceptibility from USCS classifications; when stabilizing loess with cement, increased cement content decreased the range of initial moisture contents that will result in maximum compressive strength; compared to unstabilized loess, cement-stabilized loess was found to be non-frost-susceptible, but fly ash-stabilized loess showed only slight improvement; and the coefficients of variation for ASTM D5918 test results were similar to published results. This research shows that using a test such as ASTM D5918 in the design phase to determine the relative frost-susceptibility of pavement foundation materials may ameliorate the effects of frost action.

Kalkan, E. (2009). "Effects of silica fume on the geotechnical properties of fine-grained soils exposed to freeze and thaw." Cold Regions Science and Technology, 58, 130-135.

Both the landfill liner and cover systems are the most important parts on a waste disposal landfill site. These systems are generally constructed using compacted fine-grained soils. It is known that the strength and permeability are particularly affected by freezing and thawing cycles in the cold regions. The aim of this study is to reduce the effects of freezing and thawing cycles on the strength and permeability. To modify the fine-grained soils, silica fume generated during silicon metal production as very fine dust of silica from a blast furnace and historically considered a waste product has been used as a stabilizer. The natural fine-grained soils and soil–silica fume mixtures have been compacted at the optimum moisture content and subjected to the laboratory tests. The test results show that the stabilized fine-grained soil samples containing silica fume exhibit high resistance to the freezing and thawing effects as compared to natural fine-grained soil samples. The silica fume decreases the effects of freezing and thawing cycles on the unconfined compressive strength and permeability. We have concluded that silica fume can be successfully used to reduce the effects of freezing and thawing cycles on the strength and permeability in landfill liner and cover systems constructed from compacted fine-grained soils.

Kestler, M. A. (2003). "Techniques for Extending the Life of Low-Volume Roads in Seasonal Frost Areas." Transportation Research Record: Journal of the Transportation Research Board, 1819, 275-284.

Major highways are designed to withstand heavy vehicles and high traffic volumes year round. However, low-volume roads (LVRs) in seasonal frost areas are extremely susceptible to damage from trafficking by heavy vehicles during spring thaw. As a result, the maintenance-free life of an LVR in a seasonal frost area averages less than half that of a similar road in a nonfrost area. This study serves as a practical primer on addressing thaw weakening of LVRs: it offers guidance for identifying frost-susceptible soils, summarizes methods used and currently undergoing research to determine when conditions are critical, and provides several solutions for avoiding the costly impact of spring thaw on LVRs. Diagnostic tools and recommended road-usage techniques are provided for existing roads; alternative design techniques are presented for new and reconstructed roads. Tools and techniques are applicable across much of Europe, North America, and Asia; some also apply to wet areas outside seasonal frost areas.

Kettle, R. J., and McCabe, E. Y. (1985). "Mechanical Stabilization for the Control of Frost Heave." Canadian Journal of Civil Engineering, 12, 899-905.

This paper is concerned with the role of mechanical stabilization in controlling frost susceptibility. This has been assessed in terms of the heave, developed over a 250 h period, of cylindrical specimens subjected to the Transport and Road Research Laboratory (United Kingdom) frost heave test. The basic soil matrix consisted of a highly susceptible mixture of sand and ground chalk. Three types of coarse particle (slag. basalt, limestone) were used as the stabilizing agent, and these were each subdivided into two particle groups: 20-3.35 mm and 37.5-20 mm. The introduction of up to 50% of the selected coarse aggregates produced various non-frost-susceptible mixtures. The influence of the coarse aggregate was very dependent on aggregate type but less dependent on aggregate size. The data have been examined to assess the role of these coarser particles in the freezing process, including the effects of their individual characteristics. This clearly demonstrated the possibility of using mechanical stabilization to control frost susceptibility and this was supported by the results of additional tests on natural soil. Heaving pressures are also reported and are examined in relation to the amount of aggregate added, nature of the aggregate, and particle size. The addition of coarse aggregate to the matrix is shown to reduce the measured heaving pressures.

Khoury, N., and Zaman, M. M. (2007). "Environmental Effects on Durability of Aggregates Stabilized with Cementitious Materials." Journal of Materials in Civil Engineering, 19(1), 41-48.

The present study focuses on investigating the effect of freeze–thaw (FT) cycles, referred to as environmental effect in this paper, on aggregates stabilized with various stabilizing agents, namely, cement kiln dust (CKD), Class C fly ash (CFA), and fluidized bed ash (FBA). Cylindrical specimens were compacted and cured for 28 days in a moist room with a constant temperature and controlled humidity. After curing, specimens were subjected to 0, 8, 16, and 30 FT cycles, and then tested for resilient modulus (Mr). Results showed that Mr values of stabilized specimens decreased with increasing FT cycles up to 30. The reasons for such changes

are explained by the increase in moisture content during thawing and the formation of ice lenses within the pores during freezing, causing distortion of the matrix of particles. It was also found that the decrease in Mr values varied with the type of stabilizing agents. The CKD-stabilized. Meridian and Richard Spur aggregates exhibited a higher reduction in Mr values than the corresponding values of CFA- and FBA stabilized specimens. The CFA-stabilized Sawyer specimens performed better than their CKD- and FBA-stabilized counterparts.

Less, R. A., and Paulson, C. K. (1977). "Experimental macadam stone base - Des Moines County." Project HR-175, Iowa Department of Transportation, Ames, Iowa.

The IHRB HR-175 research project evaluated the feasibility and economics of using macadam subbase material (with different thicknesses) with choke stone under PCC and asphalt pavements. The macadam subbase material used on this project had a typical gradation with 4 in. maximum particle size and 12 to 26% passing the 1 in. sieve. The choke stone had a typical gradation with 1 in. maximum particle size and 6 to 12% passing the No. 200 sieve. The study indicated that the macadam subbase performed well under both PCC and asphalt pavements, but the cost was relatively more. During construction, the finished macadam subbase showed a uniform structure with negligible amount of degradation during compaction. Production rates on placement of the macadam subbase material varied from about 2900 to 5000 tons per day. Lateral subdrain trenches backfilled with porous backfill was used on this project for drainage. This system performed well and minimized effects of frost boils, spring thaw, and other subsurface drainage issues.

Li, L., Benson, C. H., Edil, T. B., and Hatipoglu, B. (2008). "Sustainable Construction Case History: Fly Ash Stabilization of Recycled Asphalt Pavement Material." Geotechnical and Geological Engineering, 26, 177-187.

A case history is described where Class C fly ash was used to stabilize recycled pavement material (RPM) during construction of a flexible pavement in Waseca, MN, USA. The project consisted of pulverizing the existing hot-mix asphalt (HMA), base, and subgrade to a depth of 300 mm to form RPM, blending the RPM with fly ash (10% by dry weight) and water, compacting the RPM, and placement of a new HMA surface. California bearing ratio (CBR), resilient modulus (Mr), and unconfined compression (qu) tests were conducted on the RPM alone and the fly ash stabilized RPM (SRPM) prepared in the field and laboratory to evaluate how addition of fly ash improved the strength and stiffness. After 7 days of curing, SRPM prepared in the laboratory had CBR ranging between 70 and 94, Mr between 78 and 119 MPa, and qu between 284 and 454 kPa, whereas the RPM alone had CBR between 3 and 17 and Mr between 46 and 50 MPa. Lower CBR, Mr, and qu were obtained for SRPM mixed in the field relative to the SRPM mixed in the laboratory (64% lower for CBR, 25% lower for Mr, and 50% lower for qu). In situ falling weight deflectometer testing conducted 1 year after construction showed no degradation in the modulus of the SRPM, even though the SRPM underwent a freeze–thaw cycle. Analysis of leachate collected in the lysimeter showed that concentrations of all trace elements were below USEPA maximum contaminant levels.

Munro, R., Evans, R., and Saarenketo, T. (2007). "ROADEX II Project: Focusing on Low-Volume Roads in the European Northern Periphery." Transportation Research Record: Journal of the Transportation Research Board, 1989(2), 292-299.

The ROADEX Project is a living case study on the benefits of partnering across road districts to make the best use of available budgets. The ROADEX Project partners had an early shared vision of cooperation that has since materialized in great benefits to their respective areas through collaboration in research and development and enhancement of their in-house capabilities by direct access to experience within the other partners' organizations. This sharing of information and experience has enabled them to have cost-effective research programs on shorter time scales than would otherwise have been the case and has avoided "reinventing the wheel" in research and development in each national district. The ROADEX II Project addresses the specific problems that arise in dealing with low-volume road management across the northern periphery of Europe so that reliable and regular year-round road networks can be provided to remote communities there. The outputs delivered in the ROADEX II Project offer a range of sustainable fit-for-purpose solutions to local road problems that together compose a tool kit of solutions for local managers to enable them to give better public service to their areas year after year.

Parsons, R. L., and Milburn, J. P. (2003). "Engineering Behavior of Stabilized Soils." Transportation Research Record: Journal of the Transportation Research Board, 1837, 20-29.

Stabilization of soils is an effective method for improving soil properties and pavement system performance. For many soils, more than one stabilization agent may be effective, and financial considerations or availability may be the determining factor on which to use. A series of tests was conducted to evaluate the relative performance of lime, cement, Class C fly ash, and an enzymatic stabilizer. These products were combined with a total of seven different soils with Unified Soil Classification System classifications of CH, CL, ML, and SM. Durability testing procedures included freeze–thaw, wet–dry, and leach testing. Atterberg limits and strength tests also were conducted before and after selected durability tests. Changes in pH were monitored during leaching. Relative values of soil stiffness were tracked over a 28-day curing period using the soil stiffness gauge. Lime- and cement-stabilized soils showed the most improvement in soil performance for multiple soils, with fly ash–treated soils showing substantial improvement. The results showed that for many soils, more than one stabilization option may be effective for the construction of durable subgrades. The enzymatic stabilizer did not perform as well as the other stabilization alternatives.

PCA (1995). "Soil-Cement Construction Handbook." Portland Cement Association, Skokie, Illinois.

This guide describes procedures for constructing, under a wide variety of conditions, high quality soil-cement base courses for roads, streets, airports, and parking and storage areas. Includes inspection and field control, recycling flexible pavement, and a discussion of cement-modified soils.

Raymond, G. P., and Bathurst, R. J. (2000). "Facilitating cold climate pavement drainage using geosynthetics." Testing and Performance of Geosynthetics in Subusurface Drainage - ASTM STP 1390, L. D. Suits, J. B. Goddard, and J. S. Baldwin, eds., ASTM, West Conshohocken, PA.

Good highway drainage has been recognized for many centuries. The theoretical concepts are simple and the technology applicable to highways built today (1999) is widely available in the technical literature. It is widely understood that efficient drainage is essential to good highway performance independent of aggregate compacted density or aggregate stability. While the theoretical concepts are simple they are often not effective in cold climates. Indeed, for cold climates, these simple concepts are shown by field excavations described herein to be lacking in a number of aspects. Based on field excavations and performance of some selected Ontario highway locations, involving both clay and sand subgrades, recommendations are presented for the design detailing, selection and installation of geosynthetic edge drains. Installation at the investigated sites was by various techniques that included: ploughed-in-place, trench excavation, and mechanical trencher and boot. All excavated edge drains were installed as retrofits either at the time of the original pavement construction or several years later. The retrofits used the existing excavated/displaced shoulder granular material as backfill. Frost action, despite what was considered good drainage practice at the time of installation, and is shown to have had a major effect on field performance.

Saarenketo, T., and Aho, S. (2005). "Managing Spring Thaw Weakening on Low Volume Roads - Problem Description, Load Restriction Policies, Monitoring and Rehabilitation." The ROADEXII Project, The Swedish Road Administration, Northern Region, Sweden.

This is a final report from the Phase II subproject 2_3 survey of the Roadex II project, a technical transnational cooperation project between the Highland Council, the Western Isles Council, and Forest Enterprise from Scotland; the Northern Region (formerly Troms district) of the Norwegian Public Roads Administration and the Norwegian Road Haulage Association; the Northern Region of the Swedish National Road Administration; and from Finland the Regions of Central Finland and Lapland of the Finnish Road Administration, as well as Metsähallitus Region of Eastern Lapland, the Forestry Centre of Lapland (Lapin Metsäkeskus), Stora Enso Metsä, and Metsäliitto, Procurement Area of Northern Finland. The Roadex project is partly financed by the ERDF IIIB Northern Periphery Programme. The lead partner in the project is the Highland Council from Scotland and project consultant is Roadscanners Oy from Finland. Roadex II project Chairman is Ron Munro from the Highland Council and project manager is Timo Saarenketo from Roadscanners. The report summarizes the work done on Task 2_3 “Spring Thaw Weakening” of the Roadex II project. The report will describe the theory behind spring thaw weakening and different load restriction policies used in the cold climate areas. It will also report the results of the field tests done in Scotland, Sweden and Norway and present some new structural solutions which have been found to work well at spring thaw weakening sites. Finally, new technologies for both road owners and/or road users that could be used in more effective spring thaw weakening management will be revealed.

Salour, F., and Erlingsson, S. (2012). "Pavement Structural Behavior during Spring Thaw - Interpretation of FWD measurements by monitoring environmental data from county road 126 at Torpsbruk." 2009/0572-29, Swedish National Road and Transport Research Institute (VTI), Linkoping, Sweden.

The present research report has been carried out based on the environmental data and Falling Weight Deflectometer (FWD) measurements from the county road Lv 126 in Southern Sweden during the year 2010. The Lv 126 county road has a relatively thin flexible pavement structure with unbound aggregate base and subbase layers. The major intention of this study was to investigate the behaviour of the pavement structure during spring thaw. Temperature and moisture content of the pavement structure profile were continuously monitored throughout the year 2010. Layer moduli backcalculation as well as deflection basin analyses were performed using the FWD measurements data. A comprehensive study on the effect of environmental factor variations and pavement structural capacity were carried out during the spring thaw and recovery period. The result showed a considerable decrease in the bearing capacity of the pavement structure during the spring thaw period when the highest annual moisture content was also registered. Both deflection basin indices and backcalculated layer modulus indicated that the pavement was weakest during the subgrade thawing phase. Backcalculation on the FWD measurements showed a 63% loss in stiffness of the subgrade soil and 48% in the granular base and subbase course during the spring thaw compared to the summer values. In addition, the compatibility of the analysis with a predictive stiffness moduli- moisture content model for unbound materials was studied. The measured field data from the test road pavement in Torpsbruk showed promising agreement with the resilient modulus predictive model, both for the granular layer and subgrade material. Similar models could be developed or calibrated for other soils and granular materials if sufficient data become available in the future.

Shoop, S., Kester, M., Stark, J., Ryerson, C., and Affleck, R. (2003). "Rapid stabilization of thawing soils: field experience and application." Journal of Terramechanics, 39, 181-194.

Thawing soils can severely restrict vehicle travel on unpaved surfaces. However, a variety of materials and construction techniques can be used to stabilize thawing soils to reduce immobilization problems. The US Engineer Research and Development Center’s Army Cold Regions Research and Engineering Laboratory (CRREL) and the Wisconsin National Guard evaluated several stabilization techniques in a field demonstration project during spring thaw at Fort McCoy, Wisconsin, in 1995. Additional tests on chemical stabilizing techniques were conducted at CRREL’s Frost Effects Research Facility. The results of these test programs were reduced to a decision matrix for stabilizing thawing ground, and used during the deployment of US troops in Bosnia during January and February of 1996. The soil frost and moisture conditions expected during this time frame were predicted using MIDFROCAL (MIDwest FROst CALculator). This paper is an overview of the stabilization techniques evaluated and their recommended application based on the expected soil frost conditions and traffic requirements. Although the experiments were performed with military vehicles in mind, the techniques are suitable for many civilian applications such as forestry, construction, mining, and oil exploration.

Simonsen, E., Janoo, V. C., and Isacsson, U. (2002). "Resilient Properties of Unbound Road Materials during Seasonal Frost Conditions." Journal of Cold Regions Engineering, 16(1), 28-50.

During recent decades, a considerable amount of research has been devoted to the resilient properties of unbound road materials. However, the severe effects of cold region

climates on resilient behavior have been less exhaustibly -investigated. In this study, the results from extensive resilient modulus laboratory tests during full freeze-thaw cycling are presented. Various coarse and fine-grained subgrade soils were tested at selected temperatures from room temperature down to -10°C and back to room temperature. The soils are frozen and thawed inside a triaxial cell, thus eliminating external disturbances due to handling. The results indicate that all the soils exhibited a substantially reduced resilient modulus after the freeze-thaw cycle. A significant hysteresis for the clay soil in warming and cooling was also observed. This paper presents equations for different conditions. The equations may be used for selecting the appropriate resilient modulus value in current and future evaluation and design methods.

Solanki, P., Zaman, M., and Khalife, R. (2013). "Effect of freeze-thaw cycles on performance of stabilized subgrade." Sound Geotechnical Research to Practice: Honoring Robert D. Holtz II, Geotechnical Special Publication (GSP) No. 230, R. D. Holtz, A. W. Stuedlein, and B. R. Christoper, eds., ASCE, Reston, VA, 567-581.

A comparative laboratory study was conducted to evaluate the durability of three different subgrade soils stabilized with hydrated lime, class C fly ash (CFA), and cement kiln dust (CKD). Cylindrical specimens were compacted at optimum moisture content (OMC) and cured for 7 days in a moist room having a constant temperature and controlled humidity. Selected specimens were also compacted at a higher molding moisture content of OMC+4%. After curing, the specimens were subjected to different freeze-thaw (F-T) cycles and tested for unconfined compressive strength (UCS) or resilient modulus (Mr). The UCS and Mr values after F-T cycling were compared with those of the raw soil specimens to determine the influence of soil and additive type on durability. The UCS and Mr values revealed that the addition of cementitious additive increased the durability of stabilized specimens against F-T cycles. The extent of improvement in durability, however, was dependent on the characteristics of both soil and additive and number of F-T cycles.

VTrans (2005). "Preventing Muddy Roads: A Road Commissioner's Tool Box." Vermont Agency of Transportation (VTrans), Prepared by The University of Vermont in Association with US Army Engineer Research and Development Center, Inc., and Geo Design, Inc., ed. Vermont.

This technology transfer document was prepared for VTrans, and includes details of test sections constructed in Westford and Windsor, Vermont. The test sections were monitored during the 2001 through 2003 freeze-thaw seasons using temperature sensors in the roadways, along with visual monitoring and field measurements of road strength and surface distress during the thaw periods. Test sections with wrapped geotextile (called as "geowrap), geocells, and geosynthetic capillary barrier drain system (patented) showed noticeable improvements due to improved drainage during the thawing period.

White, D. J., Harrington, D., Ceylan, H., and Rupnow, T. (2005b). "Fly Ash Soil Stabilization for Non-Uniform Subgrade Soils, Volume II: Influence of Subgrade Non-Uniformity on PCC Pavement Performance." IHRB Project TR-461; FHWA Project 4, Center for Transportation Research and Education, Iowa State University, Ames, Iowa.

To provide insight into subgrade non-uniformity and its effects on pavement performance, this study investigated the influence of non-uniform subgrade support on pavement responses (stress and deflection) that affect pavement performance. Several reconstructed PCC pavement projects in Iowa were studied to document and evaluate the influence of

subgrade/subbase non-uniformity on pavement performance. In situ field tests were performed at 12 sites to determine the subgrade/subbase engineering properties and develop a database of engineering parameter values for statistical and numerical analysis. Results of stiffness, moisture and density, strength, and soil classification were used to determine the spatial variability of a given property. Natural subgrade soils, fly ash-stabilized subgrade, reclaimed hydrated fly ash subbase, and granular subbase were studied. The influence of the spatial variability of subgrade/subbase on pavement performance was then evaluated by modeling the elastic properties of the pavement and subgrade using the ISLAB2000 finite element analysis program. A major conclusion from this study is that non-uniform subgrade/subbase stiffness increases localized deflections and causes principal stress concentrations in the pavement, which can lead to fatigue cracking and other types of pavement distresses. Field data show that hydrated fly ash, self-cementing fly ash-stabilized subgrade, and granular subbases exhibit lower variability than natural subgrade soils. Pavement life should be increased through the use of more uniform subgrade support. Subgrade/subbase construction in the future should consider uniformity as a key to long-term pavement performance.

Yarbasi, N., Kalkan, E., and Akbulut, S. (2007). "Modification of the geotechnical properties, as influenced by freeze-thaw, of granular soils with waste additives." Cold Regions Science and Technology, 48, 44-54.

This paper evaluates the use of waste materials such as silica fume, fly ash, and red mud in the modification of granular soils in order to remove the effects of freezing–thawing cycles. In this study, two granular soils obtained from primary rock were stabilized by silica fume–lime, fly ash–lime, and red mud–cement additive mixtures. Natural and stabilized soil samples were subjected to freezing–thawing cycles after curing for 28 days. After the freezing–thawing cycles, compressive strength, California bearing ratio, freezing–thawing, ultrasonic wave, and resonant frequency tests were performed to investigate effects of additive mixtures on the freezing–thawing properties of natural and stabilized soil samples. The experimental results show that stabilized samples with silica fume–lime, fly ash–lime, and red mud–cement additive mixtures have high freezing–thawing durability as compared to unstabilized samples. These additive mixtures have also improved the dynamic behaviors of the soil samples. Consequently, we conclude that silica fume–lime, fly ash–lime, and red mud–cement additive mixtures, particularly silica fume–lime mixture, can be successfully used as an additive material to enhance the freezing–thawing durability of granular soils for road constructions and earthwork applications.

Zaimoglu, S. A. (2010). "Freezing-thawing behavior of fine-grained soils reinforced with polypropylene fibers." Cold Regions Science and Technology, 60, 63-65.

A number of studies have been conducted recently to investigate the influence of randomly oriented fibers on some engineering properties of cohesive and cohesionless soils. However, very few studies have been carried out on freezing–thawing behavior of soils reinforced with discrete fiber inclusions. This experimental study was performed to investigate the effect of randomly distributed polypropylene fibers on strength and durability behavior of a fine-grained soil subjected to freezing–thawing cycles. For strength behavior, a series of unconfined compression tests were conducted. Mass losses were also calculated after freezing–thawing cycles as criteria for durability behavior. The content of polypropylene fiber was varied between 0.25% and 2% by dry weight of soil in the tests. The test results for the reinforced specimens were compared with that for the unreinforced sample. It was observed that the mass loss in reinforced soils was almost 50% lower than that in the unreinforced soil. It was also found that the unconfined compressive strength of specimens subjected to freezing–thawing cycles generally increased with an increasing fiber content. On the other hand, the results indicated that the initial stiffness of the stress–strain curves was not affected significantly by the fiber reinforcement in the unconfined compression tests.

Construction Methods/Considerations and Time

Aho, S., and Saarenketo, T. (2006). "Design and repair of roads suffering spring thaw weakening." The Swedish Road Administration, Northern Region, Sweden.

The ROADEX Project is a technical cooperation between roads organizations across northern Europe that aims to share roads related information and research between the partners. The Project was started in 1998 as a 3 year pilot co-operation between the roads districts of Finnish Lapland, Troms County of Norway, the Northern Region of Sweden and The Highland Council of Scotland and this was later followed up with a second project, ROADEX II, from 2002 to 2005. The partners in the ROADEX II Project comprised public road administrations, forestry organizations, forest companies and haulage organizations from regions in the Northern Periphery. These were The Highland Council, Forest Enterprise & The Western Isles Council from Scotland. The Region Nord of The Norwegian Public Roads Administration and The Norwegian Road Haulage Association, The Northern Region of The Swedish Road Administration and The Lappi and Keski-Suomi Regions of The Finnish National Roads Administration. (These latter Finnish Regions also received aid from their local forest industry organizations of Metsähallitus, Lapin Metsäkeskus, Metsäliitto & Stora-Enso.). The goal of the project was to develop ways for interactive and innovative road condition management of low traffic volume roads integrating the needs of local industry, society and roads organizations. 8 formal reports were published together with a project DVD and full copies of all reports are available for download at the ROADEX web site at www.roadex.org. This Executive Summary report is one of 8 summaries that have been prepared under the direction of the ROADEX III project (2006-2007), a new Project where the named project Partners above were joined by the additional Northern Periphery Partners of the Municipality of Sisimiut, Greenland, The Iceland Public Roads Administration and the Finnish Road Administration Region of Savo-Karjala.

Alzubaidi, H. (1999). "Operation and Maintenance of Gravel Roads - A Literature Study." Swedish National Road and Transport Research Institute, Linkoping, Sweden, 231.

Gravel roads form a large percentage of the road network in Sweden. The public road network under the jurisdiction of the Swedish National Road Administration has a total length of some 98,000 kilometers. About 22,000 km of this network consist of gravel roads. In addition, there are about 74,000 kilometers of private road and 210,000 kilometers of forest roads. This report describes the present position in the operation and maintenance of gravel roads. It presents a comprehensive literature survey of current and recent national and international research. It deals only with summer maintenance and focuses primarily on roads surfaced with aggregate. The following aspects are covered in the report: 1. Definitions and terms regarding the operation and maintenance of gravel roads. 2. General description of the Swedish road network. 3. Major factors causing deterioration of gravel roads. 4. Technical requirements for Swedish gravel roads. 5. Factors influencing the operation and maintenance of gravel roads. 6. Operation and

maintenance methods. 7. Condition assessment of gravel roads. 8. Planning and evaluation of operation and maintenance measures.

ARTBA (1990). "Stabilization and Pavement Recycling." Stabilization, Rehabilitation, and Recycling Committee, American Road and Transportation Builders Association (ARTBA), Washington, D.C.

This report contains an overview of (1) stabilization and recycling, (2) asphalt stabilization, (3) asphalt emulsion for dust control, (4) dust control and stabilization with calcium chloride, (5) cement stabilization, (6) fly ash stabilization, (7) lime stabilization, (8) sodium chloride stabilization, and (9) pavement recycling, along with key references.

Austroads (1998). "Guide to stabilisation in roadworks." Austroads, Sydney, A4, New Zealand.

This Guide provides systematic guidance to practitioners for the selection, design and construction of stabilised pavement layers for use in the construction of new road pavements and the maintenance, rehabilitation and recycling of existing road pavements. It replaces the 1986 NAASRA Guide to Stabilisation in Roadworks. Since the NAASRA Guide was published, there have been substantial improvements in many aspects of stabilisation technology including: (1) improved pavement design procedures; (2) improved materials characterisation procedures; (3) higher capacity plant and equipment; (4) wider range of stabilisation agents with greater effectiveness; and (5) increased environmental awareness of the benefits of stabilisation. Guidance is given to assist the practitioner to select the appropriate type of stabilisation for a particular application as well as materials and pavement design guidance for the following broad types of stabilisation techniques: cementitious stabilisation, lime stabilisation, bituminous stabilisation, granular stabilisation, and other forms of stabilisation. Construction and quality management issues are also addressed. While there have been significant advances in stabilisation technology in the past decade, there are still a number of areas in need of greater understanding including: materials mix design and characterisation, erosion mechanisms, long term strength gains, and stabilisation under traffic. While the information given in the Guide is considered to represent best practice at the time of publication, with the current rate of change of stabilisation technology, it will continue to improve in the future.

Bassel, J. R., Edwards, A., Leibbrand, L., Keller, G. R., and Dauer, W. (1999). "Three road-crushing demonstration projects." Transportation Research Record: Journal of the Transportation Research Board, 1652.

At the Sixth International Conference on Low-Volume Roads Yves Provencher, Forest Engineering Research Institute of Canada, presented a paper on the F.A.H.R. rock crusher mounted to a front-end loader. At the same time the Coronado National Forest in Arizona was renting a F.A.H.R. rock crusher for an in-place road-crushing project. In 1997 San Dimas Technology and Development Center, in partnership with the Coronado National Forest, sponsored two demonstration projects to further test the crusher at unique locations to gain additional information from actual field trials. These projects were located on the Rio Grande National Forest in Colorado and the Plumas National Forest in California. The three projects are described here, with results and conclusions gained from the demonstration projects. The concentration is on the characteristics of the processed material. Samples taken from windrows during the crushing operation were tested to determine hardness and gradations before and after crushing. Cost varied from $8 to $26 per m3 including roadbed preparation, crushing, and blading. Rocks and boulders to 405-mm maximum size were crushed. The processed material has a maximum size of 50 to 75 mm. The product produced by the crusher offers a viable alternative for aggregate on a road surface, particularly as a road surface cushion material, where the quality and expense of standard crushed aggregate, such as base course material, are not needed on low-volume roads.

Berg, R. R., Christoper, B. R., and Perkins, S. (2000). "Geosynthetic Reinforcement of the Aggregate Base/Subbase Courses of Pavement Structures." Geosynthetic Materials Association, Roseville, MN.

Geosynthetic reinforcement of the base, or subbase, course of pavement structures is addressed. The value added with reinforcement, design criteria/protocols, and practices for design and for material specifications are presented. Base, or subbase, reinforcement is defined within as the use of geosynthetic reinforcement in flexible pavements to support vehicular traffic over the life of a pavement structure. Primary base reinforcement benefits are to improve the service life and/or obtain equivalent performance with a reduced structural section. Substantial life-cycle cost savings are possible with base reinforcement. Cost saving benefits should be quantified using life-cycle analyses, and on an agency specific basis due to the many input variables. Recommended design procedure and material specifications are presented. It is recommended that specification with an approved products list be utilized, as the mechanisms of reinforcement are not fully understood and the geosynthetic performance should be considered product, and test conditions, specific. Equivalent materials must demonstrate equivalent performance in test structures and/or possess equivalent material properties, as defined by the specifier. The use of geosynthetic reinforcement to aid in construction over low strength subgrades, termed subgrade restraint within, is also addressed. Geosynthetic reinforcement is used to increase the support equipment during construction of a roadway. Subgrade restraint design procedures are based upon either (i) generic material properties, wherein a generic specification can be prepared based upon those design property requirements; or (ii) product-specific, empirically derived design methods, wherein an approved products list specification approach may be used. Geogrid, geotextile, and geogrid-geotextile composite materials are addressed within. This paper provides government agencies with current, logical recommended practice for the systematic use of geosynthetic reinforcement of pavement base courses. Refined guidance should be developed as the use of base reinforcement increases and additional long-term performance data becomes available.

Bergeson, K. L., Kane, M. J., and Callen, D. O. (1990). "Crushed stone granular surfacing materials." Sponsored by the Iowa Limestone Produces Association and National Stone Association Research Program, Report by Engineering Research Institute, Iowa State University, Ames, Iowa.

The results of this research project indicate that crushed stone surfacing material graded on the fine side of IDOT Class A surfacing specifications provides lower roughness and better rideability; better braking and handling characteristics; and less dust generation than the coarser gradations. This is believed to be because there is sufficient fines (-#40 to - #200) available to act as a binder for the coarser material, which in turn promotes the formation of tight surface crust. This crust acts to provide a smooth riding surface, reduces dust generation, and improves vehicle braking and handling characteristics.

Bloser, S. M. (2007). "Commonly Used Aggregate Materials and Placement Methods: Comparative Analysis for a Wearing Course on Low-Volume Roads in Pennsylvania." Transportation Research Record: Journal of the Transportation Research Board, 1989, 178-185.

Aggregate-surfaced roads are a viable component of the transportation network; they provide significant increases in road stability over earthen surfaced roads while avoiding the high placement and maintenance costs of pavements. The use of higher-quality, more stable aggregates will significantly reduce both the cost of maintaining gravel roads and the environmental concerns related to road runoff. This paper aims to provide a better understanding of wearing course aggregates by describing a comparative analysis experiment done as part of Pennsylvania's Dirt and Gravel Road Maintenance Program. Three aggregates commonly used in Pennsylvania were placed side by side under two different placement methods for each type of aggregate as part of a 3-year study to compare their long-term durability and cost-effectiveness. The two methods tested were the "dump and spread" method known as tailgating and the application of aggregate by a motor paver. Cross-sectional surveys were done on each aggregate section for 3 years following placement to determine elevation changes in the road surfaces. No significant difference in performance was found between aggregate sections placed with a paver and the same aggregate placed by tailgating. Driving surface aggregate was the only aggregate of the three tested that did not show a statistically significant change in road elevation during the 3-year course of study. Results illustrate the importance of selecting a properly graded aggregate containing minimal clay and soil material for use as surface aggregate on low-volume roads.

Brandon, T. L., Al-Qadi, I. L., Lacina, B. A., and Bhutta, S. A. (1996). "Construction and Instrumentation of Geosynthetically Stabilized Secondary Road Test Sections." Transportation Research Record: Journal of the Transportation Research Board, 1534, 50-57.

Nine instrumented flexible pavement test sections were constructed in a rural secondary road in southwest Virginia. The nine test sections, each 15 m (50 ft) long, were built to examine the effects of geogrid and geotextile stabilization. Three lest sections were constructed with a geogrid, three were built with a geotextile, and three were nonstabilized. The test section base course thicknesses ranged from 10,2 cm (4.0 in.) to 20.3 cm (8.0 in.), and the hot-mix asphalt (HMA) thickness averaged 8.9 cm (3.5 in.). Geosynthetic stabilization was placed on top of the subgrade layer. The pavement test sections were heavily instrumented with two types of pressure cells, soil and HMA strain gauges, thermocouples, and soil moisture cells. In addition, strain gauges were installed directly on the geogrid and geotextile. An extensive instrumentation infrastructure was constructed to locate all instrumentation, cabling, and data acquisition facilities underground. Instrument survivability has ranged from 6 percent for the strain gauges mounted on the geotextile to 100 percent for the soil moisture blocks after 8 months of operation. The majority of instrument failures occurred either during construction or the first few weeks of operation. The data acquisition system is triggered by traffic passing over piezoelectric sensors and operates remotely. The corresponding data are transferred via modem to Virginia Polytechnic Institute and State University for processing. It is planned that the performance of the pavement test sections will be monitored for a minimum of 3 years.

Brandon, T. L., Brown, J. J., Daniels, W. L., DeFazio, T. L., Filz, G. M., Mitchell, J. K., Musselman, J., and Forsha, C. (2009). "Rapid stabilization/polymerization of wet clay soils - literature review." Airbase Technologies Division, Material and Manufacturing Directorate, Air Force Research Laboratory, Tyndall Air Force Base, Florida.

This report is written in response to a request from the Air Force Research Laboratory concerning research on rapid stabilization/polymerization of wet clay soils. The purpose of this report is to document the findings of a literature review (Phase I) carried out by the team assembled at Virginia Tech. The literature review covers approximately 200 papers, most of which deal with clay stabilization. This report contains the findings of this literature review, which are categorized by soil type, stabilization type, as well as other factors. This report also includes the recommendations of the Virginia Tech research team for a proposed research program for Phase II.

Bushman, W. H., Freeman, T. E., and Hoppe, E. J. (2005). "Stabilization techniques for unpaved roads." Transportation Research Record: Journal of the Transportation Research Board, 1936, 26-33.

An amendment to Virginia House Bill 1400, Item 490, No. 1h, calls for the Virginia Transportation Research Council to "continue its evaluation of soil stabilizers as an alternative to paving low-volume secondary roads." In response, promising soil stabilization products were evaluated with the relatively new technique of deeply mixing chemical additives into unpaved roadbeds. This work is based on the construction of a 1.75-m-long trial installation on Old Wheatland Road in Loudoun County, where seven commercially available stabilization products were applied to the unpaved road. A rigorous evaluation of treatment performance will provide the basis for recommendations to the Virginia Department of Transportation's operating divisions regarding improvements to the maintenance practices for gravel roads. Results thus far indicate that the introduction of soil stabilizers through deep mixing is a promising technique. The life-cycle cost analysis indicates that constructing a standard bituminous surface-treated roadway and maintaining it as such is much more cost-effective than using any of the products in this trial. Further, the analysis indicates that using the bituminous surface treatment alternative is also much more cost-effective than maintaining an unpaved road.

Campbell, A. E., and Jones, D. (2011). "Soil Stabilization in Low-Volume Roads - Obstacles to Product Implementation from Additive Supplier's Standpoint." Transportation Research Record: Journal of the Transportation Research Board (2204), 172-178.

Overwhelming evidence supports the importance of gravel roads. However, road agencies are increasingly faced with the necessity of relying on marginal materials in construction of low-volume roads. Use of these materials necessitates that stabilization be used to alter the engineering parameters to ensure that corrugation, erosion, rutting, poor passability, dust, and low-bearing capacity are avoided. Soil stabilization is increasingly being used as an unsealed-road asset management tool in an attempt to reduce the impacts of these issues, and nontraditional soil stabilizers have been a primary area of focus. Yet few such products have gained widespread acceptance. This paper looks at the lack of usage of alternative stabilizers in the marketplace today from the viewpoint of the product supplier. It aims to identify the issues facing the supplier in introducing a competent nontraditional soil stabilizer product to road agencies and to identify the measures such suppliers can take to advance those products that show good potential. Measures that could be introduced to better manage the field of soil stabilization for unsealed and low-volume sealed roads have been suggested. These measures include the following: established guidelines, specifications, test methods, and management principles, all prepared in a format that is readily acceptable and adoptable by industry engineers;

an industry association; and the adoption of a dedicated research protocol establishing minimum requirements for research on such additives.

Christoffersson, P., and Johansson, S. (2012). "Rehabilitation of the Timmerleden Forest Road - Condition Survey, Design Proposals, Construction and Quality Control." A ROADEX demonstration report, The Swedish Transport Administration, Northern Region, Sweden.

The European Union ROADEX Project 1998 – 2012 was a trans-national roads cooperation that aimed at developing ways for interactive and innovative management of low volume roads across the European Northern Periphery. Its main goals were to facilitate co-operation and research into the common problems of constructing and maintaining low volume roads in harsh climates. This report gives a summary of a local demonstration of ROADEX methods for assessing forest roads for heavy timber traffic and based on the results making a rehabilitation design proposal. The report also gives a short description of the construction of the rehabilitation and the quality control. Using the ROADEX-method the road was first surveyed using the modern non-destructive road survey techniques of video, ground penetrating radar and falling weight deflectometer. Three samples were also taken to check the grading and to verify the GPR-results. Following this an integrated analysis was carried out using Road Doctor software to produce a strength assessment of the road. The results were then used to do an analytical design of the strengthening measures needed to carry the load from the timber trucks. The ROADEX method was compared to regular road condition assessments and rehabilitation proposals from the project partners: The Swedish Forest Agency and the forest companies Sveaskog and SCA Forest. The partners used their normal procedures for field surveys, analyses and design. The comparison included: (1) Design, (2) Volumes of road materials used, (3) Environmental influence, (4) costs for design, materials, construction, and environmental impacts. To make the ROADEX forest road rehabilitation package complete a quality control was carried out to check if the measures were done right in place, if the layer thicknesses were constructed in accordance with the design and if the bearing capacity target was reached. New GPR- and FWD surveys were carried out about a month after the rehabilitation work was finished. It was found from the GPR survey that measures were very well in place but in some places the base course was a little thinner than the design thickness. A new calculation in accordance with the Odemark method based on the new survey results showed that 98 % of the road length met the bearing capacity target of 90 MPa. The results demonstrate that making a more careful road condition investigation and an analytical road rehabilitation design based on the road condition analyses, can reduce the overall rehabilitation costs and the environmental impacts significantly. The demonstration project has shown that the use of the ROADEX method in this case reduced the costs between 15 and 50%.

DOD (1985). "Pavement design for seasonal frost conditions." Technical Manual No. 5-818-2, Air Force Manual No. 88-6, Chapter 4, Departments of the Army and Air Force, Washington, D.C.

This manual presents criteria and procedures for the design and construction of pavements placed on subgrade or base course materials subject to seasonal frost action. The criteria are applicable to Air Force and Air National Guard airfields, and to roads. This manual is concerned with modes unique to frost areas. The principal non-traffic-associated distress modes are distortion caused by frost heave and reconsolidation, and cracking caused by low temperatures. The principal traffic-load-associated distress modes are cracking and distortion as affected by the extreme seasonal changes in supporting capacity of subgrades and bases that may take place in frost areas.

Glogowski, P. E., Kelly, J. M., McLaren, R. J., and Burns, D. L. (1992). "Fly Ash Design Manual for Road and Site Applications - Volume 1: Dry or Conditioned Placement." TR-100472, GAI Consultants, Inc., Palo Alto, California.

This design manual describes the use of fly ash as a construction material for use as structural and nonstructural fills, backfills, embankments, base courses, and roller compacted concrete dams and pavements, soil stabilization, land reclamation and other high volume uses. The manual details the physical, engineering and chemical properties of bituminous, subbituminous and lignite fly ash. Included are field and laboratory testing methods, design data, procedures and examples, specifications, quality control, and pre- and post-construction monitoring. Volume 1 describes uses where fly ash is used dry or conditioned with small amounts of moisture. Volume 2 describes uses where fly ash is placed as a slurry with relatively large amounts of water. The manual is primarily the result of editing and updating previous publications. High volume ash utilization has been documented in various manuals. These publications have been produced by several agencies including EPRI, Federal Highway Administration (FHWA), American Coal Ash Association (ACAA) and others. However, many of these publications were produced several years ago and are not readily available. Also, the information was published by several sources at various times. Therefore, these earlier publications are summarized and updated in this manual with state-of-practice design methods for use by design engineers. References to additional sources of information are provided.

Helstrom, C. L., Humphrey, D. N., and Labbe, J. M. (2007). "Performance and Effectiveness of a Thin Pavement Section Using Geogrids and Drainage Geocomposites in a Cold Region." NETCR60, Department of Civil and Environmental Engineering, University of Maine, Orono, Maine.

Test sections were constructed in two portions of Maine Route 9 to investigate the use of geosynthetics for reinforcement and drainage for subbase courses that were 300 mm (12 in.) and 600 mm (24 in.) thick with 150 mm (6-in.) of flexible pavement. Four types of test sections were constructed: geogrid reinforcement, drainage geocomposite, drainage geocomposite with geogrid reinforcement, and control. Test sections using reinforcement geogrid have strain gages attached to the geogrid to measure induced forces. Some of the reinforcement sections have geogrid on subgrade whereas some have geogrid in the center of the subbase to evaluate the effects of geogrid location. Drainage geocomposite and control sections have vibrating wire piezometers to monitor porewater pressure in the subgrade and subbase course. Thermocouples were used to measure the depth of frost penetration. The results of falling weight deflectometer tests were used to backcalculate the effective structural number for each section. Reinforcement geogrid and drainage geocomposite increased the effective structural number by between 5% and 17% for sections with 300 mm (12 in.) subbase. However, they had no apparent effect for sections with 600 mm (24 in.) of subbase. The increase in backcalculated effective structural number that was produced by geogrid and/or drainage geocomposite in the 300-mm (12-in.) subbase sections could also be obtained by adding between 25 and 75 mm (1 and 3 in.) of subbase aggregate to an unreinforced section.

Henry, K. S., Olson, J. P., Farrington, S. P., and Lens, J. (2005). "Improved performance of unpaved roads during spring thaw." ERDC/CRREL TR-05-01, Engineer Research and Development Center Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Unpaved roads in Vermont are subject to deterioration from seasonal freezing and thawing, and many towns have roads that suffer chronic serviceability problems during the so-called “spring thaw,” or mud season. Several techniques thought to mitigate deterioration of unpaved roads during spring thaw were constructed on test sections of unpaved roads in two towns. Each potential remedy was aimed at providing some combination of limiting the availability of moisture in the winter, improving drainage during spring, and strengthening the upper portion of the road. Each technique used local and/or commercially available materials, and all were easy to construct, i.e., a town road crew could build them. For two spring thaw seasons, we compared strength estimates based on dynamic cone penetrometer tests and the percentage of the road surface rutted for treated and control sections. Methods that permanently improved the strength of the top 12 inches of the road or decreased the water content of the upper 12 inches of the road resulted in significant performance improvement during spring thaw. Cement and cellular confinement systems worked well by improving the strength of the upper layers of the soil. Two new techniques— geowrap, comprising clean sand sandwiched by geotextile separators placed 12–18 inches deep, and the patented Geosynthetic Capillary Barrier Drain—provided benefit by keeping the upper layers of the soil relatively dry. Geogrid and geotextile separators placed 12 inch deep and trench drains parallel to the road provided no observable benefit.

Hoover, J. M. (1973). "Surface improvements and dust palliation of unpaved secondary roads and streets." Iowa Highway Research Board Project HR-151, Engineering Research Institute, Iowa State University, Ames, Iowa.

The report contains five parts:

(I) Project Summary by Hoover, J. M. - As of December 31, 1970 there were 57,270 miles of Local Secondary roads and 32,958 miles of Farm to Market roads in the Iowa secondary road system. The Local Secondary system carried a traffic load of 2,714,180 daily vehicle miles, accounting for 32% of all traffic in secondary system. For all Local Secondary roads having some form of surfacing, 98% were surfaced with gravel or crushed stone. During the 1970 construction year, 335 miles of surfaced roads were constructed in the Local Secondary system with 78% being surfaced with gravel or crushed stone. The total maintenance expenditure for all secondary roads in Iowa during 1970 amounted to $40,086,091. Of this, 42%, or $17,020,332, was spent for aggregate replacement on existing gravel or crushed stone roads with an additional 31% ($12,604,456) being spent on maintenance other than resurfacing. This amounts to 73% of the total maintenance budget and are the largest two maintenance expenditure items out of a list of 10 ranging from bridges to drainage assessments. The next largest item was 7%, for maintenance of existing flexible bases. Present costs of high-type flexible or rigid pavements range from $40,000 per mile up. Because of high cost, budget limitations, and low mileage of high traffic volume on Local Secondary roads, most Iowa counties are severely restricted as to the number of miles of roads that may be paved each year. Present design and construction standards provide adequate means for improvement of grade and cross section of secondary roads followed by: (a) immediate road metal surfacing, or (b) eventual high-type surfacing. There are, at present, no formal provisions for an intermediate type surfacing between these two extremes. Therefore, nearly all Iowa counties are in a situation in which they have only a few miles of high-type pavements with the bulk being surfaced with gravel or crushed stone. From the maintenance expenditures for 1970, it can be seen that the primary method of maintaining aggregate surfaced secondary roads remains, as it has in the past, as aggregate replacement. Roads continue to rut, washboard, ravel, pothole, and become the source for billowing clouds of dust. Loose aggregate makes driving hazardous, and results in cases of vehicle damage including cracked windshields, chipped paint, and dents, as well as increased fatalities. During the spring thaw and subsequent rains, many roads become extremely soft, slippery, and heavily rutted. As aggregate supplies decrease, inferior quality soft limestones and gravels are being used, resulting in faster degradation contributing to the dusting problem. Dust creates a safety hazard to both passing and oncoming traffic. It is also a definite household nuisance in rural areas, especially in heavily populated regions surrounding larger towns and cities where traffic on unpaved roads may range as high as 500 vehicles per day. The severity of these problems continues to increase as: (a) traffic volume increases, (b) more people move to rural areas surrounding larger towns and cities, and (c) the current concern over air pollution increases. The Iowa Air Pollution Control Commission has drafted guidelines with respect to "fugitive" dust, which ultimately will affect all unpaved state, county, and city roads and streets. Besides the above problems, most counties are faced with (a) rising costs of high-type pavement, (b) rising costs of maintenance, and (c) rising costs of replacement aggregates. The foregoing considerations dictated the need for finding a means to provide for low-cost surface improvement and dust control, using existing in-place materials, for immediate (and intermediate) use as a treated surface course on unpaved secondary roads - the objective of this research project. Three concurrent phases of study were included in the project: (1) laboratory screenings studies of various additives thought to have potential for long-lasting dust palliation, soil additive strength, durability, and additive retention potential; (2) test road construction using those additives that indicated promise for performance-serviceability usage; and (3) observations and tests of constructed sections for evaluation of the additive's contribution to performance and serviceability as well as the relationship to initial costs.

(II) Asphaltic products and elastometers as dust palliatives and surface improvement agents for unpaved secondary roads, by Bergeson, K. H. and Hoover, J. M.: Bituminous materials have long been used, with varying degrees of success, as soil stabilizers and waterproofing agents. With advancing technological developments many new asphaltic products, whose properties have been altered and supposedly enhanced by the addition of chemicals and selected emulsifying agents, are being marketed. Elastomers, which contain rubber in a modified form, have also been introduced. The beneficial effects of these products, as soil stabilizers and dust palliatives, can only be determined by laboratory evaluation and field trials. This investigation was conducted essentially as a three phase project consisting of (a) laboratory screenings of various asphaltic products and elastomers to evaluate their effectiveness as soil stabilizers and dust palliatives, (b) construction of a test road, based on the results of the laboratory screening phase, using those additives that appeared to be the most effective and economical, and (c) observation and tests of the various sections of the test road for evaluation of the additives' performance and serviceability with respect to dust palliation and surface improvement. The primary purpose of this study is to present the results of each of the above phases. The test road was constructed in September 1971 and had been in service only one year and three months at the time of termination of research. Therefore, phase 3 analyses are somewhat limited due to the period of time covered.

(III) Ammonium lignosulfonates as dust palliatives and surface improvement agents for unpaved secondary roads, by Fox, D. E., and Hoover, J. M.: At the time the research project was initiated in mid-1970, county engineer offices in Iowa were requested to propose locations for test roads within their respective counties. It was explained that all men, material, and equipment would be furnished by the individual counties. Laboratory screenings of additives and field testing of experimental roads would be carried out by the researchers, who would also be present to observe construction and provide technical assistance when and where needed. Four counties responded with interest in lignosulfonate stabilization. Lignosulfonates are available in almost unlimited quantities from paper mills. Ten years ago, lignosulfonates cost 6 cents per gallon at the mill and the price has not increased, although production has. Due to different pulping processes, the cation associated with lignosulfonate varies. Sodium, calcium, and ammonium lignosulfonates have all been used in soil stabilization and prices are similar. The study reported here utilized commercially-available lignosulfonate with ammonium as the associated cation. The following paragraphs explain the participation offered for lignosulfonate research by the corresponding county. The county engineer's office of Clinton County, Iowa made available a section of road 2620 ft long to which crushed limestone had been added at a rate of 2000 tons per mile. This length was naturally divided into three approximately equal sections, a flat upland location, a curve on a hill of about 6% grade, and a level bottomland section on a backwater area of the Mississippi River. The road was located between, and connected with, paved roads terminating at the Clinton and Camanche city limits. Two nearby industries contributed to a 1967 ADT (average daily traffic) of 500 vehicles per day, and maintenance was a problem. The researchers were invited to perform field tests on several roads within Floyd County, both prior to and following treatment with lignosulfonate. Construction was done by county personnel under the supervision of the lignosulfonate supplier. A dirt road near Marion, Linn County, was made available by the county engineer for research. Of 6000 ft length, the 1968 traffic survey showed an ADT of 44 vehicles. Prior to treatment, the grade was built up and improved by the ditch clean-out method typical of much secondary road construction. Using lignosulfonate from a local source, stabilization of nearly 150 miles of roads was begun in Lee County in the late 1950s and early 1960s. Treatment consisted of only light surface blading and occasional application of aggregate coupled with a lignosulfonate surface spray application. Over the years, an in-depth treatment was produced. Extensive cost and maintenance records on treated roads were kept and made available to the researchers.

(IV) Soil-chemical additives as surface improvement agents for unpaved roads, by Denny, C. K., and Hoover, J. M.: The use of polyester and plastic resins as soil stabilizers is relatively new and untried. The objective of this research was to investigate the capabilities of these resins and several other chemicals and commercial dust palliatives as potential low-cost dust palliatives and surface improvement agents. The investigation was conducted entirely in the laboratory but care was taken to approximate field conditions as accurately as possible. Various soil-chemical additives were evaluated on the basis of the following tests: (1) unconfined compressive strength, (2) durability and erosibility, (3) trafficability, (4) resistance to freezing and thawing, and (5) moisture retention and density. Some of the tests were standard while others were specifically modified, but in every case the treated specimens were compared with untreated control specimens.

(V) Appendix: Mineralogical analyses of dust samples, by Handy, R. L.: This part contains results of differential thermal-thermogravimetric analysis and petrographic analysis. Thermogravimetric analysis offers a rapid, accurate method for the measurement of carbonates

and organic matter in 50 mg dust samples, and gives a reliable semi-quantitative indication of the amount of clay minerals. Analysis by petrographic microscope is less accurate but requires less sample, and therefore is a valuable supplemental technique for very small samples. Dust analyses show conclusively that selective sorting is operative, calcium carbonate dominating in dust samples collected near the road, and gradually decreasing to near zero several hundred feet away from the road. Simultaneously, the contents of clay and organic matter increase with distance from the road. The efficiency of the sorting indicates that it is size-selective rather than specific gravity-selective (i.e., carbonate contents are higher close to the road because the grains are larger and settle faster). Lignin treatment will drastically reduce the carbonate percentage in road dust, by more than a factor of 10, provided the added rock amount does not exceed 1000 T/mile. The total amount of dust is less drastically reduced, and the amount roughly coincides with the amounts of noncarbonate components in dusts from untreated roads. This suggests that lignin and clay build up a protective patina at the road surface, by migration upward due to evaporation. This patina protects the limestone and is worn off by traffic; however, it should renew so long as sufficient lignin remains in the road. (Alternatively, it probably can be renewed by surface treatments.) The existence of such a coating, while greatly reducing the limestone aggregate loss from the dry road, also may contribute some slipperiness on a wet road, and probably acts to reduce bonding between the road metal and a bituminous overlay. Rock added in excess of about 1000 T/mile is not effectively protected by a 1% lignin treatment, or lignin plus lime. In addition, at the higher rock application levels, added Ca(OH)* lime tends to further reduce the protective effect on carbonates, probably by flocculating the clay and reducing migration and development of a film.

Hopkins, T. C., Beckham, T. L., and Hunsucker, D. Q. (1995). "Modification of highway soil subgrades." Report KTC 94-11, Kentucky Transportation Center, University of Kentucky, Lexington, KY.

Major study objectives were to develop highway pavement subgrade stabilization guidelines, examine long-term benefits of chemical stabilizers, such as cement, hydrated lime, and two byproducts from industrial processes, and to establish a subgrade stabilization program in Kentucky. In developing a program, a number of design and construction issues had to be resolved. Factors affecting subgrade behavior are examined. Changes in moisture content and CBR strengths of untreated and chemically treated subgrades at three experimental highway routes were monitored over a 7-year period. CBR strengths of the untreated subgrades decreased dramatically while moisture contents increased. CBR strengths of subgrade sections treated with hydrated lime, cement and multicone kiln dust generally exceeded 12 and increased over the study period. At four other highway routs ranging in ages from 10 to 30 years, CBR strengths of soil-cement subgrades exceed 90. Knowing when subgrade stabilization is needed is critical to the development of an economical design and to insure the efficient construction of pavements. Bearing capacity analyses using a newly developed, stability model based on limit equilibrium and assuming a tire constant stress of 552 kPa show that stabilization should be considered when the CBR strength is less than 6.5. For other tire contact stresses, relationships corresponding to factors of safety of 1 and 1.5 are presented. Stability analysis of the first lifts of the paving materials showed that CBR strengths of untreated subgrade should be > 9. Guidelines for using geogrids as subgrade reinforcement are presented. Factors of safety of geogrid reinforced granular bases are approximately 10 to 25 percent larger than granular bases without reinforcement. As shown by strength tests and stability analysis, when the percent finer than the

0.002mm particle size of a soil increases to a value greater than about 15%, the factor of safety decreases significantly. Guidelines are also presented for this selection of the design strengths of untreated and treated subgrades with hydrated lime and cement. Based on a number of stabilization projects, recommended design undrained shear strengths of hydrated lime- and cement-treated subgrades are about 300 and 690 kPa, respectively. A laboratory testing procedure for determining the optimum percentage of chemical admixture is described. Correlations of dynamic cone penetrometer and Clegg impact hammer and in situ CBR strengths and unconfined compressive strengths are presented.

Jahren, C. T., White, D. J., Phan, T. H., Westercamp, C., and Becker, P. (2011). "Stabilization Procedures to Mitigate Edge Rutting for Granular Shoulders – Phase II." IHRB Project TR-591, Institute for Transportation, Iowa State University, Ames, Iowa.

A multifaceted investigation was undertaken to develop recommendations for methods to stabilize granular road shoulders with the goal of mitigating edge ruts. Included was reconnaissance of problematic shoulder locations, a laboratory study to develop a method to test for changes in granular material stability when stabilizing agents are used, and the construction of three sets of test sections under traffic at locations with problematic granular shoulders. Full results of this investigation are included in this report and its appendices. Based on the results of the investigation, the following was concluded: (1) Problematic shoulders are generally stiff enough to carry expected traffic loads for emergency pull-off and temporary parking. Material gradations are generally finer than specified for new construction and cross slopes are often steeper than called out on cross sections for new construction. However, such differences in what is expected for original construction are consistent with damage that would be expected during use and maintenance (degradation of size due to breakage and abrasion and loss of material through erosion and winter and summer maintenance). Therefore, it seems likely that edge ruts develop from a combination of vehicle offtracking and time elapsed between maintenance cycles, rather than defects regarding original geometry and material gradation or from structural weakness. Some effort to renew cross slope and material gradation may be helpful in mitigating edge ruts. In addition, a shorter maintenance cycle would most likely be required to mitigate edge ruts. (2) Calcium chloride, magnesium chloride, and Base One did not provide noticeable improvements on the US 20 shoulders. However, they were easily applied and have the potential to be applied with the Iowa DOT's own maintenance staff, using its own equipment that could be modified from winter use. These methods were attempted because it was hypothesized that an important failure mode was that fine particles near the pavement edge were being removed by wind erosion, leaving only large particles that are easily displaced by off-tracking vehicles. These products bind fine particles, mechanically with Base One and by attracting moisture with calcium chloride and magnesium chloride. Apparently, some other mechanism causes the edge ruts, despite the presence of fine particles near the pavement edge. (3) If full-depth reclamation is used to incorporate stabilizers, the Iowa DOT does not currently own and operate the necessary equipment to compact and stabilize the reclaimed material. To provide the needed compaction effort, heavier equipment would have to be purchased or rented. In particular, it would be necessary to have a pneumatic compactor that could operate bi-directionally. Typically-available, pull-behind compactors do not allow enough passes to be made quickly enough when consideration is given to the time required to safely turn the units, especially on limited access highways. (4) DUSTLOCK appears to wear well in locations where the shoulder material provides a stable base and vehicles do not off-track to the extent that they do on the US 20 test section. In areas of heavy off-tracking, preliminary indications are that stabilizing the shoulders reduces the number of maintenance cycles to half of what they would be without the stabilizer. (5) The laboratory test method for investigating stabilizer performance appeared to be a reasonable effort that provided some information about stabilized material behavior in confined situations. However, the method would have to be combined with a test similar to an asphalt rut test to detect instability for unconfined circumstances.

Jobgen, M. C., Callahan, M., Harris, G., and Tymkowicz, S. (1994). "Low cost techniques of base stabilization." Project HR-312, Iowa Department of Transportation, Ames, Iowa.

The IHRB HR-312 research project (Jobgen et al. 1994) evaluated performance of four different stabilization methods for on unsurfaced roads. These stabilization methods included using: a) high float emulsion (HFE-300) to treat top 3 in. of base stone, b) a bio-chemical formula called as BIO CAT 300-1 to treat the base stone for different thicknesses (6 in., 8in., and 10 in.), c) Consolid System method in the top 10 in. of subgrade soil, wherein when the soil is dry a combination of two inverted emulsions are used and when the soil is wet a combination of an inverted emulsion and a lime hydrated base powder are used to treat the base stone, and d) 5 in. of macadam base and 2 in. of choke stone along with fabric under one of the sections. All test sections were sealed using a double seal coat and performance evaluation was conducted on these sections using Iowa Road Rater, Roughometer, and visual inspection annually from 1989 to 1992. Some key findings from the field testing were as follows: (a) Test sections stabilized with BIO CAT300-1 and Consolid system showed the highest average k-value (207 pci to 225+ pci) four years after construction. HFE-300 stabilized section showed an average k-value of 181 pci, macadam subbase section showed an average k-value of 172 pci, and macadam subbase with fabric section showed an average k-value of 116 pci, four years after construction. (b) Although the BIO CAT 300-1 and Consolid System stabilized sections showed high k-values, they showed poor performance with alligator cracking and rutting under traffic, and continued deterioration every year. It is speculated in the report that these failures could have been due to freeze-thaw cycles in the stabilized layers. (c) HFE-300 treated test sections showed some deterioration with alligator cracking. Macadam subbase test sections (with and without fabric) experienced minor rutting and showed the best overall performance than all other sections. The use of fabric did not show noticeable improvement. (d) Use of macadam base and HFE-300 treatment showed cost effectiveness than other treatment options evaluated in this study.

Keller, G. R., and Sherar, J. (2003). "Low-Volume Roads Engineering - Best Management Practices Field Guide." Forest Service, United States Department of Agriculture, Washington, D.C.

This Low-Volume Roads Engineering Best Management Practices Field Guide is intended to provide an overview of the key planning, location, design, construction, and maintenance aspects of roads that can cause adverse environmental impacts and to list key ways to prevent those impacts. Best Management Practices are general techniques or design practices that, when applied and adapted to fit site specific conditions, will prevent or reduce pollution and maintain water quality. BMPs for roads have been developed by many agencies since roads often have a major adverse impact on water quality, and most of those impacts are preventable with good engineering and management practices. Roads that are not well planned or located, not properly designed or constructed, not well maintained, or not made with durable materials often have negative effects on water quality and the environment. This Guide presents many of those desirable practices. Fortunately, most of these “Best Management Practices” are also sound engineering practices and ones that are cost-effective by preventing failures and reducing maintenance needs and repair costs. Also keep in mind that “best” is relative and so appropriate practices depend to some degree upon the location or country, degree of need for improvements, and upon local laws and regulations. Best practices are also constantly evolving with time. This guide tries to address most basic roads issues in as simple a manner as possible. Complex issues should be addressed by experienced engineers and specialists. Included are key “DO’s” (RECOMMENDED PRACTICES) and “DON’Ts” (PRACTICES TO AVOID) in low-volume roads activities, along with some relevant basic design information. These fundamental practices apply to roads worldwide and for a wide range of road uses and standards. Often recommended practices have to be adapted to fit local conditions and available materials. Additional information on how to do the work is found in other Selected References, such as the “Minimum Impact Low-Volume Roads Manual”. Most practices apply to a wide range of road standards, from native surfaced, single-lane roads to double-lane paved roads. Desirable general practices include good road planning and location, performing environmental analysis, recognizing the need for positive surface drainage, ensuring adequately sized drainage crossing structures, using stable cut and fill slopes, using erosion control measures, developing good materials sources, and reclaiming sites once work has been completed. Certain design practices, such as use of rolling dips, outsloped roads, or low-water stream crossings, are very cost-effective and practical but typically apply to low-volume, low-speed roads because of safety concerns, vertical alignment issues, or unacceptable traffic delays. Other issues, such as the use of log stringer bridges, are very desirable for stream crossings in developing regions to avoid driving through the water, yet their use is now discouraged by some agencies, such as the U.S. Forest Service, because of their short design life and potentially unpredictable performance. Thus the information presented herein must be considered in terms of local conditions, available materials, road standards, project or resource priorities, and then applied in a manner that is practical and safe. Local rules, agency policies or regulations, or laws may conflict with some of this information or may include more specific information than that included herein. Thus, good judgment should be used in the application of the information presented in this guide, and local regulations and laws should be followed or modified as needed.

Kestler, M. A. (2009). "Stabilization selection guide for aggregate and native-surfaced low-volume roads." National Technology and Development Program, Forest Service, U.S. Department of Agriculture, Washington, D.C.

The purpose of this guide is to facilitate the selection of modification/stabilization agents and techniques for aggregate surfaced and native/unsurfaced LVRs. The objective is to provide low-cost alternatives that reduce aggregate wear and loss, reduce road-surface maintenance (i.e., blading out ruts), and reduce the time period between major rehabilitation (i.e., between adding new aggregate and the total reconditioning of the road pavement). This guide provides information on available stabilizing agents, appropriate conditions for use, selection procedures, quantity determination, and contact information for manufacturers/suppliers. Emphasis is on the modification/stabilization of existing in-place road surface materials, but many of the methods can be used in the construction of new roads. Construction procedures for application are also presented. The intended audience includes road managers, engineers, and technicians involved in road maintenance, construction, and reconstruction. Those involved in trail maintenance and

construction also may find the guide beneficial, as stabilizers used on trails, particularly accessible trails, help provide a smooth, durable surface.

Koch, S., Ksaibati, K., and Huntington, G. (2011). "Performance of Recycled Asphalt Pavement in Gravel Roads." Transportation Research Record: Journal of the Transportation Research Board, 2204, 221-229.

Because more recycled asphalt pavement (RAP) has become available to use in roadways, the Wyoming Technology Transfer–Local Technical Assistance Program Center and two Wyoming counties saw a need to investigate the use of RAP in gravel roads. The Wyoming Department of Transportation along with the Mountain Plains Consortium funded this study. The investigation explored the use of RAP as a means of dust suppression while considering road serviceability. Test sections were constructed in the two counties and were monitored for dust loss by means of the Colorado State University dustometer. Surface distress evaluations of the test sections were performed following a technique developed by the U.S. Army Corps of Engineers in Unsurfaced Road Maintenance Management (Special Report 92-26). The data collected were statistically summarized and then analyzed. The performance of RAP sections was compared with that of gravel control sections. This comparison allowed fundamental conclusions and recommendations to be made for RAP and its ability to abate dust. It was found that RAP-incorporated gravel roads can reduce dust loss without adversely affecting the road's serviceability. Other counties and agencies can expand on this research to add to the toolbox for dust control on gravel roads.

Less, R. A., and Paulson, C. K. (1977). "Experimental macadam stone base - Des Moines County." Project HR-175, Iowa Department of Transportation, Ames, Iowa.

The IHRB HR-175 research project evaluated the feasibility and economics of using macadam subbase material (with different thicknesses) with choke stone under PCC and asphalt pavements. The macadam subbase material used on this project had a typical gradation with 4 in. maximum particle size and 12 to 26% passing the 1 in. sieve. The choke stone had a typical gradation with 1 in. maximum particle size and 6 to 12% passing the No. 200 sieve. The study indicated that the macadam subbase performed well under both PCC and asphalt pavements, but the cost was relatively more. During construction, the finished macadam subbase showed a uniform structure with negligible amount of degradation during compaction. Production rates on placement of the macadam subbase material varied from about 2900 to 5000 tons per day. Lateral subdrain trenches backfilled with porous backfill was used on this project for drainage. This system performed well and minimized effects of frost boils, spring thaw, and other subsurface drainage issues.

Newman, J. K., and White, D. J. (2008). "Rapid Assessment of Cement and Fiber-Stabilized Soil Using Roller-Integrated Compaction Monitoring." Transportation Research Record: Journal of the Transportation Research Board, 2059, 95-102.

Test sections of high-early strength (Type III) portland cement and polypropylene monofilament fibers were constructed at the Bradshaw Field Training Area in the Northern Territory (NT), Australia as part of a Joint Rapid Airfield Construction (JRAC) project. Aprons, taxiways, and a helipad were stabilized using these materials in combination with screened native soil. The purpose of the test sections was to (a) evaluate the resulting properties for different stabilization dosage rates; (b) develop construction methods, criteria (including limits),

and quality control guidelines; and (c) provide a hands-on training opportunity for the joint United States and Australia military construction team. Testing and monitoring consisted of roller-integrated compaction monitoring (global position systems monitoring pass coverages and compaction machine values) and in situ testing, which included dynamic cone penetration tests, Clegg impact tests, and light-weight deflectometer tests. After the test sections, construction of the helipad helped refine the construction methods and quality control testing for the selected stabilization dosage rates and machine speed. Lessons learned on the helipad were applied to the subsequent aircraft parking aprons and taxiways. Recommendations were developed for rapid stabilization construction procedures and quality control testing using Clegg impact values and light-weight deflectometer for cement-fiber stabilized soils, and the application of roller-integrated compaction technology was demonstrated to document compaction effort and uniformity.

Shoop, S., Kester, M., Stark, J., Ryerson, C., and Affleck, R. (2003). "Rapid stabilization of thawing soils: field experience and application." Journal of Terramechanics, 39, 181-194.

Thawing soils can severely restrict vehicle travel on unpaved surfaces. However, a variety of materials and construction techniques can be used to stabilize thawing soils to reduce immobilization problems. The US Engineer Research and Development Center's Army Cold Regions Research and Engineering Laboratory (CRREL) and the Wisconsin National Guard evaluated several stabilization techniques in a field demonstration project during spring thaw at Fort McCoy, Wisconsin, in 1995. Additional tests on chemical stabilizing techniques were conducted at CRREL's Frost Effects Research Facility. The results of these test programs were reduced to a decision matrix for stabilizing thawing ground, and used during the deployment of US troops in Bosnia during January and February of 1996. The soil frost and moisture conditions expected during this time frame were predicted using MIDFROCAL (MIDwest FROst CALculator). This paper is an overview of the stabilization techniques evaluated and their recommended application based on the expected soil frost conditions and traffic requirements. Although the experiments were performed with military vehicles in mind, the techniques are suitable for many civilian applications such as forestry, construction, mining, and oil exploration.

Sigurdsson, O. (1991). "Geosynthetic stabilization of unpaved roads on soft ground: a field evaluation." MS, The University of British Columbia, British Columbia, Canada.

A full scale field trial was carried out to investigate the performance of different geosynthetics in unpaved road construction over soft ground. The test site comprises of five 16 m long by 4.5 m wide test sections, build on a subgrade of undrained shear strength approximately 40 kPa. One is unreinforced and serves as a control section in the study, three sections include a geotextile, and one includes a geogrid. Each test section incorporated a variable thickness of sandy gravel base course material, between 25 and 50 cm thick. They were trafficked in sequence by a vehicle of standard axle load. An important governing parameter for interpretation of behavior is the influence of base course thickness on the relationship between number of passes and rut depth, base course thickness, base course deformations, geosynthetic strain, and deformed profile of the geosynthetic, with increasing number of vehicle passes. Vehicle trafficking was continued to a rut depth of about 20 cm, which constitutes a serviceability failure. Results from the full scale field trial show a better performance in the reinforced sections than the unreinforced section. The performance of the unreinforced section shows good agreement with other well-documented field data at large rut depths, between 10 and 15 cm, but not at small

ruts. Although the four geosynthetics exhibited a broad range of stiffness and material properties, the general performance of the four reinforced sections was similar on the thicker base course layers. This is attributed to a reinforced mechanism governed by stiffness and separation, and all materials appear adequately stiff for the site conditions and vehicle loading. On the thinner subgrades, a tensioned-membrane effect is mobilized and a significant difference is observed between the geosynthetics.

Stormont, J. C., Ramos, R., and Henry, K. S. (2001). "Geocomposite capillary barrier drain systems with fiberglass transport layer." Transportation Research Record: Journal of the Transportation Research Board, 1772, 131-136.

A geocomposite capillary barrier drain (GCBD) removes water from soil while pore pressures remain negative, that is, the soil to be drained does not need to be saturated. GCBDs are being evaluated for inclusion in pavement systems, particularly between the base course and subgrade layer. The GCBD system comprises a capillary barrier layer (a geonet) sandwiched between transport layers (certain geotextiles). Improved GCBD performance is expected with a transport layer that has a greater affinity for water compared with conventional geotextiles. After many materials were evaluated, a woven fiberglass product was selected for further evaluation as a transport layer. A GCBD with a fiberglass transport layer was placed between a subgrade and a base course in a 3-m-long sloped test device used to measure lateral drainage. Water was infiltrated on the top of the base course, and drainage from the GCBD and the soil layers was collected. Measurements of soil suction were made within the soil layers. The GCBD performance was evaluated during three test phases: constant rate infiltration, subsequent drainage with no infiltration, and transient infiltration corresponding to a design storm. The GCBD was successful in draining sufficient water under suction to prevent positive pore water pressures from developing in the base course and to limit water movement into the underlying subgrade soil.

Stormont, J. C., and Stockton, T. B. (2000). "Preventing positive pore water pressures with a geocomposite capillary barrier drain." Testing and Performance of Geosynthetics in Subsurface Drainage, ASTM STP 1390, L. D. Suits, J. B. Goddard, and J. S. Baldwin, eds., ASTM, West Conshohocken, PA, 15-31.

The Geocomposite Capillary Barrier Drain (GCBD) has been developed and tested to prevent positive pore water pressures from developing by laterally draining water while it is still in tension. The GCBD consists of two key layers that function as long as the water pressures in the system remain negative: (I) a transport layer that laterally drains water and (2) a capillary barrier layer that prevents water from moving downward. Prototype GCBD systems have been tested in a 3 m long lateral drainage test apparatus. For most test conditions, the GCBD systems drained water under negative pressures at a rate sufficient to prevent any positive water pressures from developing in the overlying soil. Further, the drain system served as a barrier as it prevented downward flowing water from moving into the underlying soil.

Terrel, R. L., Epps, J. A., Barenberg, E. J., Mitchell, J. K., and Thompson, M. R. (1979). "Soil Stabilization in Pavement Structures - A User's Manual." COT-FH-11-9406, Federal Highway Administration, Department of Transportation, Washington D.C.

This manual contains two volumes. Volume 1 covers the pavement design and construction considerations of soil stabilization, while Volume 2 covers the mix design considerations. The primary purpose of this manual is to provide background information for those engineers responsible for utilizing soil stabilization as an integral part of a pavement structure. Information is included which will allow the pavement design engineer to determine the thickness of stabilized layer(s) for a pavement in a specific climate and subjected to definable highway traffic. The construction engineer will find information on quality control, specifications and construction sequences. The materials engineer has been provided with information that will allow the determination of the type and amount of stabilizers that are suitable for a particular soil. The manual has not been written to endorse one type of a chemical stabilizer over another. Nor is it intended to provide the specific features of one manufacturer's products. Rather, it explains the general characteristics of chemical soil stabilization and offers a method for evaluating the benefits of chemical stabilization versus the conventional mechanical stabilization operations. A thorough study of the manual should enable the engineer to recommend where, when and how soil stabilization should be used. It may also act as an aid in solving problems that may arise on soil stabilization projects.

VTrans (2005). "Preventing Muddy Roads: A Road Commissioner's Tool Box." Vermont Agency of Transportation (VTrans), Prepared by The University of Vermont in Association with US Army Engineer Research and Development Center, Inc., and Geo Design, Inc., ed. Vermont.

This technology transfer document was prepared for VTrans, and includes details of test sections constructed in Westford and Windsor, Vermont. The test sections were monitored during the 2001 through 2003 freeze-thaw seasons using temperature sensors in the roadways, along with visual monitoring and field measurements of road strength and surface distress during the thaw periods. Test sections with wrapped geotextile (called as "geowrap), geocells, and geosynthetic capillary barrier drain system (patented) showed noticeable improvements due to improved drainage during the thawing period.

White, D. J., Harrington, D., and Thomas, Z. (2005a). "Fly Ash Soil Stabilization for Non-Uniform Subgrade Soils, Volume I: Engineering Properties and Construction Guidelines." IHRB Project TR-461, FHWA Project 4, Center for Transportation Research and Education, Iowa State University, Ames, Iowa.

Soil treated with self-cementing fly ash is increasingly being used in Iowa to stabilize fine-grained pavement subgrades, but without a complete understanding of the short- and long-term behavior. To develop a broader understanding of fly ash engineering properties, mixtures of five different soil types, ranging from ML to CH, and several different fly ash sources (including hydrated and conditioned fly ashes) were evaluated. Results show that soil compaction characteristics, compressive strength, wet/dry durability, freeze-thaw durability, hydration characteristics, rate of strength gain, and plasticity characteristics are all affected by the addition of fly ash. Specifically, Iowa self-cementing fly ashes are effective at stabilizing fine-grained Iowa soils for earthwork and paving operations; fly ash increases compacted dry density and reduces the optimum moisture content; strength gain in soil-fly ash mixtures depends on cure time and temperature, compaction energy, and compaction delay; sulfur contents can form expansive minerals in soil–fly ash mixtures, which severely reduces the long-term strength and durability; fly ash increases the California bearing ratio of fine-grained soil–fly ash effectively dries wet soils and provides an initial rapid strength gain; fly ash decreases swell potential of expansive soils; soil-fly ash mixtures cured below freezing temperatures and then soaked in water are highly susceptible to slaking and strength loss; soil stabilized with fly ash exhibits

increased freeze-thaw durability; soil strength can be increased with the addition of hydrated fly ash and conditioned fly ash, but at higher rates and not as effectively as self-cementing fly ash. Based on the results of this study, three proposed specifications were developed for the use of self-cementing fly ash, hydrated fly ash, and conditioned fly ash. The specifications describe laboratory evaluation, field placement, moisture conditioning, compaction, quality control testing procedures, and basis of payment.

Equipment and Contractors

Hicks, R. G. (2002). "Alaska soil stabilization design guide." FHWA-AK-RD-01-6B, State of Alaska Department of Transportation and Public Facilities, Fairbanks, Alaska.

This guide presents information on the types of soil stabilization techniques that have or can be used in the state of Alaska. It covers techniques including asphalt, cement, lime, mechanical, chemical, and other methods. For each method there is a discussion on materials and design considerations, construction issues, and expected performance and costs. The appendices include a glossary of terms, a reading list on prior stabilization used in Alaska, a discussion on the soils in Alaska, and a slide presentation summarizing the highlights of the guide.

Jobgen, M. C., Callahan, M., Harris, G., and Tymkowicz, S. (1994). "Low cost techniques of base stabilization." Project HR-312, Iowa Department of Transportation, Ames, Iowa.

The IHRB HR-312 research project (Jobgen et al. 1994) evaluated performance of four different stabilization methods for on unsurfaced roads. These stabilization methods included using: a) high float emulsion (HFE-300) to treat top 3 in. of base stone, b) a bio-chemical formula called as BIO CAT 300-1 to treat the base stone for different thicknesses (6 in., 8in., and 10 in.), c) Consolid System method in the top 10 in. of subgrade soil, wherein when the soil is dry a combination of two inverted emulsions are used and when the soil is wet a combination of an inverted emulsion and a lime hydrated base powder are used to treat the base stone, and d) 5 in. of macadam base and 2 in. of choke stone along with fabric under one of the sections. All test sections were sealed using a double seal coat and performance evaluation was conducted on these sections using Iowa Road Rater, Roughometer, and visual inspection annually from 1989 to 1992. Some key findings from the field testing were as follows: (a) Test sections stabilized with BIO CAT300-1 and Consolid system showed the highest average k-value (207 pci to 225+ pci) four years after construction. HFE-300 stabilized section showed an average k-value of 181 pci, macadam subbase section showed an average k-value of 172 pci, and macadam subbase with fabric section showed an average k-value of 116 pci, four years after construction. (b) Although the BIO CAT 300-1 and Consolid System stabilized sections showed high k-values, they showed poor performance with alligator cracking and rutting under traffic, and continued deterioration every year. It is speculated in the report that these failures could have been due to freeze-thaw cycles in the stabilized layers. (c) HFE-300 treated test sections showed some deterioration with alligator cracking. Macadam subbase test sections (with and without fabric) experienced minor rutting and showed the best overall performance than all other sections. The use of fabric did not show noticeable improvement. (d) Use of macadam base and HFE-300 treatment showed cost effectiveness than other treatment options evaluated in this study.

Kestler, M. A. (2009). "Stabilization selection guide for aggregate and native-surfaced low-volume roads." National Technology and Development Program, Forest Service, U.S. Department of Agriculture, Washington, D.C.

The purpose of this guide is to facilitate the selection of modification/stabilization agents and techniques for aggregate surfaced and native/unsurfaced LVRs. The objective is to provide low-cost alternatives that reduce aggregate wear and loss, reduce road-surface maintenance (i.e., blading out ruts), and reduce the time period between major rehabilitation (i.e., between adding new aggregate and the total reconditioning of the road pavement). This guide provides information on available stabilizing agents, appropriate conditions for use, selection procedures, quantity determination, and contact information for manufacturers/suppliers. Emphasis is on the modification/stabilization of existing in-place road surface materials, but many of the methods can be used in the construction of new roads. Construction procedures for application are also presented. The intended audience includes road managers, engineers, and technicians involved in road maintenance, construction, and reconstruction. Those involved in trail maintenance and construction also may find the guide beneficial, as stabilizers used on trails, particularly accessible trails, help provide a smooth, durable surface.

Lynam, D., and Jones, K. (1979). "Pavement surface on macadam base - Adair County." Project HR-209, Iowa Department of Transportation, Ames, Iowa.

The IHRB HR-209 research project evaluated the feasibility and economics of using macadam subbase material (without choke stone) under PCC and asphalt pavements. The macadam subbase material used on this project had a typical gradation with 3 in. maximum particle size and < 1% passing the #8 sieve. Field testing was conducted using Road Rater testing and visual crack/distress surveys. Some key findings from this study were as follows: (a) Road Rater testing indicated that the structural rating of a PCC pavement is improved if macadam subbase is used under the pavement. However, the improvement structural rating from using 5 in. of macadam subbase is equivalent to about additional ½ or ¾ in. PCC. The macadam subbase served primarily as a drainage layer and therefore could be reduced to 3.5 to 4 in. thickness instead of 5 in. Asphalt treating the macadam stone could be of additional benefit for stability of the base. (b) 2 to 3 in. thick PCC pavements over 5 in. macadam subbase showed poor performance and low structural rating. It is indicated that a minimum 5.5 in. PCC pavement is required over macadam to obtain 20 year design life. (c) Macadam served as a good drainage layer and prevented D-cracking on PCC pavements (within the 5 years of evaluation), which was a common problem in the area with using Class 1 aggregate (which contained fines). (d) Significant allowance should be made for material overruns when placing either PCC or asphalt pavement on macadam without chokestone (215 cubic yards per mile for PCC). (E) The quarry must be in close proximity for the project (within 10 to 20 miles) for macadam stone base to be economically practical.

Newman, J. K., and White, D. J. (2008). "Rapid Assessment of Cement and Fiber-Stabilized Soil Using Roller-Integrated Compaction Monitoring." Transportation Research Record: Journal of the Transportation Research Board, 2059, 95-102.

Test sections of high-early strength (Type III) portland cement and polypropylene monofilament fibers were constructed at the Bradshaw Field Training Area in the Northern Territory (NT), Australia as part of a Joint Rapid Airfield Construction (JRAC) project. Aprons, taxiways, and a helipad were stabilized using these materials in combination with screened

native soil. The purpose of the test sections was to (a) evaluate the resulting properties for different stabilization dosage rates; (b) develop construction methods, criteria (including limits), and quality control guidelines; and (c) provide a hands-on training opportunity for the joint United States and Australia military construction team. Testing and monitoring consisted of roller-integrated compaction monitoring (global position systems monitoring pass coverages and compaction machine values) and in situ testing, which included dynamic cone penetration tests, Clegg impact tests, and light-weight deflectometer tests. After the test sections, construction of the helipad helped refine the construction methods and quality control testing for the selected stabilization dosage rates and machine speed. Lessons learned on the helipad were applied to the subsequent aircraft parking aprons and taxiways. Recommendations were developed for rapid stabilization construction procedures and quality control testing using Clegg impact values and light-weight deflectometer for cement-fiber stabilized soils, and the application of roller-integrated compaction technology was demonstrated to document compaction effort and uniformity.

Rollings, M. P., and Rollings, R. S. (1996). Geotechnical Materials in Construction, McGraw-Hill, New York, NY.

Chapter 6 of this book provides information on Stabilization: Seldom does nature provide the ideal soil or aggregate for construction. To overcome deficiencies in soil or aggregate properties such as poor grading, excess plasticity, or inadequate strength, we may blend two or more soils together, or we may add stabilizing admixtures such as lime, Portland cement, or bituminous materials to the soil or aggregates. These techniques are effective if we can readily mix the materials. Other techniques for improving soil conditions at depth will be covered in Chap. 7. We often think of stabilization as a method of providing structural strength, but it can have a number of other construction and behavioral effects that are equally beneficial. These might include improved soil workability, an all-weather construction platform, or reduced swelling of expansive materials. Stabilization may improve the properties of an on-site or local material to allow its use rather than incurring the cost of importing a better material from a distant source. In the following sections we will examine the effects of blending and stabilizing with lime, portland cement, bituminous materials, pozzolanic and slag materials, and specialty admixtures.

Specifications/Contract Related Aspects

Cabana, G., Liautaud, G., and Faiz, A. (1999). "Areawide Performance-Based Rehabilitation and Maintenance Contracts for Low-Volume Roads." Transportation Research Record: Journal of the Transportation Research Board, 1652, 128-137.

To address internal inefficiency and accountability issues, a number of Latin American countries have moved decisively and successfully over the last decade from force-account (direct labor) to contract maintenance. Also, there has been considerable progress in the region in transferring to the private sector, through concessions, the responsibility for improving, maintaining, and operating high-traffic-volume roads, the cost of which is recovered from tolls. Argentina, Brazil, and Chile are among the most advanced countries in this respect. More recently, some countries-particularly Argentina-have switched from the traditional quantities and unit price-based short-term maintenance contracts to long-term performance-type or results-based contracts. The new approach encompasses either routine maintenance activities alone or integrated contracts involving both the rehabilitation and routine maintenance of road networks. The latter form, the so-called CREMA system (Contrato de Recuperacion Mantenimiento), is now being implemented in Argentina and covers approximately 12 000 km (i.e., about 40 percent of the national paved road network). Such contracts comprise the rehabilitation and subsequent maintenance over a 5-year period of 200-km- to 300-km-long subnetworks. A framework for extending the CREMA concept to low volume roads is presented. The means by which this newly developed system could be extended to cover both the paving and future maintenance of low-volume roads is explained. Reasons are analyzed as to why this type of contract, which extends the contractor's share of responsibility over a relatively long period of time, would be well suited to the specific design and construction features of low-cost, low-volume paved roads-in particular, in the risks related to uncertain traffic projections and in the use of local or nontraditional materials in thin pavement structures. Finally, issues related to the use of the CREMA system-especially the need to prepare adequate contract bidding documents, conduct proper bid proposal evaluations, and monitor contractor's performance during the rehabilitation/paving and maintenance phases-are explored.

Foye, K. C. (2011). "Use of reclaimed asphalt pavement in conjunction with ground improvement: A case history." Advances in Civil Engineering, Hindawi Publishing Corporation, 2011(Article ID808561).

The use of Reclaimed Asphalt Pavement (RAP) in lieu of virgin crushed stone aggregate is becoming a widely accepted practice for a number of construction applications, particularly pavement base courses. A number of laboratory RAP studies have considered the mechanical properties of RAP bases in order to support pavement designs incorporating RAP. These studies have revealed a number of interesting relationships between RAP moisture content, compaction, and stiffness. This paper discusses the experiences of a design-build contractor integrating a geosynthetic ground improvement program with a RAP base during the reconstruction of a 1.95 ha asphalt parking lot. Field observations of base course construction with RAP explore some of the implications of laboratory findings. A number of interesting observations on the technical, construction, and economic issues resulting from the project challenges and the use of RAP are presented.

Glogowski, P. E., Kelly, J. M., McLaren, R. J., and Burns, D. L. (1992). "Fly Ash Design Manual for Road and Site Applications - Volume 1: Dry or Conditioned Placement." TR-100472, GAI Consultants, Inc., Palo Alto, California.

This design manual describes the use of fly ash as a construction material for use as structural and nonstructural fills, backfills, embankments, base courses, and roller compacted concrete dams and pavements, soil stabilization, land reclamation and other high volume uses. The manual details the physical, engineering and chemical properties of bituminous, subbituminous and lignite fly ash. Included are field and laboratory testing methods, design data, procedures and examples, specifications, quality control, and pre- and post-construction monitoring. Volume 1 describes uses where fly ash is used dry or conditioned with small amounts of moisture. Volume 2 describes uses where fly ash is placed as a slurry with relatively large amounts of water. The manual is primarily the result of editing and updating previous publications. High volume ash utilization has been documented in various manuals. These publications have been produced by several agencies including EPRI, Federal Highway Administration (FHWA), American Coal Ash Association (ACAA) and others. However, many of these publications were produced several years ago and are not readily available. Also, the information was published by several sources at various times. Therefore, these earlier publications are summarized and updated in this manual with state-of-practice design methods for use by design engineers. References to additional sources of information are provided.

McHattie, R. L. (2010). "Evaluating & Upgrading Gravel Roads For Paving." Alaska Department of Transportation.

Scenario: The Matanuska-Susitna Borough wants to consider paving an existing gravel road. As a Borough engineer you are assigned to develop and/or manage such a project. The road must handle only light, local traffic, and you would therefore like to pave it at the lowest possible cost. As an engineer you need a comfortable degree of confidence that you can properly design the new pavement, and that it can be justified, economically and otherwise. Is it possible to simply go ahead and apply new hot mix asphalt concrete or an asphalt surface treatment (AST) pavement to that old gravel road surface? For a number of good reasons that would not be prudent. As the engineer assigned to the project, your involvement begins with a couple of basic questions: (a) Is the Borough committed to a road management program, including new maintenance and load restriction policies that will sustain the service life of the new pavement? (b) Have you considered the public's opinions, user costs, and safety issues? You must answer these questions before this engineering guide will be of use. Then, in order to provide Borough management with realistic estimates of economic feasibility, and design requirements, you must answer these questions: (a) Do predicted traffic levels confirm that asphalt concrete pavement is appropriate? (b) What kind of asphalt pavement is best? (c) Are you prepared, in terms of engineering time and resources, to evaluate and upgrade the existing gravel road, as necessary, to obtain a predictable service life? (d) Is the candidate gravel road in nearly good enough condition to receive pavement? (e) Does the existing road need to be significantly upgraded prior to paving? (f) If upgrading is needed, what type and how much is necessary? These latter questions are directly related to evaluating the existing gravel road and designing for a new asphalt pavement surface — the subject of this guide.

QC/QA Testing

Addison, M. B., and Polma, F. A. (2007). "Extending Durability of Lime Modified Clay Subgrades With Cement Stabilization." GSP 172 Soil Improvement, V. R. Schaefer, G. M. Filz, P. M. Gallagher, A. L. Sehn, and K. J. Wissmann, eds., ASCE, Denver, Colorado.

Many municipalities and private owners have faced increased pavement maintenance and replacement costs when lime modified clay subgrades prematurely fail. Preliminary laboratory test results determined that the typical lime treatment (7% by dry weight) used by the City of Garland, TX was approximately one-half the amount of lime necessary to permanently stabilize a high P.I. (39) clay. Further laboratory and a field testing program was then undertaken to determine if an economical alternative to 14% lime could be used to extend the durability of street subgrades. Four test sections were constructed using various combinations of lime to pre-treat the clays before stabilizing with cement. The testing program revealed that using combinations of lime and cement increased the typical subgrade durability based upon 4.8 to 5.7 times greater strengths after one year of exposure to in-place conditions. In addition, 28 day moist cured then saturated samples had 3.7 times greater compressive strength and 3.5 times better strength following 12 cycles of wetting and drying after 4 months of moist curing.

Aho, S., and Saarenketo, T. (2006). "Design and repair of roads suffering spring thaw weakening." The Swedish Road Administration, Northern Region, Sweden.

The ROADEX Project is a technical cooperation between roads organizations across northern Europe that aims to share roads related information and research between the partners. The Project was started in 1998 as a 3 year pilot co-operation between the roads districts of Finnish Lapland, Troms County of Norway, the Northern Region of Sweden and The Highland Council of Scotland and this was later followed up with a second project, ROADEX II, from 2002 to 2005. The partners in the ROADEX II Project comprised public road administrations, forestry organizations, forest companies and haulage organizations from regions in the Northern Periphery. These were The Highland Council, Forest Enterprise & The Western Isles Council from Scotland. The Region Nord of The Norwegian Public Roads Administration and The Norwegian Road Haulage Association, The Northern Region of The Swedish Road Administration and The Lappi and Keski-Suomi Regions of The Finnish National Roads Administration. (These latter Finnish Regions also received aid from their local forest industry organizations of Metsähallitus, Lapin Metsäkeskus, Metsäliitto & Stora-Enso.). The goal of the project was to develop ways for interactive and innovative road condition management of low traffic volume roads integrating the needs of local industry, society and roads organizations. 8 formal reports were published together with a project DVD and full copies of all reports are available for download at the ROADEX web site at www.roadex.org. This Executive Summary report is one of 8 summaries that have been prepared under the direction of the ROADEX III project (2006-2007), a new Project where the named project Partners above were joined by the additional Northern Periphery Partners of the Municipality of Sisimiut, Greenland, The Iceland Public Roads Administration and the Finnish Road Administration Region of Savo-Karjala.

Aiban, S. A., Wahhab, H. I. A., Al-Amoudi, O. S. B., and Ahmed, H. R. (1998). "Performance of a stabilized marl base: a case study." Construction and Building Materials, 12, 329-340.

The formation of depressions and settlement in roads shortly after being constructed is one of the major challenges facing the road authorities in the Arabian Gulf States. Such problems have been closely related to the nature of pavement materials and loading conditions as well as to the proximity of groundwater tables to the surface. A major road in eastern Saudi Arabia was reported for frequent deterioration even when the construction was properly carried out. A preliminary investigation was conducted to quantify the properties of the base course material i.e. marl soil, and the cause of failure. The laboratory investigation indicated that the marl used in the construction, similar to other marls, has acute water sensitivity and loss of strength whenever the soil is inundated. A precautionary and immediate solution was proposed to stabilize the soil with cement. Consequently, a comprehensive laboratory program was carried out to assess the performance of cement-stabilized marl mixtures under different exposure conditions. Based on the laboratory results and the traffic data for the road under investigation, four sections were constructed, two of them being without any additive while in the other two the base course being treated with 4% cement. Continuous monitoring and evaluation of the four sections for 4 years indicated that the cement-treated road sections have exhibited superior performance over the untreated ones. Unlike the untreated sections, which have experienced various forms of deterioration within a few months after construction, the stabilized sections are still in an excellent condition.

Al-Qadi, I. L., and Appea, A. K. (2003). "Eight-Year Field Performance of Secondary Road Incorporating Geosynthetics at Subgrade-Base Interface." Transportation Research Record: Journal of the Transportation Research Board, 1849, 212-220.

In June 1994 an instrumented 150-m-long secondary road pavement section was built in Bedford County, Virginia. This pavement section was composed of nine individual segments each 15 m long. The nine sections include three groups with aggregate base layer thicknesses of 100, 150, and 200 mm. Three sections from each group were stabilized with geotextiles and three were stabilized with geogrids at the base-sub grade interface. The remaining three sections were kept as control sections. As part of the structural analysis, deflection data parameters such as the base damage index and surface curvature index calculated from falling weight deflectometer (FWD) data were analyzed after being corrected for temperature variations from the time of construction until October 2001. Performance criteria such as rutting measurements were also collected over the whole period. A nonlinear exponential model was used to describe the development of rutting versus cumulative equivalent single-axle loads for the 100-mm base course. A linear elastic program incorporating constitutive material properties was used to calculate vertical compressive stresses, which were used with FWD deflections to predict rutting rates with a mechanistic equation. The rutting rate results confirmed the separation function of geosynthetics that prevented the migration of fines from the subgrade to the base course layer and the penetration of the aggregate base layer into the subgrade. Rutting results, deflection data, and service life analysis showed that geosynthetically-stabilized sections significantly improved the performance of the 100-mm base course sections.

Arnold, G. (1999). "Design of Rehabilitation Treatments for New Zealand's Thin-Surfaced Unbound Granular Pavements." Transportation Research Record: Journal of the Transportation Research Board, 1652, 42-50.

Most thin-surfaced unbound granular pavements are rehabilitated by overlaying with an unbound granular material and surfaced with a chip seal (thin-surfacing). The unbound granular overlay thickness is the difference between the total granular thickness required for future traffic and the granular thickness required for past traffic as determined from the design chart. However, where there are signs of shoving or other indications of a weak and degraded aggregate base layer then a smoothing treatment will not be adequate. For this situation the appropriate rehabilitation is either in situ stabilization (to improve the strength of the aggregate base material) or to cover with a minimum thickness of unbound granular material (determined from the thickness design chart by assuming the existing pavement acts as a subbase). This method of unbound granular overlay design has resulted in significant cost savings over the past 20 years in rehabilitation treatments for New Zealand roads, as the existing pavement has been fully utilized. In 1995 New Zealand adopted the Austroads (the Association of State, Territory and Federal Road and Traffic Authorities in Australia) procedures for pavement design. The Austroads procedures encourage the use of mechanistic procedures for pavement design. By using the same assumptions as the design chart method for determination of granular overlay depths, a mechanistic design procedure for rehabilitation treatments was developed. This method produces comparable results and has the advantage of being able to design a range of rehabilitation treatments.

Austroads (1998). "Guide to stabilisation in roadworks." Austroads, Sydney, A4, New Zealand.

This Guide provides systematic guidance to practitioners for the selection, design and construction of stabilised pavement layers for use in the construction of new road pavements and

the maintenance, rehabilitation and recycling of existing road pavements. It replaces the 1986 NAASRA Guide to Stabilisation in Roadworks. Since the NAASRA Guide was published, there have been substantial improvements in many aspects of stabilisation technology including: (1) improved pavement design procedures; (2) improved materials characterisation procedures; (3) higher capacity plant and equipment; (4) wider range of stabilisation agents with greater effectiveness; and (5) increased environmental awareness of the benefits of stabilisation. Guidance is given to assist the practitioner to select the appropriate type of stabilisation for a particular application as well as materials and pavement design guidance for the following broad types of stabilisation techniques: cementitious stabilisation, lime stabilisation, bituminous stabilisation, granular stabilisation, and other forms of stabilisation. Construction and quality management issues are also addressed. While there have been significant advances in stabilisation technology in the past decade, there are still a number of areas in need of greater understanding including: materials mix design and characterisation, erosion mechanisms, long term strength gains, and stabilisation under traffic. While the information given in the Guide is considered to represent best practice at the time of publication, with the current rate of change of stabilisation technology, it will continue to improve in the future.

Bassel, J. R., Edwards, A., Leibbrand, L., Keller, G. R., and Dauer, W. (1999). "Three road-crushing demonstration projects." Transportation Research Record: Journal of the Transportation Research Board, 1652.

At the Sixth International Conference on Low-Volume Roads Yves Provencher, Forest Engineering Research Institute of Canada, presented a paper on the F.A.H.R. rock crusher mounted to a front-end loader. At the same time the Coronado National Forest in Arizona was renting a F.A.H.R. rock crusher for an in-place road-crushing project. In 1997 San Dimas Technology and Development Center, in partnership with the Coronado National Forest, sponsored two demonstration projects to further test the crusher at unique locations to gain additional information from actual field trials. These projects were located on the Rio Grande National Forest in Colorado and the Plumas National Forest in California. The three projects are described here, with results and conclusions gained from the demonstration projects. The concentration is on the characteristics of the processed material. Samples taken from windrows during the crushing operation were tested to determine hardness and gradations before and after crushing. Cost varied from $8 to $26 per m3 including roadbed preparation, crushing, and blading. Rocks and boulders to 405-mm maximum size were crushed. The processed material has a maximum size of 50 to 75 mm. The product produced by the crusher offers a viable alternative for aggregate on a road surface, particularly as a road surface cushion material, where the quality and expense of standard crushed aggregate, such as base course material, are not needed on low-volume roads.

Behak, L. (2011). "Performance of Full-Scale Test Section of Low-Volume Road with Reinforcing Base Layer of Soil–Lime." Transportation Research Record: Journal of the Transportation Research Board, 2204, 158-164.

The roads of the rice region of Merin Lake in Uruguay are subjected to low annual average traffic. However, the average daily traffic is approximately 100 trucks during harvest time. The local soils, characterized as clayey silts, are unsuitable for such traffic demands and are generally replaced or reinforced by materials found more than 70 km away, with high transportation costs. An investigation of the performance of a full-scale test section of pavement with a base layer of local silty clay soil stabilized with lime was conducted. The design of the test section consisted of soil selection, determination of lime content for stabilization, compaction, and California bearing ratio laboratory tests. Two test sections, each 50 m, were built, with a base layer of selected soil mixed with 3% lime in one section and with 5% lime in the other. After the rice harvest, the performance of the test sections was evaluated by visual observation of the base layer and deflection measures with a Benkelman beam. Despite some construction difficulties, the deflection average values changed from 244 x 10−2 cm immediately after the section was built to 77 x 10−2 cm 4 months later. The use of soil–lime material for base layers of low-volume roads is a technical and economical alternative that provides a significant improvement of the rural road network with socioeconomic benefits.

Benson, C. H., Edil, T. B., Tanyu, B. F., and Kim, W.-H. (2005). "Equivalency of Crushed Rock with Industrial By-Products and Geosynthetic-Reinforced Aggregates Used for Working Platforms during Pavement Construction." WHRP Final Report No. 0092-00-12, Department of Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, WI.

A study was conducted to define an equivalency criterion for five materials used for working platforms during pavement construction on a poor subgrade: conventional crushed rock (referred to as “breaker run”) and four alternatives (i.e. Grade 2 granular backfill (referred to as “Grade 2”), foundry slag, bottom ash, and foundry sand). Total deflection data for the equivalency assessment were obtained from a large-scale model experiment (LSME) simulating a prototype-scale pavement structure and in the field using a rolling wheel deflectometer (RWD). Design charts were developed for selecting the equivalent thickness of alternative working platform materials so that the alternative provides equal deflection as a layer of breaker run. Another phase of the study was conducted to determine the equivalency of geosynthetic reinforced aggregate working platforms in providing support during pavement construction over soft subgrade. Four reinforcing geosynthetics (a geogrid, a woven geotextile, a non-woven geotextile, and drainage geocomposite) incorporated into two granular materials: Grade 2 and breaker run were used in this study. Design charts were developed for selecting the equivalent thickness of an alternative geosynthetic-reinforced working platform material so that the alternative provides equal deflection as a layer of breaker run.

Bergeson, K. L., Kane, M. J., and Callen, D. O. (1990). "Crushed stone granular surfacing materials." Sponsored by the Iowa Limestone Produces Association and National Stone Association Research Program, Report by Engineering Research Institute, Iowa State University, Ames, Iowa.

The results of this research project indicate that crushed stone surfacing material graded on the fine side of IDOT Class A surfacing specifications provides lower roughness and better rideability; better braking and handling characteristics; and less dust generation than the coarser gradations. This is believed to be because there is sufficient fines (-#40 to - #200) available to act as a binder for the coarser material, which in turn promotes the formation of tight surface crust. This crust acts to provide a smooth riding surface, reduces dust generation, and improves vehicle braking and handling characteristics.

Bhatty, J. I., Bhattacharja, S., and Todres, H. A. (1996). "Use of cement kiln dust in stabilizing clay soils." Portland Cement Association, Skokie, Illinois.

This report is part of an overall Portland Cement Association (PCA) project on the role of cement kiln dust (CKD), portland cement, and lime in the stabilization of clay soils. In this report, the term "clay soils" means soils having a variable clay content which normally manifests itself by causing the soil to have undesirable properties from an engineering point of view. The effect of the clay can thus be considered to be due to a combination of the clay's activity (plasticity, volume change, etc.) and its proportion of the whole. In a few special cases, non-clay soils have been stabilized using CKDs; clearly the mechanism of the stabilization is different for these soils. These cases are referenced in this report for completeness, and are differentiated from clay soils. Because of the (sometimes) high lime content and the fineness of CKD particles, the use of dust in stabilizing highly expansive clay soils for subbase and related applications is getting increased attention. Literature suggests that CKD enhances many of the engineering properties of the sub grade soils, and reduces the swelling potential of expansive clays. However, available information on the use of CKD for such applications is preliminary, isolated, and lacks quantitative data, as most of the work has been done only on selected soils and selected CKDs. It has been suggested that in order to have an insight on the stabilization potential of CKD and a complete understanding of the underlying mechanism, comprehensive and systematic studies on CKD-soil stabilization are needed. This would require a selection of CKDs from different plant operations, and a selection of sub grade soils and expansive clays. The effect of CKD on the engineering properties needs to be optimized and compared with traditionally used stabilizing agents such as hydrated lime, fly ash, and portland cement.

Christoffersson, P., and Johansson, S. (2011). "Rehabilitation of the Forest Road Timmerleden." A ROADEX demonstration report, The Swedish Transport Administration, Northern Region, Sweden.

The European Union ROADEX Project 1998 – 2012 was a trans-national roads cooperation that aimed at developing ways for interactive and innovative management of low volume roads across the European Northern Periphery. Its main goals were to facilitate co-operation and research into the common problems of constructing and maintaining low volume roads in harsh climates. This report gives a summary of a local demonstration of ROADEX methods for assessing forest roads for heavy timber traffic and based on the results making a rehabilitation design proposal. Using the ROADEX-method the road was first surveyed using the modern non-destructive road survey techniques of video, ground penetrating radar and falling weight deflectometer. Three samples were also taken to check the grading and to verify the GPR-results. Following this an integrated analysis was carried out using Road Doctor software to produce a strength assessment of the road. The results were then used to do an analytical design of the strengthening measures needed to carry the load from the timber trucks. The ROADEX method was compared to regular road condition assessments and rehabilitation proposals from the project partners: The Swedish Forest Agency and the forest companies Sveaskog and SCA Forest. The partners used their normal procedures for field surveys, analyses and design. The comparison included: (1) Design, (2) Volumes of road materials used, (3) Environmental influence, (4) costs for design, materials, construction, and environmental impacts. The results demonstrate that making a more careful road condition investigation and an analytical road rehabilitation design based on the road condition analyses, can reduce the overall rehabilitation costs.

Christoffersson, P., and Johansson, S. (2012). "Rehabilitation of the Timmerleden Forest Road - Condition Survey, Design Proposals, Construction and Quality Control." A ROADEX demonstration report, The Swedish Transport Administration, Northern Region, Sweden.

The European Union ROADEX Project 1998 – 2012 was a trans-national roads cooperation that aimed at developing ways for interactive and innovative management of low volume roads across the European Northern Periphery. Its main goals were to facilitate co-operation and research into the common problems of constructing and maintaining low volume roads in harsh climates. This report gives a summary of a local demonstration of ROADEX methods for assessing forest roads for heavy timber traffic and based on the results making a rehabilitation design proposal. The report also gives a short description of the construction of the rehabilitation and the quality control. Using the ROADEX-method the road was first surveyed using the modern non-destructive road survey techniques of video, ground penetrating radar and falling weight deflectometer. Three samples were also taken to check the grading and to verify the GPR-results. Following this an integrated analysis was carried out using Road Doctor software to produce a strength assessment of the road. The results were then used to do an analytical design of the strengthening measures needed to carry the load from the timber trucks. The ROADEX method was compared to regular road condition assessments and rehabilitation proposals from the project partners: The Swedish Forest Agency and the forest companies Sveaskog and SCA Forest. The partners used their normal procedures for field surveys, analyses and design. The comparison included: (1) Design, (2) Volumes of road materials used, (3) Environmental influence, (4) costs for design, materials, construction, and environmental impacts. To make the ROADEX forest road rehabilitation package complete a quality control was carried out to check if the measures were done right in place, if the layer thicknesses were constructed in accordance with the design and if the bearing capacity target was reached. New GPR- and FWD surveys were carried out about a month after the rehabilitation work was finished. It was found from the GPR survey that measures were very well in place but in some places the base course was a little thinner than the design thickness. A new calculation in accordance with the Odemark method based on the new survey results showed that 98 % of the road length met the bearing capacity target of 90 MPa. The results demonstrate that making a more careful road condition investigation and an analytical road rehabilitation design based on the road condition analyses, can reduce the overall rehabilitation costs and the environmental impacts significantly. The demonstration project has shown that the use of the ROADEX method in this case reduced the costs between 15 and 50%.

Christopher, B. R., Hayden, S. A., and Zhao, A. (2000). "Roadway base and subgrade geocomposite drainage layers." Testing and Performance of Geosynthetics in Subsurface Drainage, ASTM STP1390, L. D. Suits, J. B. Goddard, and J. S. Baldwin, eds., ASTM, West Conshohocken, PA.

The Maine Department of Transportation (DOT) in conjunction with the University of Maine and the U.S. Army Cold Regions Research Laboratory evaluated the use of a special geocomposite drainage net as a drainage layer and capillary barrier (to mitigate frost heave) on a section of road plagued with weak, frost-susceptible subgrade soils and poor pavement performance. The special geocomposite drainage net that is being used has a higher flow capacity than conventional geonets and, based on tests performed by the University of Illinois, does not deform significantly under heavy traffic loading. For the 425-m-long test section, the geonet drainage geocomposite was placed horizontally across the entire roadway but varied in vertical location to form three separate subsections for evaluating drainage of 1) the base coarse aggregate, 2) the asphaltic concrete pavement, and 3) the subgrade to allow for a capillary break in order to reduce frost action. An integral drainage collection system was installed to collect the water flowing in the geonet. This paper includes a project description, material and construction specifications, installation procedures, instrumentation, and test results based upon two seasons of monitoring. Laboratory characterization and performance testing initially used to evaluate the geocomposite are compared with the monitored results.

Collings, D., Lindsay, R., and Shunmugam, R. "LTPP Exercise on a Foamed Bitumen Treated Base - Evaluation of Almost 10 Years of Heavy Trafficking on MR504 in Kwazulu-Natal." Proc., 8th Conference on Asphalt Pavements for Southern Africa (CAPSA'04), Document Transformation Technologies.

Situated halfway between the cities of Pietermaritzburg and Durban, Provincial Main Road (MR) 504 provides primary access to a large asphalt plant, a commercial quarry and a pre-cast concrete products factory. A 700m section of this road, located on a steep gradient (+10%), was upgraded to blacktop standards during 1995 by constructing a single layer of foamed bitumen treated material on top of a prepared subbase layer. The single slurry seal that was applied soon after construction proved adequate for three years before requiring a competent surfacing. This road provides an ideal opportunity for assessing the performance of what was originally termed an "experimental" pavement. The relevant traffic that this pavement has carried is estimated from dispatch records at each of the plants. In addition to as-built data, information is available from investigations that were carried out in 1997 by the CSIR Transportek Division, commissioned by the Provincial Department of Transport to evaluate this and other pavements with foamed bitumen treated bases. This information is reviewed and supplemented by additional surveys and tests conducted in the first quarter of 2004. This paper portrays the change that has taken place in the pavement between the time it was constructed, two years after trafficking, and again six years later. Deflection data is used as a primary measure of changing conditions. Additional tests include those carried out on cores extracted from the foamed bitumen treated base, test pit excavations and a DCP survey. Prediction models that were compiled in 2002 from HVS trials on foamed bitumen treated materials are also reviewed. As the first LTPP exercise on a foamed bitumen treated material, this paper endeavours to portray the difference between the condition of a such material in a pavement subjected to continuous HVS loading over a short time period compared to heavy trafficking over an extended period of nine years.

DOD (1985). "Pavement design for seasonal frost conditions." Technical Manual No. 5-818-2, Air Force Manual No. 88-6, Chapter 4, Departments of the Army and Air Force, Washington, D.C.

This manual presents criteria and procedures for the design and construction of pavements placed on subgrade or base course materials subject to seasonal frost action. The criteria are applicable to Air Force and Air National Guard airfields, and to roads. This manual is concerned with modes unique to frost areas. The principal non-traffic-associated distress modes are distortion caused by frost heave and reconsolidation, and cracking caused by low temperatures. The principal traffic-load-associated distress modes are cracking and distortion as affected by the extreme seasonal changes in supporting capacity of subgrades and bases that may take place in frost areas.

Drake, A. (2012). "Gleann Mor Forest Road Argyll and Bute, Scotland." A ROADEX "Implementing Accessibility" Project, The Swedish Transport Administration, Northern Region, Sweden.

The ROADEX Project was a technical co-operation between road organisations across northern Europe that aimed to share road related information and research between the partners. The project was started in 1998 as a 3 year pilot co-operation between the districts of Finnish Lapland, Troms County of Norway, the Northern Region of Sweden and The Highland Council of Scotland and was subsequently followed and extended with a second project, ROADEX II, from 2002 to 2005, a third, ROADEX III from 2006 to 2007 and a fourth, ROADEX “Implementing Accessibility” from 2009 to 2012. The Partners in the ROADEX “Implementing Accessibility” project comprised public road administrations and forestry organisations from across the European Northern Periphery. These were The Highland Council, Forestry Commission Scotland and the Western Isles Council from Scotland, The Northern Region of The Norwegian Public Roads Administration, The Northern Region of The Swedish Transport Administration and the Swedish Forest Agency, The Centre of Economic Development, Transport and the Environment of Finland, The Government of Greenland, The Icelandic Road Administration and The National Roads Authority and The Department of Transport of Ireland. The aim of the project was to implement the road technologies developed by ROADEX on to the partner road networks to improve operational efficiency and save money. The lead partner for the project was The Swedish Transport Administration and the main project consultant was Roadscanners Oy of Finland. A main part of the project was a programme of 23 demonstration projects showcasing the ROADEX methods in the Local Partner areas supported by a new pan-regional “ROADEX Consultancy Service” and “Knowledge Centre”. Three research tasks were also pursued as part of the project: D1 “Climate change and its consequences on the maintenance of low volume roads”, D2 “Road Widening” and D3 “Vibration in vehicles and humans due to road condition”. The following are lessons learned from the project: Most of the older Forestry Commission forest roads have had temporary repairs to keep the timber moving, and sections have been completely reconstructed following landslides etc. During these and subsequent maintenance operations, different sources and types of stone have been used which can make GPR interpretation of layer depths challenging. It is also true to say that although the performance specification of the FC timber haulage roads is the same throughout England, Scotland and Wales, ground conditions and materials are extremely variable so the structural composition of roads can be totally different from area to area. Therefore, the establishment of appropriate area parameters using local knowledge and ground truth is important. The FWD testing procedure is intended for hard road surfaces. URS Scott Wilson has confirmed that when the surface of a forest road is soft, it can be difficult to achieve a 50 kN load as some of the force is actually absorbed by the road. Consequently, FWD work should be carried out in dry conditions but this can only be aspirational in Scotland! (Note: In Sweden FWD measurements are carried out in the spring after the frost has gone. It has been found that if measurements are taken in the middle of a dry summer the values might be too good.) It is difficult to get consistent dielectric value readings from the sides of an excavated trench using the Adek Percometer. This survey and assessment method has subsequently been used to analyse a totally new forest road which was built to a carefully designed and monitored specification. The Stone Depth analysis procedure showed that no additional stone was required at any point. The Forestry Commission have also surveyed a road formation with no pavement at all. The same procedure showed that not only was stone required along the entire length of the alignment, but it also calculated the depths and volumes. These results were as expected and they have established an "envelope" within which all other survey data from existing forest roads should fall. Surveys to-date have given the Forestry Commission confidence in the efficacy of the technique and the next stage of the project will be to develop improved site procedures. The aim will be to devise a method of applying the survey outputs on future roads in a manner which not only closely relates to the calculated lengths, depths and volumes but which is also practical to set out and control.

Edil, T. B., Benson, C. H., Bin-Shafique, M. S., Tanyu, B. F., Kim, W.-H., and TSenol, A. (2002). "Field Evaluation of Construction Alternatives for Roadways over Soft Subgrade." Transportation Research Record: Journal of the Transportation Research Board, 1786, 36-48.

Alternative methods for providing a stable platform over soft subgrades were evaluated using a 1.4-km section along a Wisconsin State highway that incorporated 12 test sections to evaluate 9 different stabilization alternatives. A variety of industrial by-products and geosynthetics were evaluated for stabilization. The industrial by-products included foundry slag, foundry sand, bottom ash, and fly ash as subbase layer materials. The geosynthetics included geocells, a nonwoven geotextile, a woven geotextile, a drainage geocomposite, and a geogrid. The same pavement structure was used for all test sections except for the subbase layer, which varied depending on the properties of the alternative material being used. All test sections were designed to have approximately the same structural number as the conventional pavement structure used for the highway, which included a subbase of granular excavated rock. Observations made during and after construction indicated that all sections provided adequate support for the construction equipment and no distress was evident in any part of the highway. Each of the alternative stabilization methods, except a subbase prepared with foundry sand, appear to provide equivalent or greater stiffness than that provided by control sections constructed with excavated rock. However, the foundry sand subbase is providing adequate support. Analysis of leachate collected from the base of the test sections shows that the by-products discharge contaminants of concern at very low concentrations.

Embacher, R. A. (2006). "Duration of Spring-Thaw Recovery for Aggregate-Surfaced Roads." MN/RC-2006-12, Minnesota Department of Transportation, St. Paul, Minnesota.

Low-volume roads constructed in regions susceptible to freezing and thawing periods are often at risk of load-related damage during the spring-thaw period. The reduced support capacity during the thawing period is a result of excess melt water that becomes trapped above the underlying frozen layers. Many agencies place spring load restrictions (SLR) during the thaw period to reduce unnecessary damage to the roadways. The period of SLR set forth by the Minnesota Department of Transportation is effective for all flexible pavements; however, experience suggests that many aggregate-surfaced roads require additional time relative to flexible pavements to recover strength sufficient to carry unrestricted loads. An investigation was performed to improve local agencies' ability to evaluate the duration of SLR on aggregate-surfaced roadways. This was accomplished through seasonal measurements of in situ shear strengths, measured using the dynamic cone penetrometer (DCP), on various Minnesota county routes. In situ strength tests were conducted on selected county gravel roads over the course of three years. Strength levels recorded during the spring-thaw weakened period were compared to fully recovered periods that typically occur in late spring/summer. The results indicate that aggregate-surfaced roads generally require 1 to 3 additional weeks, over that of flexible pavements, to reach recovered bearing capacity. Additionally, a strong correlation was found

between duration required to attain given strength recovery values and climatic and grading inputs.

Fannin, R. J., and Sigurdsson, O. (1996). "Field observations on stabilization of unpaved roads with geosynthetics." Journal of Geotechnical Engineering, 122(7), 544-553.

The construction, instrumentation, and response to vehicle trafficking of an unpaved road on soft ground are described. The road is comprised of an unreinforced section, three sections with different geotextiles, and a section with geogrid. The performance of the unreinforced section compares reasonably well, at large rut depths, to prediction using the analytical approach most commonly used in current design practice. Inclusion of a geosynthetic between the base course layer and subgrade soil led to a significant improvement in trafficability. The improvement was greatest for the thinner base layer of 25 cm, and diminished with increasing layer thickness. Reasonable agreement was, again, observed between the field performance and analytical predictions at large rut depths. The analytical approach was found to significantly over predict the number of vehicle passes to develop a 5 cm rut. The lack of agreement at small to moderate rut depths is attributed to compaction of the base course layer in response to vehicle trafficking that is not accounted for in the analytical approach. Some implications of the field observations for selection of a geosynthetic are discussed, with reference to separation and reinforcement of gravel layers over soft soils.

Glogowski, P. E., Kelly, J. M., McLaren, R. J., and Burns, D. L. (1992). "Fly Ash Design Manual for Road and Site Applications - Volume 1: Dry or Conditioned Placement." TR-100472, GAI Consultants, Inc., Palo Alto, California.

This design manual describes the use of fly ash as a construction material for use as structural and nonstructural fills, backfills, embankments, base courses, and roller compacted concrete dams and pavements, soil stabilization, land reclamation and other high volume uses. The manual details the physical, engineering and chemical properties of bituminous, subbituminous and lignite fly ash. Included are field and laboratory testing methods, design data, procedures and examples, specifications, quality control, and pre- and post-construction monitoring. Volume 1 describes uses where fly ash is used dry or conditioned with small amounts of moisture. Volume 2 describes uses where fly ash is placed as a slurry with relatively large amounts of water. The manual is primarily the result of editing and updating previous publications. High volume ash utilization has been documented in various manuals. These publications have been produced by several agencies including EPRI, Federal Highway Administration (FHWA), American Coal Ash Association (ACAA) and others. However, many of these publications were produced several years ago and are not readily available. Also, the information was published by several sources at various times. Therefore, these earlier publications are summarized and updated in this manual with state-of-practice design methods for use by design engineers. References to additional sources of information are provided.

Heath, A., Theyse, H., and Lea, J. (1999). "Use of ash in low-volume road construction in South Africa." Transportation Research Record: Journal of the Transportation Research Board, 1652, 196-202.

Sasol Chemical Industries produces large quantities of coarse clinker and fly ash as a by-product of the coal gasification process at their Sasolburg plant in South Af1ica. If this ash could be used as an aggregate in roads, the demand on natural reserves for aggregates would be reduced and an effective method of disposing of these materials would result. The ash is processed at a blending plant in Sasolburg and is marketed under the name Premamix. Trial sections were constructed using labor-based techniques with unstabilized and bitumen emulsion-treated Premamix as a base course material. As the Premamix is a lightweight material and is delivered at a specified moisture content (the optimum moisture content for compaction), it is ideal for labor-based construction of low-volume roads as only spreading and compaction of the layers are required. The trial sections were subjected to accelerated pavement testing with the heavy-vehicle simulator. Although high deflections were measured in the pavement structure, the Premamix performed well under trafficking, even after the base was soaked with water.

Helstrom, C. L., Humphrey, D. N., and Labbe, J. M. (2007). "Performance and Effectiveness of a Thin Pavement Section Using Geogrids and Drainage Geocomposites in a Cold Region." NETCR60, Department of Civil and Environmental Engineering, University of Maine, Orono, Maine.

Test sections were constructed in two portions of Maine Route 9 to investigate the use of geosynthetics for reinforcement and drainage for subbase courses that were 300 mm (12 in.) and 600 mm (24 in.) thick with 150 mm (6-in.) of flexible pavement. Four types of test sections were constructed: geogrid reinforcement, drainage geocomposite, drainage geocomposite with geogrid reinforcement, and control. Test sections using reinforcement geogrid have strain gages attached to the geogrid to measure induced forces. Some of the reinforcement sections have geogrid on subgrade whereas some have geogrid in the center of the subbase to evaluate the effects of geogrid location. Drainage geocomposite and control sections have vibrating wire piezometers to monitor porewater pressure in the subgrade and subbase course. Thermocouples were used to measure the depth of frost penetration. The results of falling weight deflectometer tests were used to backcalculate the effective structural number for each section. Reinforcement geogrid and drainage geocomposite increased the effective structural number by between 5% and 17% for sections with 300 mm (12 in.) subbase. However, they had no apparent effect for sections with 600 mm (24 in.) of subbase. The increase in backcalculated effective structural number that was produced by geogrid and/or drainage geocomposite in the 300-mm (12-in.) subbase sections could also be obtained by adding between 25 and 75 mm (1 and 3 in.) of subbase aggregate to an unreinforced section.

Henry, K. S., Olson, J. P., Farrington, S. P., and Lens, J. (2005). "Improved performance of unpaved roads during spring thaw." ERDC/CRREL TR-05-01, Engineer Research and Development Center Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Unpaved roads in Vermont are subject to deterioration from seasonal freezing and thawing, and many towns have roads that suffer chronic serviceability problems during the so-called “spring thaw,” or mud season. Several techniques thought to mitigate deterioration of unpaved roads during spring thaw were constructed on test sections of unpaved roads in two towns. Each potential remedy was aimed at providing some combination of limiting the availability of moisture in the winter, improving drainage during spring, and strengthening the upper portion of the road. Each technique used local and/or commercially available materials, and all were easy to construct, i.e., a town road crew could build them. For two spring thaw seasons, we compared strength estimates based on dynamic cone penetrometer tests and the percentage of the road surface rutted for treated and control sections. Methods that permanently improved the strength of the top 12 inches of the road or decreased the water content of the upper 12 inches of the road resulted in significant performance improvement during spring thaw. Cement and cellular confinement systems worked well by improving the strength of the upper layers of the soil. Two new techniques— geowrap, comprising clean sand sandwiched by geotextile separators placed 12–18 inches deep, and the patented Geosynthetic Capillary Barrier Drain—provided benefit by keeping the upper layers of the soil relatively dry. Geogrid and geotextile separators placed 12 inch deep and trench drains parallel to the road provided no observable benefit.

Hicks, R. G. (2002). "Alaska soil stabilization design guide." FHWA-AK-RD-01-6B, State of Alaska Department of Transportation and Public Facilities, Fairbanks, Alaska.

This guide presents information on the types of soil stabilization techniques that have or can be used in the state of Alaska. It covers techniques including asphalt, cement, lime, mechanical, chemical, and other methods. For each method there is a discussion on materials and design considerations, construction issues, and expected performance and costs. The appendices include a glossary of terms, a reading list on prior stabilization used in Alaska, a discussion on the soils in Alaska, and a slide presentation summarizing the highlights of the guide.

Holtz, R. D., Christopher, B. R., and Berg, R. R. (2008). "Geosynthetic Design and Construction Guidelines." FHWA-NHI-07-092, National Highway Institute, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

This manual is an updated version of the FHWA Reference Manual for the National Highway Institute’s training courses on geosynthetic design and construction. The update was performed to reflect current practice and codes for geosynthetics in highway works. The manual was prepared to enable the Highway Engineer to correctly identify and evaluate potential applications of geosynthetics as alternatives to other construction methods and as a means to solve construction problems. With the aid of this text, the Highway Engineer should be able to properly design, select, test, specify, and construct with geotextiles, geocomposite drains, geogrids and related materials in drainage, sediment control, erosion control, roadway, and embankment of soft soil applications. Steepened reinforced soil slopes and MSE retaining wall applications are also addressed within, but designers are referred to the more detailed FHWA NHI-00-043 reference manual on these subjects. This manual is directed toward geotechnical, hydraulic, pavement, bridge and structures, construction, maintenance, and route layout highway engineers, and construction inspectors and technicians involved with design and/or construction and/or maintenance of transportation facilities that incorporate earthwork.

Holtz, R. D., and Sivakugan, N. (1987). "Design charts for roads with geotextiles." Geotextiles and Geomembranes, 5, 191-199.

Design charts have been developed to determine the required aggregate thickness for geotextile-reinforced roads using the Giroud and Noiray procedure. The charts are for rut depths of 75, 100, 150, 200, and 300 mm, with tire pressures of 480 and 620 kPa for a standard design axle load of 80 kN. The charts can be used for the design of geotextile-reinforced unpaved roads, roadway stabilization aggregate, and for the first construction lift for embankments on very soft foundations.

Hoover, J. M. (1973). "Surface improvements and dust palliation of unpaved secondary roads and streets." Iowa Highway Research Board Project HR-151, Engineering Research Institute, Iowa State University, Ames, Iowa.

The report contains five parts:

(I) Project Summary by Hoover, J. M. - As of December 31, 1970 there were 57,270 miles of Local Secondary roads and 32,958 miles of Farm to Market roads in the Iowa secondary road system. The Local Secondary system carried a traffic load of 2,714,180 daily vehicle miles, accounting for 32% of all traffic in secondary system. For all Local Secondary roads having some form of surfacing, 98% were surfaced with gravel or crushed stone. During the 1970 construction year, 335 miles of surfaced roads were constructed in the Local Secondary system with 78% being surfaced with gravel or crushed stone. The total maintenance expenditure for all secondary roads in Iowa during 1970 amounted to $40,086,091. Of this, 42%, or $17,020,332, was spent for aggregate replacement on existing gravel or crushed stone roads with an additional 31% ($12,604,456) being spent on maintenance other than resurfacing. This amounts to 73% of the total maintenance budget and are the largest two maintenance expenditure items out of a list of 10 ranging from bridges to drainage assessments. The next largest item was 7%, for maintenance of existing flexible bases. Present costs of high-type flexible or rigid pavements range from $40,000 per mile up. Because of high cost, budget limitations, and low mileage of high traffic volume on Local Secondary roads, most Iowa counties are severely restricted as to the number of miles of roads that may be paved each year. Present design and construction standards provide adequate means for improvement of grade and cross section of secondary roads followed by: (a) immediate road metal surfacing, or (b) eventual high-type surfacing. There are, at present, no formal provisions for an intermediate type surfacing between these two extremes. Therefore, nearly all Iowa counties are in a situation in which they have only a few miles of high-type pavements with the bulk being surfaced with gravel or crushed stone. From the maintenance expenditures for 1970, it can be seen that the primary method of maintaining aggregate surfaced secondary roads remains, as it has in the past, as aggregate replacement. Roads continue to rut, washboard, ravel, pothole, and become the source for billowing clouds of dust. Loose aggregate makes driving hazardous, and results in cases of vehicle damage including cracked windshields, chipped paint, and dents, as well as increased fatalities. During the spring thaw and subsequent rains, many roads become extremely soft, slippery, and heavily rutted. As aggregate supplies decrease, inferior quality soft limestones and gravels are being used, resulting in faster degradation contributing to the dusting problem. Dust creates a safety hazard to both passing and oncoming traffic. It is also a definite household nuisance in rural areas, especially in heavily populated regions surrounding larger towns and cities where traffic on unpaved roads may range as high as 500 vehicles per day. The severity of these problems continues to increase as: (a) traffic volume increases, (b) more people move to rural areas surrounding larger towns and cities, and (c) the current concern over air pollution increases. The Iowa Air Pollution Control Commission has drafted guidelines with respect to "fugitive" dust, which ultimately will affect all unpaved state, county, and city roads and streets. Besides the above problems, most counties are faced with (a) rising costs of high-type pavement, (b) rising costs of maintenance, and (c) rising costs of replacement aggregates. The foregoing considerations dictated the need for finding a means to provide for low-cost surface improvement and dust control, using existing in-place materials, for immediate (and intermediate) use as a treated surface course on unpaved secondary roads - the objective of this research project. Three concurrent phases of study were included in the project: (1) laboratory screenings studies of various additives thought to have potential for long-lasting dust palliation, soil additive strength, durability, and additive retention potential; (2) test road construction using those additives that indicated promise for performance-serviceability usage; and (3) observations and tests of constructed sections for evaluation of the additive's contribution to performance and serviceability as well as the relationship to initial costs.

(II) Asphaltic products and elastometers as dust palliatives and surface improvement agents for unpaved secondary roads, by Bergeson, K. H. and Hoover, J. M.: Bituminous materials have long been used, with varying degrees of success, as soil stabilizers and waterproofing agents. With advancing technological developments many new asphaltic products, whose properties have been altered and supposedly enhanced by the addition of chemicals and selected emulsifying agents, are being marketed. Elastomers, which contain rubber in a modified form, have also been introduced. The beneficial effects of these products, as soil stabilizers and dust palliatives, can only be determined by laboratory evaluation and field trials. This investigation was conducted essentially as a three phase project consisting of (a) laboratory screenings of various asphaltic products and elastomers to evaluate their effectiveness as soil stabilizers and dust palliatives, (b) construction of a test road, based on the results of the laboratory screening phase, using those additives that appeared to be the most effective and economical, and (c) observation and tests of the various sections of the test road for evaluation of the additives' performance and serviceability with respect to dust palliation and surface improvement. The primary purpose of this study is to present the results of each of the above phases. The test road was constructed in September 1971 and had been in service only one year and three months at the time of termination of research. Therefore, phase 3 analyses are somewhat limited due to the period of time covered.

(III) Ammonium lignosulfonates as dust palliatives and surface improvement agents for unpaved secondary roads, by Fox, D. E., and Hoover, J. M.: At the time the research project was initiated in mid-1970, county engineer offices in Iowa were requested to propose locations for test roads within their respective counties. It was explained that all men, material, and equipment would be furnished by the individual counties. Laboratory screenings of additives and field testing of experimental roads would be carried out by the researchers, who would also be present to observe construction and provide technical assistance when and where needed. Four counties responded with interest in lignosulfonate stabilization. Lignosulfonates are available in almost unlimited quantities from paper mills. Ten years ago, lignosulfonates cost 6 cents per gallon at the mill and the price has not increased, although production has. Due to different pulping processes, the cation associated with lignosulfonate varies. Sodium, calcium, and ammonium lignosulfonates have all been used in soil stabilization and prices are similar. The study reported here utilized commercially-available lignosulfonate with ammonium as the associated cation. The following paragraphs explain the participation offered for lignosulfonate research by the corresponding county. The county engineer's office of Clinton County, Iowa made available a section of road 2620 ft long to which crushed limestone had been added at a rate of 2000 tons per mile. This length was naturally divided into three approximately equal sections, a flat upland location, a curve on a hill of about 6% grade, and a level bottomland section on a backwater area of the Mississippi River. The road was located between, and connected with, paved roads terminating at the Clinton and Camanche city limits. Two nearby industries contributed to a 1967 ADT (average daily traffic) of 500 vehicles per day, and maintenance was a problem. The researchers were invited to perform field tests on several roads within Floyd County, both prior to and following treatment with lignosulfonate. Construction was done by county personnel under the supervision of the lignosulfonate supplier. A dirt road near Marion, Linn County, was made available by the county engineer for research. Of 6000 ft length, the 1968 traffic survey showed an ADT of 44 vehicles. Prior to treatment, the grade was built up and improved by the ditch clean-out method typical of much secondary road construction. Using lignosulfonate from a local source, stabilization of nearly 150 miles of roads was begun in Lee County in the late 1950s and early 1960s. Treatment consisted of only light surface blading and occasional application of aggregate coupled with a lignosulfonate surface spray application. Over the years, an in-depth treatment was produced. Extensive cost and maintenance records on treated roads were kept and made available to the researchers.

(IV) Soil-chemical additives as surface improvement agents for unpaved roads, by Denny, C. K., and Hoover, J. M.: The use of polyester and plastic resins as soil stabilizers is relatively new and untried. The objective of this research was to investigate the capabilities of these resins and several other chemicals and commercial dust palliatives as potential low-cost dust palliatives and surface improvement agents. The investigation was conducted entirely in the laboratory but care was taken to approximate field conditions as accurately as possible. Various soil-chemical additives were evaluated on the basis of the following tests: (1) unconfined compressive strength, (2) durability and erosibility, (3) trafficability, (4) resistance to freezing and thawing, and (5) moisture retention and density. Some of the tests were standard while others were specifically modified, but in every case the treated specimens were compared with untreated control specimens.

(V) Appendix: Mineralogical analyses of dust samples, by Handy, R. L.: This part contains results of differential thermal-thermogravimetric analysis and petrographic analysis. Thermogravimetric analysis offers a rapid, accurate method for the measurement of carbonates and organic matter in 50 mg dust samples, and gives a reliable semi-quantitative indication of the amount of clay minerals. Analysis by petrographic microscope is less accurate but requires less sample, and therefore is a valuable supplemental technique for very small samples. Dust analyses show conclusively that selective sorting is operative, calcium carbonate dominating in dust samples collected near the road, and gradually decreasing to near zero several hundred feet away from the road. Simultaneously, the contents of clay and organic matter increase with distance from the road. The efficiency of the sorting indicates that it is size-selective rather than specific gravity-selective (i.e., carbonate contents are higher close to the road because the grains are larger and settle faster). Lignin treatment will drastically reduce the carbonate percentage in road dust, by more than a factor of 10, provided the added rock amount does not exceed 1000 T/mile. The total amount of dust is less drastically reduced, and the amount roughly coincides with the amounts of noncarbonate components in dusts from untreated roads. This suggests that lignin and clay build up a protective patina at the road surface, by migration upward due to evaporation. This patina protects the limestone and is worn off by traffic; however, it should renew so long as sufficient lignin remains in the road. (Alternatively, it probably can be renewed by surface treatments.) The existence of such a coating, while greatly reducing the limestone aggregate loss from the dry road, also may contribute some slipperiness on a wet road, and probably acts to reduce bonding between the road metal and a bituminous overlay. Rock added in excess of about 1000 T/mile is not effectively protected by a 1% lignin treatment, or lignin plus lime. In addition, at the higher rock application levels, added Ca(OH)* lime tends to further reduce the protective effect on carbonates, probably by flocculating the clay and reducing migration and development of a film.

Hoover, J. M., Moeller, D. T., Pitt, J. M., Smith, S. G., and Wainaina, N. W. (1982). "Performance of randomly oriented, fiber-reinforced roadway soils: A laboratory and field investigation." Iowa Highway Research Board Project HR-211, Engineering Research Institute, Iowa State University, Ames, Iowa.

The purpose of the study was to conduct a laboratory and field investigation into the potential of improving (a) soil-aggregate surfaced and subgrade materials, including those that are frost-prone and/or highly moisture susceptible, and (b) localized base course materials, by uniting such materials through fibrous reinforcement. The envisioned objective of the project was the development of a simple construction technique(s) that could be (a) applied on a selective basis to specific areas having a history of poor performance, or (b) used for improvement of potential base materials prior to surfacing. Little background information on such purpose and objective was available. Though the envisioned process had similarities to fibrous reinforced concrete, and to fibrous reinforced resin composites, the process was devoid of a cementitious binder matrix and thus highly dependent on the cohesive and frictional interlocking processes of a soil and/or aggregate with the fibrous reinforcement; a condition not unlike the introduction of reinforcing bars into a concrete sand/aggregate mixture without benefit of portland cement. Thus the study was also directed to answering some fundamental questions: (1) would the technique work; (2) what type or types of fibers are effective; (3) are workable fibers commercially available; and (4) can such fibers be effectively incorporated with conventional construction equipment, and employed in practical field applications? The approach to obtaining answers to these questions, was guided by the philosophy that an understanding of basic fundamentals was essential to developing a body of engineering knowledge that would serve as the basis for eventual development of design procedures with fibrous products for the applications previously noted.

Hoover, J. M., Pitt, J. M., Handfelt, L. D., and Stanley, R. L. (1981a). "Performance of soil-aggregate-fabric systems in frost-susceptible roads, Linn County, Iowa." Transportation Research Record: Journal of the Transportation Research Board, 827, 6-14.

Geotechnical construction fabric applied in soil-aggregate and granular-surfaced low-volume roadways indicate that fabric systems can, under certain circumstances, reduce thaw-induced deformations and improve field performance. Eleven test sections that involved different soil-aggregate-fabric systems were constructed on subgrades that displayed varying degrees of frost-related performance. Field evaluations were conducted over three cycles of spring thaw plus summer healing. Laboratory simulation of freeze-thaw action along with strength and deformation parameters obtained through the Iowa K-test were used on a fabric-reinforced, frost-susceptible soil to provide insight into soil fabric mechanisms and the potential for predicting field performance. Variation in the constructed soil-aggregate-fabric systems was achieved by locating fabric at different positions relative to layers of soil-aggregate or existing roadway materials, a choked macadam base course, and a thick granular backfill. Improvement was most noticeable where fabric was used as a reinforcement between a soil-aggregate surface and a frost-prone subgrade. Fabric used in conjunction with granular backfill, macadam base, and non-frost-susceptible subgrade did not appear justifiable.

Hopkins, T. C., Beckham, T. L., and Hunsucker, D. Q. (1995). "Modification of highway soil subgrades." Report KTC 94-11, Kentucky Transportation Center, University of Kentucky, Lexington, KY.

Major study objectives were to develop highway pavement subgrade stabilization guidelines, examine long-term benefits of chemical stabilizers, such as cement, hydrated lime, and two byproducts from industrial processes, and to establish a subgrade stabilization program in Kentucky. In developing a program, a number of design and construction issues had to be resolved. Factors affecting subgrade behavior are examined. Changes in moisture content and CBR strengths of untreated and chemically treated subgrades at three experimental highway routes were monitored over a 7-year period. CBR strengths of the untreated subgrades decreased dramatically while moisture contents increased. CBR strengths of subgrade sections treated with hydrated lime, cement and multicone kiln dust generally exceeded 12 and increased over the study period. At four other highway routs ranging in ages from 10 to 30 years, CBR strengths of soil-cement subgrades exceed 90. Knowing when subgrade stabilization is needed is critical to the development of an economical design and to insure the efficient construction of pavements. Bearing capacity analyses using a newly developed, stability model based on limit equilibrium and assuming a tire constant stress of 552 kPa show that stabilization should be considered when the CBR strength is less than 6.5. For other tire contact stresses, relationships corresponding to factors of safety of 1 and 1.5 are presented. Stability analysis of the first lifts of the paving materials showed that CBR strengths of untreated subgrade should be > 9. Guidelines for using geogrids as subgrade reinforcement are presented. Factors of safety of geogrid reinforced granular bases are approximately 10 to 25 percent larger than granular bases without reinforcement. As shown by strength tests and stability analysis, when the percent finer than the 0.002mm particle size of a soil increases to a value greater than about 15%, the factor of safety decreases significantly. Guidelines are also presented for this selection of the design strengths of untreated and treated subgrades with hydrated lime and cement. Based on a number of stabilization projects, recommended design undrained shear strengths of hydrated lime- and cement-treated subgrades are about 300 and 690 kPa, respectively. A laboratory testing procedure for determining the optimum percentage of chemical admixture is described. Correlations of dynamic cone penetrometer and Clegg impact hammer and in situ CBR strengths and unconfined compressive strengths are presented.

Hufenus, R., Rueegger, R., Banjac, R., Mayor, P., Springman, S. M., and Bronnimann, R. (2006). "Full-scale field tests on geosynthetic reinforced unpaved roads on soft subgrade." Geotextiles and Geomembranes, 24, 21-37.

A full-scale field test on a geosynthetic reinforced unpaved road was carried out, including compaction and trafficking, to investigate the bearing capacity and its performance on a soft subgrade. The test track was built with three layers of crushed, recycled fill material. The 1st layer was compacted statically, whereas the 2nd and 3rd were dynamically compacted. The geogrids were instrumented with strain gauges to measure the short- and long-term deformations and the ongoing formation of ruts was assessed from profile measurements. The various geosynthetics used for this reinforced unpaved road were found to have a relevant reinforcing effect only when used under a thin aggregate layer on a soft subgrade. Under such conditions, ruts can form in the subgrade, mobilizing strains and thus tensile forces in the geosynthetic. The achievable degree of reinforcement depends on the stiffness of the geosynthetic and is limited by finite lateral anchoring forces.

Hyvonen, L., Vuorimies, N., and Kolisoja, P. (2012a). "Road 16589 Saalahti - Mode 2 rutting site on a soft subgrade." The ROADEX “Implementing Accessibility” Project, The Swedish Transport Administration, Northern Region, Sweden.

Rutting of the road surface due to the development of permanent deformations, both in the road structure itself and in the underlying subgrade, is in most cases the dominant distress mechanism on low volume roads of the Northern Periphery area. From a road users’ point of view rutting both lowers driving comfort and reduces traffic safety. This is particularly the case when surface water is trapped in ruts, thereby increasing the risk of aquaplaning in summertime and of icing in the wheel path in winter when temperatures fall below 0°C. In addition, rutting can also be very harmful to the structural condition of the road, as it speeds up water infiltration into the road structure, increasing the effects of dynamic wheel loads etc. Rutting can develop in a road for a number of reasons. It may develop in the structural layers due to poor quality material, or as a result of poor drainage making the material more susceptible to permanent deformations. It may also develop in a weak subgrade material if the overall thickness of the structural layers is low. This is a very typical situation on the low volume roads of the Northern Periphery area, particularly during the spring thaw where the subgrade material is frost susceptible. Rutting mechanisms are discussed in greater detail in the ROADEX reports available at www.roadex.org, together with a new method of classifying rutting modes. This report describes a ROADEX demonstration exercise carried out on a low volume road section of Road 16589 Saalahti in Jämsä, Central Finland. A geogrid reinforcement was used in the demonstration to retard the development of permanent deformations of a gravel road section located on a silty subgrade. The demonstration section had been suffering from deformations primarily taking place in the subgrade material that had become very soft during the spring thaw of the seasonal frost. This had also resulted in severe widening of the road cross-section and almost total clogging of the side ditches. According to the GPR profiles the total thickness of the structural layers was much higher in the middle of the road than towards the edges of the road which was a clear indication of Mode 2 rutting. The reinforced structure consisted of two subsections in addition to which there was a reference section. One subsection was constructed with one layer of geogrid, rather than the standard rehabilitation solution of a geotextile. The second subsection was constructed with two layers of reinforcing geogrid 150 mm apart from each other. The standard rehabilitation structure of a geotextile was used in the reference structure. After one year of service it only can be concluded that both of the test structures and the reference structure have been performing equally well, and that the road is still in very good condition. Further monitoring of the settlement tubes installed in six cross sections of the road will reveal any differences in the development rate of permanent deformations between the test structure and reference structure. According to the life cycle analysis performed, the subsection reinforced with one layer of geogrid needs to last at least one year longer and the subsection reinforced with two layers of geogrid at least three years longer to be cost effective in comparison to the reference structure, if that is assumed to have a service life of 10 years. This is slightly longer than the typical assumption of 8 years life as in this case the reference structure was also about 50 mm thicker than would have been the standard solution.

Hyvonen, L., Vuorimies, N., and Kolisoja, P. (2012b). "Road 16583 Ehikki-Juikslahti - Mode 2 rutting site on peat." The ROADEX “Implementing Accessibility” Project, The Swedish Transport Administration, Northern Region, Sweden.

Rutting of the road surface due to the development of permanent deformations, both in the road structure itself and in the underlying subgrade, is in most cases the dominant distress mechanism on low volume roads of the Northern Periphery area. From a road users’ point of view rutting both lowers driving comfort and reduces traffic safety. This is particularly the case when surface water is trapped in ruts, thereby increasing the risk of aquaplaning in summertime and of icing in the wheel path in winter when temperatures fall below 0°C. In addition, rutting can also be very harmful to the structural condition of the road, as it speeds up water infiltration into the road structure, increasing the effects of dynamic wheel loads etc. Rutting can develop in a road for a number of reasons. It may develop in the structural layers due to poor quality material, or as a result of poor drainage making the material more susceptible to permanent deformations. It may also develop in a weak subgrade material if the overall thickness of the structural layers is low. This is a very typical situation on the low volume roads of the Northern Periphery area, particularly during the spring thaw where the subgrade material is frost susceptible. Rutting mechanisms are discussed in greater detail in the ROADEX reports available at www.roadex.org, together with a new method of classifying rutting modes. This report describes a ROADEX demonstration exercise carried out on a low volume road section of Road 16583 from Ehikki to Juokslahti in Jämsä, Central Finland. The section was located on a peat subgrade and was reinforced with a geogrid. The road had been deforming and widening significantly over the section mainly due to clogged side ditches, a low outlet ditch, and settlement of the road structure into the peat subgrade. As it was very difficult in practice to improve the operation of the outlet ditch, it was decided to reduce the further development of permanent deformations on the road by the addition of a new base course layer reinforced with a geogrid. As a reference structure, half of the test section was built with the addition of a new base course layer underlain by a geotextile, which could be considered as a standard solution in this type of problem site. After the first year of service, it only can be concluded that both the test structure and the reference structure have been performing equally well, and that the road is still in very good condition. Further monitoring of the settlement tubes installed in four cross sections of the road will reveal any differences in the development rate of permanent deformations between the test structure and the reference structure. According to the life cycle analysis performed, the section reinforced with geogrid needs to last at least 1.5 years longer to be cost effective in comparison to the reference structure, assuming that the reference structure will have a typical service life of 8 years. This had also resulted in severe widening of the road cross-section and almost total clogging of the side ditches. According to the GPR profiles the total thickness of the structural layers was much higher in the middle of the road than towards the edges of the road which was a clear indication of Mode 2 rutting. The reinforced structure consisted of two subsections in addition to which there was a reference section. One subsection was constructed with one layer of geogrid, rather than the standard rehabilitation solution of a geotextile. The second subsection was constructed with two layers of reinforcing geogrid 150 mm apart from each other. The standard rehabilitation structure of a geotextile was used in the reference structure. After one year of service it only can be concluded that both of the test structures and the reference structure have been performing equally well, and that the road is still in very good condition. Further monitoring of the settlement tubes installed in six cross sections of the road will reveal any differences in the development rate of permanent deformations between the test structure and reference structure. According to the life cycle analysis performed, the subsection reinforced with one layer of geogrid needs to last at least one year longer and the subsection reinforced with two layers of geogrid at least three years longer to be cost effective in comparison to the reference structure, if that is assumed to have a service life of 10 years. This is slightly longer than the typical assumption of 8 years life as in this case the reference structure was also about 50 mm thicker than would have been the standard solution.

Jahren, C. T., White, D. J., Phan, T. H., Westercamp, C., and Becker, P. (2011). "Stabilization Procedures to Mitigate Edge Rutting for Granular Shoulders – Phase II." IHRB Project TR-591, Institute for Transportation, Iowa State University, Ames, Iowa.

A multifaceted investigation was undertaken to develop recommendations for methods to stabilize granular road shoulders with the goal of mitigating edge ruts. Included was reconnaissance of problematic shoulder locations, a laboratory study to develop a method to test for changes in granular material stability when stabilizing agents are used, and the construction of three sets of test sections under traffic at locations with problematic granular shoulders. Full results of this investigation are included in this report and its appendices. Based on the results of the investigation, the following was concluded: (1) Problematic shoulders are generally stiff enough to carry expected traffic loads for emergency pull-off and temporary parking. Material gradations are generally finer than specified for new construction and cross slopes are often steeper than called out on cross sections for new construction. However, such differences in what is expected for original construction are consistent with damage that would be expected during use and maintenance (degradation of size due to breakage and abrasion and loss of material through erosion and winter and summer maintenance). Therefore, it seems likely that edge ruts develop from a combination of vehicle offtracking and time elapsed between maintenance cycles, rather than defects regarding original geometry and material gradation or from structural weakness. Some effort to renew cross slope and material gradation may be helpful in mitigating edge ruts. In addition, a shorter maintenance cycle would most likely be required to mitigate edge ruts. (2) Calcium chloride, magnesium chloride, and Base One did not provide noticeable improvements on the US 20 shoulders. However, they were easily applied and have the potential to be applied with the Iowa DOT's own maintenance staff, using its own equipment that could be modified from winter use. These methods were attempted because it was hypothesized that an important failure mode was that fine particles near the pavement edge were being removed by wind erosion, leaving only large particles that are easily displaced by off-tracking vehicles. These products bind fine particles, mechanically with Base One and by attracting moisture with calcium chloride and magnesium chloride. Apparently, some other mechanism causes the edge ruts, despite the presence of fine particles near the pavement edge. (3) If full-depth reclamation is used to incorporate stabilizers, the Iowa DOT does not currently own and operate the necessary equipment to compact and stabilize the reclaimed material. To provide the needed compaction effort, heavier equipment would have to be purchased or rented. In particular, it would be necessary to have a pneumatic compactor that could operate bi-directionally. Typically-available, pull-behind compactors do not allow enough passes to be made quickly enough when consideration is given to the time required to safely turn the units, especially on limited access highways. (4) DUSTLOCK appears to wear well in locations where the shoulder material provides a stable base and vehicles do not off-track to the extent that they do on the US 20 test section. In areas of heavy off-tracking, preliminary indications are that stabilizing the shoulders reduces the number of maintenance cycles to half of what they would be without the stabilizer.

(5) The laboratory test method for investigating stabilizer performance appeared to be a reasonable effort that provided some information about stabilized material behavior in confined situations. However, the method would have to be combined with a test similar to an asphalt rut test to detect instability for unconfined circumstances.

Jobgen, M. C., Callahan, M., Harris, G., and Tymkowicz, S. (1994). "Low cost techniques of base stabilization." Project HR-312, Iowa Department of Transportation, Ames, Iowa.

The IHRB HR-312 research project (Jobgen et al. 1994) evaluated performance of four different stabilization methods for on unsurfaced roads. These stabilization methods included using: a) high float emulsion (HFE-300) to treat top 3 in. of base stone, b) a bio-chemical formula called as BIO CAT 300-1 to treat the base stone for different thicknesses (6 in., 8in., and 10 in.), c) Consolid System method in the top 10 in. of subgrade soil, wherein when the soil is dry a combination of two inverted emulsions are used and when the soil is wet a combination of an inverted emulsion and a lime hydrated base powder are used to treat the base stone, and d) 5 in. of macadam base and 2 in. of choke stone along with fabric under one of the sections. All test sections were sealed using a double seal coat and performance evaluation was conducted on these sections using Iowa Road Rater, Roughometer, and visual inspection annually from 1989 to 1992. Some key findings from the field testing were as follows: (a) Test sections stabilized with BIO CAT300-1 and Consolid system showed the highest average k-value (207 pci to 225+ pci) four years after construction. HFE-300 stabilized section showed an average k-value of 181 pci, macadam subbase section showed an average k-value of 172 pci, and macadam subbase with fabric section showed an average k-value of 116 pci, four years after construction. (b) Although the BIO CAT 300-1 and Consolid System stabilized sections showed high k-values, they showed poor performance with alligator cracking and rutting under traffic, and continued deterioration every year. It is speculated in the report that these failures could have been due to freeze-thaw cycles in the stabilized layers. (c) HFE-300 treated test sections showed some deterioration with alligator cracking. Macadam subbase test sections (with and without fabric) experienced minor rutting and showed the best overall performance than all other sections. The use of fabric did not show noticeable improvement. (d) Use of macadam base and HFE-300 treatment showed cost effectiveness than other treatment options evaluated in this study.

Kendall, M., Baker, B., Evans, P., and Ramanujan, J. "Foamed Bitumen Stabilization - The Queensland Experience." Proc., 20th Australian Road Research Board (ARRB) Conference, Sydney, Australia.

This paper addresses: (a) the basics of foamed bitumen stabilization, (b) situations where foamed bitumen stabilization could be considered, (c) the design method used by the Queensland Department of Main Roads, (d) lessons learnt from the $2.5M, 17.6 km New England Highway Project, (e) what to look for when carrying out foamed bitumen stabilsation, and (f) the future of foamed bitumen stabilisation within the Queensland Department of Main Roads.

Kestler, M. A. (2003). "Techniques for Extending the Life of Low-Volume Roads in Seasonal Frost Areas." Transportation Research Record: Journal of the Transportation Research Board, 1819, 275-284.

Major highways are designed to withstand heavy vehicles and high traffic volumes year round. However, low-volume roads (LVRs) in seasonal frost areas are extremely susceptible to damage from trafficking by heavy vehicles during spring thaw. As a result, the maintenance-free

life of an LVR in a seasonal frost area averages less than half that of a similar road in a nonfrost area. This study serves as a practical primer on addressing thaw weakening of LVRs: it offers guidance for identifying frost-susceptible soils, summarizes methods used and currently undergoing research to determine when conditions are critical, and provides several solutions for avoiding the costly impact of spring thaw on LVRs. Diagnostic tools and recommended road-usage techniques are provided for existing roads; alternative design techniques are presented for new and reconstructed roads. Tools and techniques are applicable across much of Europe, North America, and Asia; some also apply to wet areas outside seasonal frost areas.

Kestler, M. A., Hanek, G., Truebe, M., and Bolander, P. (1999). "Removing spring thaw load restrictions from low volume roads: Development of a reliable, cost-effective method." Transportation Research Record: Journal of the Transportation Research Board, 1652, 188-197.

Low-volume roads in areas of seasonal freezing are highly susceptible to damage from trafficking during spring thaw. To minimize pavement damage, many agencies and states impose load restrictions during periods in which damage is most likely to occur. However, the magnitude and duration of reduced or prohibited hauling vary widely among agencies, and an optimal balance between maximizing local economy and minimizing road damage is rarely achieved. The U.S. Department of Agriculture Forest Service and the U.S. Army Cold Regions Research and Engineering Laboratory are evaluating a quantitative technique for removing load restrictions by developing correlations between pavement stiffness and soil moisture. Laboratory tests of the moisture sensors showed them to be accurate and repeatable under adverse freeze-thaw cycling. Preliminary analysis of field data showed that permanently installed time domain reftectometry and radio frequency soil moisture sensors strategically located throughout the forest road network will provide an affordable method for quantitatively determining when to remove load restrictions. Load restriction practices are reviewed, economic ramifications on the forest industry are briefly discussed, and laboratory and field test programs conducted to monitor soil moisture and pavement stiffness are outlined. In addition, instrumentation used for the study is described, observations from one of four national forest pavement test sites are presented, and the ongoing research to develop a method to remove load restrictions is discussed.

Lynam, D., and Jones, K. (1979). "Pavement surfaced on macadam base - Adair County." Project HR-209, Iowa Department of Transportation, Ames, Iowa.

The IHRB HR-209 research project evaluated the feasibility and economics of using macadam subbase material (without choke stone) under PCC and asphalt pavements. The macadam subbase material used on this project had a typical gradation with 3 in. maximum particle size and < 1% passing the #8 sieve. Field testing was conducted using Road Rater testing and visual crack/distress surveys. Some key findings from this study were as follows: (a) Road Rater testing indicated that the structural rating of a PCC pavement is improved if macadam subbase is used under the pavement. However, the improvement structural rating from using 5 in. of macadam subbase is equivalent to about additional ½ or ¾ in. PCC. The macadam subbase served primarily as a drainage layer and therefore could be reduced to 3.5 to 4 in. thickness instead of 5 in. Asphalt treating the macadam stone could be of additional benefit for stability of the base. (b) 2 to 3 in. thick PCC pavements over 5 in. macadam subbase showed poor performance and low structural rating. It is indicated that a minimum 5.5 in. PCC pavement is required over macadam to obtain 20 year design life. (c) Macadam served as a good drainage layer and prevented D-cracking on PCC pavements (within the 5 years of evaluation), which was a common problem in the area with using Class 1 aggregate (which contained fines). (d) Significant allowance should be made for material overruns when placing either PCC or asphalt pavement on macadam without chokestone (215 cubic yards per mile for PCC). (E) The quarry must be in close proximity for the project (within 10 to 20 miles) for macadam stone base to be economically practical.

Mekkawy, M. M., White, D. J., Suleiman, M. T., and Jahren, C. T. (2011). "Mechanically reinforced granular shoulders on soft subgrade: Laboratory and full scale studies." Geotextiles and Geomembranes, 29, 149-160.

A recently completed field study in Iowa showed that many granular shoulders overlie clayey subgrade layer with California Bearing Ratio (CBR) value of 10 or less. When subjected to repeated traffic loads, some of these sections develop considerable rutting. Due to costly recurring maintenance and safety concerns, the authors evaluated the use of biaxial geogrids in stabilizing a severely rutted 310 m tests section supported on soft subgrade soils. Monitoring the test section for about one year, demonstrated the application of geogrid as a relatively simple method for improving the shoulder performance. The field test was supplemented with a laboratory testing program, where cyclic loading was used to study the performance of nine granular shoulder models. Each laboratory model simulated a granular shoulder supported on soft subgrade with geogrid reinforcement at the interface between both layers. Based on the research findings, a design chart correlating rut depth and number of load cycles to subgrade CBR was developed. The chart was verified by field and laboratory measurements and used to optimize the granular shoulder design parameters and better predict the performance of granular shoulders.

Munro, R., Evans, R., and Saarenketo, T. (2007). "ROADEX II Project: Focusing on Low-Volume Roads in the European Northern Periphery." Transportation Research Record: Journal of the Transportation Research Board, 1989(2), 292-299.

The ROADEX Project is a living case study on the benefits of partnering across road districts to make the best use of available budgets. The ROADEX Project partners had an early shared vision of cooperation that has since materialized in great benefits to their respective areas through collaboration in research and development and enhancement of their in-house capabilities by direct access to experience within the other partners’ organizations. This sharing of information and experience has enabled them to have cost-effective research programs on shorter time scales than would otherwise have been the case and has avoided “reinventing the wheel” in research and development in each national district. The ROADEX II Project addresses the specific problems that arise in dealing with low-volume road management across the northern periphery of Europe so that reliable and regular year-round road networks can be provided to remote communities there. The outputs delivered in the ROADEX II Project offer a range of sustainable fit-for-purpose solutions to local road problems that together compose a tool kit of solutions for local managers to enable them to give better public service to their areas year after year.

Newman, J. K., and White, D. J. (2008). "Rapid Assessment of Cement and Fiber-Stabilized Soil Using Roller-Integrated Compaction Monitoring." Transportation Research Record: Journal of the Transportation Research Board, 2059, 95-102.

Test sections of high-early strength (Type III) portland cement and polypropylene monofilament fibers were constructed at the Bradshaw Field Training Area in the Northern Territory (NT), Australia as part of a Joint Rapid Airfield Construction (JRAC) project. Aprons, taxiways, and a helipad were stabilized using these materials in combination with screened native soil. The purpose of the test sections was to (a) evaluate the resulting properties for different stabilization dosage rates; (b) develop construction methods, criteria (including limits), and quality control guidelines; and (c) provide a hands-on training opportunity for the joint United States and Australia military construction team. Testing and monitoring consisted of roller-integrated compaction monitoring (global position systems monitoring pass coverages and compaction machine values) and in situ testing, which included dynamic cone penetration tests, Clegg impact tests, and light-weight deflectometer tests. After the test sections, construction of the helipad helped refine the construction methods and quality control testing for the selected stabilization dosage rates and machine speed. Lessons learned on the helipad were applied to the subsequent aircraft parking aprons and taxiways. Recommendations were developed for rapid stabilization construction procedures and quality control testing using Clegg impact values and light-weight deflectometer for cement-fiber stabilized soils, and the application of roller-integrated compaction technology was demonstrated to document compaction effort and uniformity.

Rollings, M. P., and Rollings, R. S. (1996). Geotechnical Materials in Construction, McGraw-Hill, New York, NY.

Chapter 6 of this book provides information on Stabilization: Seldom does nature provide the ideal soil or aggregate for construction. To overcome deficiencies in soil or aggregate properties such as poor grading, excess plasticity, or inadequate strength, we may blend two or more soils together, or we may add stabilizing admixtures such as lime, portland cement, or bituminous materials to the soil or aggregates. These techniques are effective if we can readily mix the materials. Other techniques for improving soil conditions at depth will be covered in Chap. 7. We often think of stabilization as a method of providing structural strength, but it can have a number of other construction and behavioral effects that are equally beneficial. These might include improved soil workability, an all-weather construction platform, or reduced swelling of expansive materials. Stabilization may improve the properties of an on-site or local material to allow its use rather than incurring the cost of importing a better material from a distant source. In the following sections we will examine the effects of blending and stabilizing with lime, portland cement, bituminous materials, pozzolanic and slag materials, and specialty admixtures.

Saarenketo, T., and Aho, S. (2005). "Managing Spring Thaw Weakening on Low Volume Roads - Problem Description, Load Restriction Policies, Monitoring and Rehabilitation." The ROADEXII Project, The Swedish Road Administration, Northern Region, Sweden.

This is a final report from the Phase II subproject 2_3 survey of the Roadex II project, a technical transnational cooperation project between the Highland Council, the Western Isles Council, and Forest Enterprise from Scotland; the Northern Region (formerly Troms district) of the Norwegian Public Roads Administration and the Norwegian Road Haulage Association; the

Northern Region of the Swedish National Road Administration; and from Finland the Regions of Central Finland and Lapland of the Finnish Road Administration, as well as Metsähallitus Region of Eastern Lapland, the Forestry Centre of Lapland (Lapin Metsäkeskus), Stora Enso Metsä, and Metsäliitto, Procurement Area of Northern Finland. The Roadex project is partly financed by the ERDF IIIB Northern Periphery Programme. The lead partner in the project is the Highland Council from Scotland and project consultant is Roadscanners Oy from Finland. Roadex II project Chairman is Ron Munro from the Highland Council and project manager is Timo Saarenketo from Roadscanners. The report summarizes the work done on Task 2_3 "Spring Thaw Weakening" of the Roadex II project. The report will describe the theory behind spring thaw weakening and different load restriction policies used in the cold climate areas. It will also report the results of the field tests done in Scotland, Sweden and Norway and present some new structural solutions which have been found to work well at spring thaw weakening sites. Finally, new technologies for both road owners and/or road users that could be used in more effective spring thaw weakening management will be revealed.

Salour, F., and Erlingsson, S. (2012). "Pavement Structural Behavior during Spring Thaw - Interpretation of FWD measurements by monitoring environmental data from county road 126 at Torpsbruk." 2009/0572-29, Swedish National Road and Transport Research Institute (VTI), Linkoping, Sweden.

The present research report has been carried out based on the environmental data and Falling Weight Deflectometer (FWD) measurements from the county road Lv 126 in Southern Sweden during the year 2010. The Lv 126 county road has a relatively thin flexible pavement structure with unbound aggregate base and subbase layers. The major intention of this study was to investigate the behaviour of the pavement structure during spring thaw. Temperature and moisture content of the pavement structure profile were continuously monitored throughout the year 2010. Layer moduli backcalculation as well as deflection basin analyses were performed using the FWD measurements data. A comprehensive study on the effect of environmental factor variations and pavement structural capacity were carried out during the spring thaw and recovery period. The result showed a considerable decrease in the bearing capacity of the pavement structure during the spring thaw period when the highest annual moisture content was also registered. Both deflection basin indices and backcalculated layer modulus indicated that the pavement was weakest during the subgrade thawing phase. Backcalculation on the FWD measurements showed a 63% loss in stiffness of the subgrade soil and 48% in the granular base and subbase course during the spring thaw compared to the summer values. In addition, the compatibility of the analysis with a predictive stiffness moduli- moisture content model for unbound materials was studied. The measured field data from the test road pavement in Torpsbruk showed promising agreement with the resilient modulus predictive model, both for the granular layer and subgrade material. Similar models could be developed or calibrated for other soils and granular materials if sufficient data become available in the future.

Shoop, S., Kester, M., Stark, J., Ryerson, C., and Affleck, R. (2003). "Rapid stabilization of thawing soils: field experience and application." Journal of Terramechanics, 39, 181-194.

Thawing soils can severely restrict vehicle travel on unpaved surfaces. However, a variety of materials and construction techniques can be used to stabilize thawing soils to reduce immobilization problems. The US Engineer Research and Development Center's Army Cold Regions Research and Engineering Laboratory (CRREL) and the Wisconsin National Guard evaluated several stabilization techniques in a field demonstration project during spring thaw at Fort McCoy, Wisconsin, in 1995. Additional tests on chemical stabilizing techniques were conducted at CRREL’s Frost Effects Research Facility. The results of these test programs were reduced to a decision matrix for stabilizing thawing ground, and used during the deployment of US troops in Bosnia during January and February of 1996. The soil frost and moisture conditions expected during this time frame were predicted using MIDFROCAL (MIDwest FROst CALculator). This paper is an overview of the stabilization techniques evaluated and their recommended application based on the expected soil frost conditions and traffic requirements. Although the experiments were performed with military vehicles in mind, the techniques are suitable for many civilian applications such as forestry, construction, mining, and oil exploration.

Sigurdsson, O. (1991). "Geosynthetic stabilization of unpaved roads on soft ground: a field evaluation." MS, The University of British Columbia, British Columbia, Canada.

A full scale field trial was carried out to investigate the performance of different geosynthetics in unpaved road construction over soft ground. The test site comprises of five 16 m long by 4.5 m wide test sections, build on a subgrade of undrained shear strength approximately 40 kPa. One is unreinforced and serves as a control section in the study, three sections include a geotextile, and one includes a geogrid. Each test section incorporated a variable thickness of sandy gravel base course material, between 25 and 50 cm thick. They were trafficked in sequence by a vehicle of standard axle load. An important governing parameter for interpretation of behavior is the influence of base course thickness on the relationship between number of passes and rut depth, base course thickness, base course deformations, geosynthetic strain, and deformed profile of the geosynthetic, with increasing number of vehicle passes. Vehicle trafficking was continued to a rut depth of about 20 cm, which constitutes a serviceability failure. Results from the full scale field trial show a better performance in the reinforced sections than the unreinforced section. The performance of the unreinforced section shows good agreement with other well-documented field data at large rut depths, between 10 and 15 cm, but not at small ruts. Although the four geosynthetics exhibited a broad range of stiffness and material properties, the general performance of the four reinforced sections was similar on the thicker base course layers. This is attributed to a reinforced mechanism governed by stiffness and separation, and all materials appear adequately stiff for the site conditions and vehicle loading. On the thinner subgrades, a tensioned-membrane effect is mobilized and a significant difference is observed between the geosynthetics.

Sirivitmaitrie, C., Puppala, A. J., Saride, S., and Hoyos, L. (2011). "Combined lime–cement stabilization for longer life of low-volume roads." Transportation Research Record: Journal of the Transportation Research Board, 2204, 140-147.

Low-volume roads are an important part of the world’s transportation infrastructure and a direct cause of the socioeconomic development of small city and rural communities. Construction, maintenance, and rehabilitation of these roads are major tasks and require a major part of the public works budget. Better design and construction methods can prolong pavement service life and result in lower maintenance and rehabilitation costs. This paper presents a research study done for the city of Arlington in north Texas to stabilize road subsoils with a combined lime and cement stabilizer, which in turn is expected to enhance service life of the roads. Both laboratory tests on stabilized soil mixtures and field performance data are analyzed and presented.

Vennapusa, P., White, D. J., and Miller, D. K. (2013). "Western Iowa Missouri River Flooding—Geo-Infrastructure Damage Assessment, Repair, and Mitigation Strategies." IHRB Project TR-638, Center for Earthworks Engineering Research, Iowa State University, Ames, Iowa.

The 2011 Missouri River flooding caused significant damage to many geo-infrastructure systems including levees, bridge abutments/foundations, paved and unpaved roadways, culverts, and embankment slopes in western Iowa. The flooding resulted in closures of several interchanges along Interstate 29 and of more than 100 miles of secondary roads in western Iowa, causing severe inconvenience to residents and losses to local businesses. The main goals of this research project were to assist county and city engineers by deploying and using advanced technologies to rapidly assess the damage to geo-infrastructure and develop effective repair and mitigation strategies and solutions for use during future flood events in Iowa. The research team visited selected sites in western Iowa to conduct field reconnaissance, in situ testing on bridge abutment backfills that were affected by floods, flooded and non-flooded secondary roadways, and culverts. In situ testing was conducted shortly after the flood waters receded, and several months after flooding to evaluate recovery and performance. Tests included falling weight deflectometer, dynamic cone penetrometer, three-dimensional (3D) laser scanning, ground penetrating radar, and hand auger soil sampling. Field results indicated significant differences in roadway support characteristics between flooded and non-flooded areas. Support characteristics in some flooded areas recovered over time, while others did not. Voids were detected in culvert and bridge abutment backfill materials shortly after flooding and several months after flooding. A catalog of field assessment techniques and 20 potential repair/mitigation solutions are provided in this report. A flow chart relating the damages observed, assessment techniques, and potential repair/mitigation solutions is provided. These options are discussed for paved/unpaved roads, culverts, and bridge abutments, and are applicable for both primary and secondary roadways.

White, D. J., Ceylan, H., Jahren, C. T., Phan, T. H., Kim, S. H., Gopalakrishnan, K., and Suleiman, M. T. (2008). "Performance Evaluation of Concrete Pavement Granular Subbase—Pavement Surface Condition Evaluation." IHRB Project TR-554, Center for Transportation Research and Education, Iowa State University, Ames, Iowa.

This research project covered a wide range of activities that allowed researchers to understand the relationship between stability, pavement distress, and recycled portland cement concrete (RPCC) subbase aggregate materials. Detailed laboratory and field tests, including pavement distress surveys, were conducted at 26 sites in Iowa were conducted. Findings show that specific gravities of RPCC are lower than those of crushed limestone. RPCC aggregate material varies from poorly or well-graded sand to gravel. A modified Micro-Deval test procedure showed that abrasion losses of virgin aggregate materials were within the maximum Micro-Deval abrasion loss of 30% recommended by ASTM D6028-06. Micro-Deval abrasion loss of RPCC aggregate materials, however were much higher than those of virgin materials and exceeded 30% loss. Modulus of elasticity of RPCC subbase materials is high but variable. RPCC subbase layers normally have low permeability. The pavement surfaces for both virgin and RPCC subbase across Iowa were evaluated to fulfill the objectives of this study related to field evaluation. Visual distress surveys were conducted to gather the detailed current pavement condition information including the type, extent, and severity of the pavement distresses. The historical pavement condition information for the surveyed field sections was extracted from the

Iowa DOT's Pavement Management Information System (PMIS). The current surface condition of existing field pavements with RPCC subbase was compared with the virgin aggregate subbase sections using two different approaches. The changes in pavement condition indices (PCI and IRI) with time for both types of pavements (subbases) were compared.

White, D. J., Harrington, D., and Thomas, Z. (2005a). "Fly Ash Soil Stabilization for Non-Uniform Subgrade Soils, Volume I: Engineering Properties and Construction Guidelines." IHRB Project TR-461, FHWA Project 4, Center for Transportation Research and Education, Iowa State University, Ames, Iowa.

Soil treated with self-cementing fly ash is increasingly being used in Iowa to stabilize fine-grained pavement subgrades, but without a complete understanding of the short- and long-term behavior. To develop a broader understanding of fly ash engineering properties, mixtures of five different soil types, ranging from ML to CH, and several different fly ash sources (including hydrated and conditioned fly ashes) were evaluated. Results show that soil compaction characteristics, compressive strength, wet/dry durability, freeze-thaw durability, hydration characteristics, rate of strength gain, and plasticity characteristics are all affected by the addition of fly ash. Specifically, Iowa self-cementing fly ashes are effective at stabilizing fine-grained Iowa soils for earthwork and paving operations; fly ash increases compacted dry density and reduces the optimum moisture content; strength gain in soil-fly ash mixtures depends on cure time and temperature, compaction energy, and compaction delay; sulfur contents can form expansive minerals in soil–fly ash mixtures, which severely reduces the long-term strength and durability; fly ash increases the California bearing ratio of fine-grained soil–fly ash effectively dries wet soils and provides an initial rapid strength gain; fly ash decreases swell potential of expansive soils; soil-fly ash mixtures cured below freezing temperatures and then soaked in water are highly susceptible to slaking and strength loss; soil stabilized with fly ash exhibits increased freeze-thaw durability; soil strength can be increased with the addition of hydrated fly ash and conditioned fly ash, but at higher rates and not as effectively as self-cementing fly ash. Based on the results of this study, three proposed specifications were developed for the use of self-cementing fly ash, hydrated fly ash, and conditioned fly ash. The specifications describe laboratory evaluation, field placement, moisture conditioning, compaction, quality control testing procedures, and basis of payment.

White, D. J., Mekkawy, M. M., Jahren, C. T., Smith, D., and Suleiman, M. T. (2007). "Effective Shoulder Design and Maintenance." IHRB Project TR-531, Center for Transportation Research and Education, Iowa State University, Ames, Iowa.

Granular shoulders are an important element of the transportation system and are constantly subjected to performance problems due to wind- and water-induced erosion, rutting, edge drop-off, and slope irregularities. Such problems can directly affect drivers' safety and often require regular maintenance. The present research study was undertaken to investigate the factors contributing to these performance problems and to propose new ideas to design and maintain granular shoulders while keeping ownership costs low. This report includes observations made during a field reconnaissance study, findings from an effort to stabilize the granular and subgrade layer at six shoulder test sections, and the results of a laboratory box study where a shoulder section overlying a soft foundation layer was simulated. Based on the research described in this report, the following changes are proposed to the construction and maintenance methods for granular shoulders: • A minimum CBR value for the granular and subgrade layer

should be selected to alleviate edge drop-off and rutting formation. • For those constructing new shoulder sections, the design charts provided in this report can be used as a rapid guide based on an allowable rut depth. The charts can also be used to predict the behavior of existing shoulders. • In the case of existing shoulder sections overlying soft foundations, the use of geogrid or fly ash stabilization proved to be an effective technique for mitigating shoulder rutting.

Performance Monitoring

Addison, M. B., and Polma, F. A. (2007). "Extending Durability of Lime Modified Clay Subgrades With Cement Stabilization." GSP 172 Soil Improvement, V. R. Schaefer, G. M. Filz, P. M. Gallagher, A. L. Sehn, and K. J. Wissmann, eds., ASCE, Denver, Colorado.

Many municipalities and private owners have faced increased pavement maintenance and replacement costs when lime modified clay subgrades prematurely fail. Preliminary laboratory test results determined that the typical lime treatment (7% by dry weight) used by the City of Garland, TX was approximately one-half the amount of lime necessary to permanently stabilize a high P.I. (39) clay. Further laboratory and a field testing program was then undertaken to determine if an economical alternative to 14% lime could be used to extend the durability of street subgrades. Four test sections were constructed using various combinations of lime to pre-treat the clays before stabilizing with cement. The testing program revealed that using combinations of lime and cement increased the typical subgrade durability based upon 4.8 to 5.7 times greater strengths after one year of exposure to in-place conditions. In addition, 28 day moist cured then saturated samples had 3.7 times greater compressive strength and 3.5 times better strength following 12 cycles of wetting and drying after 4 months of moist curing.

Al-Qadi, I. L., and Appea, A. K. (2003). "Eight-Year Field Performance of Secondary Road Incorporating Geosynthetics at Subgrade-Base Interface." Transportation Research Record: Journal of the Transportation Research Board, 1849, 212-220.

In June 1994 an instrumented 150-m-long secondary road pavement section was built in Bedford County, Virginia. This pavement section was composed of nine individual segments each 15 m long. The nine sections include three groups with aggregate base layer thicknesses of 100, 150, and 200 mm. Three sections from each group were stabilized with geotextiles and three were stabilized with geogrids at the base-sub grade interface. The remaining three sections were kept as control sections. As part of the structural analysis, deflection data parameters such as the base damage index and surface curvature index calculated from falling weight deflectometer (FWD) data were analyzed after being corrected for temperature variations from the time of construction until October 2001. Performance criteria such as rutting measurements were also collected over the whole period. A nonlinear exponential model was used to describe the development of rutting versus cumulative equivalent single-axle loads for the 100-mm base course. A linear elastic program incorporating constitutive material properties was used to calculate vertical compressive stresses, which were used with FWD deflections to predict rutting rates with a mechanistic equation. The rutting rate results confirmed the separation function of geosynthetics that prevented the migration of fines from the subgrade to the base course layer and the penetration of the aggregate base layer into the subgrade. Rutting results, deflection data, and service life analysis showed that geosynthetically-stabilized sections significantly improved the performance of the 100-mm base course sections.

Behak, L. (2011). "Performance of Full-Scale Test Section of Low-Volume Road with Reinforcing Base Layer of Soil–Lime." Transportation Research Record: Journal of the Transportation Research Board, 2204, 158-164.

The roads of the rice region of Merin Lake in Uruguay are subjected to low annual average traffic. However, the average daily traffic is approximately 100 trucks during harvest time. The local soils, characterized as clayey silts, are unsuitable for such traffic demands and are generally replaced or reinforced by materials found more than 70 km away, with high transportation costs. An investigation of the performance of a full-scale test section of pavement with a base layer of local silty clay soil stabilized with lime was conducted. The design of the test section consisted of soil selection, determination of lime content for stabilization, compaction, and California bearing ratio laboratory tests. Two test sections, each 50 m, were built, with a base layer of selected soil mixed with 3% lime in one section and with 5% lime in the other. After the rice harvest, the performance of the test sections was evaluated by visual observation of the base layer and deflection measures with a Benkelman beam. Despite some construction difficulties, the deflection average values changed from 244 x 10−2 cm immediately after the section was built to 77 x 10−2 cm 4 months later. The use of soil–lime material for base layers of low-volume roads is a technical and economical alternative that provides a significant improvement of the rural road network with socioeconomic benefits.

Bergeson, K. L., Kane, M. J., and Callen, D. O. (1990). "Crushed stone granular surfacing materials." Sponsored by the Iowa Limestone Produces Association and National Stone Association Research Program, Report by Engineering Research Institute, Iowa State University, Ames, Iowa.

The results of this research project indicate that crushed stone surfacing material graded on the fine side of IDOT Class A surfacing specifications provides lower roughness and better rideability; better braking and handling characteristics; and less dust generation than the coarser gradations. This is believed to be because there is sufficient fines (-#40 to - #200) available to act as a binder for the coarser material, which in turn promotes the formation of tight surface crust. This crust acts to provide a smooth riding surface, reduces dust generation, and improves vehicle braking and handling characteristics.

Bergeson, K. L., Waddingham, J. W., Brocka, S. G., and Lapke, R. K. (1995). "Bentonite treatment for economical dust reduction on limestone surface secondary roads." Iowa DOT Project HR-351, Engineering Research Institute, Iowa State University, Ames, Iowa.

This research project was directed at laboratory and field evaluation of sodium montmorillonite clay (Bentonite) as a dust palliative for limestone surfaced secondary roads. It was postulated that the electrically charged surfaces (negative) of the clay particles could interact with the charged surfaces (positive) of the limestone and act as a bonding agent to agglomerate fine (- #200) particulates, and also to bond the fine particulates to larger (+ #200) limestone panicles. One mile test roads were constructed in Tama, Appanoose, and Hancock counties in Iowa using Bentonite treatment levels (by weight of aggregate) ranging from 3.0 to 12.0 percent. Construction was accomplished by adding dry Bentonite to the surfacing material and then dry road mixing. The soda ash water solution (dispersing agent) was spray applied and the treated surfacing material wet mixed by motor graders to a consistency of 2 to 3 inch slump concrete. Two motor graders working in tandem provided rapid mixing. Following wet mixing the material was surface spread and compacted by local traffic. Quantitative and qualitative periodic evaluations and testing of the test roads was conducted with respect to dust generation, crust development, roughness, and braking characteristics. As the Bentonite treatment level increased dust generation decreased. From a cost benefit standpoint, an optimum level of treatment is about 8 percent (by weight of aggregate). For roads with light traffic, one application at this treatment level resulted in a 60-70 percent average dust reduction in the first season, 40-50 percent in the second season, and 20-30 percent in the third season. Crust development was rated at two times better than untreated control sections. No discernible trend was evident with respect to roughness. There was no evident difference in any of the test sections with respect to braking distance and braking handling characteristics, under wet surface conditions compared to the control sections. Chloride treatments are more effective in dust reduction in the short term (3-4 months). Bentonite treatment is capable dust reduction over the lone: term (2-3 seasons). Normal maintenance blading operations can be used on Bentonite treated areas. Soda ash dispersed Bentonite treatment is conservatively estimated to be more than twice as cost effective per percent dust reduction than conventional chloride treatments, with respect to time. However, the disadvantage is that there is not the initial dramatic reduction in dust generation as with the chloride treatment. Although dust is reduced significantly after treatment there is still dust being generated. Video evidence indicates that the dust cloud in the Bentonite treated sections does not rise as high, or spread as wide as the cloud in the untreated section. It also settles faster than the cloud in the untreated section. This is considered important for driving safety of following traffic, and for nuisance dust invasion of residences and residential areas. The Bentonite appears to be functioning as a bonding agent to bind small limestone particulates to larger particles and is acting to agglomerate fine particles of limestone as evidenced by laboratory sieve analysis data, and by SEM micrographs. This bonding capability appears recoverable from environmental effects of winter, and from alternating wet and dry periods. The Bentonite is able to interact with new applications of limestone maintenance material and maintains a dust reduction capability.

Bland, A. E., Brown, T. H., and Sheesley, D. C. (1991). "Fly ash use for unpaved road stabilization - Phase I." Interim Technical Report WRI-92-R017, The University of Wyoming, Laramie, Wyoming.

Western Research Institute (WRI) has conducted both laboratory and field demonstrations of a relatively new nonstandard unpaved road stabilization technique burning Class C fly ash from coal-fired power generation plants using Wyoming subbituminous coals. The experimental construction technique uses lean fly ash/soil/water formulations for stabilizing unpaved road materials to reduce maintenance costs and to provide new expanded markets for coal fly ash. The experimental testing program was designed to evaluate different soil/fly ash conditions as well as different construction techniques. Laboratory testing was conducted using ash from the PacifiCorp Dave Johnston Power Plant (DJPP) near Glenrock, Wyoming and five different soil types from a road adjacent to the plant. The laboratory testing examined the geotechnical performance of the various amounts of fly ash treatment of the soils. Moisture-density relationships and moisture-strength relationships were determined. The Dave Johnston fly ash is a slow-reacting fly ash, and early strength development was low (less than 100 psi) for all mixtures tested up to 25% fly ash. A twofold increase in strength was noted between the low fly ash dosage rates (5%) and the high fly ash dosage (25%). Based on the results of the laboratory testing, it is recommended to use 20% fly ash and optimum moisture for compaction of 11 to 13% water. Two 1,000-ft experimental test sections demonstrating the fly ash stabilized unpaved road process were constructed in July 1991, near the DJPP. The unpaved road had a continued history of washboarding and required regular high levels of maintenance. Based on the laboratory testing and design, the experimental test road was constructed using Dave Johnston fly ash as a binder to stabilize the upper 9 inches of the road surface. The intent was to treat the road sections by scarifying\ adding fly ash, and thoroughly mixing these materials with water and compacting the mixture to a highly densified and stable road surface. It was intended that the road be immediately available to traffic and continue to improve in strength and durability with time. WRI decided to use a fly ash application of 20% to construct the test section for several reasons: (1) The fly ash source was adjacent to the road construction site, and no transportation costs would be incurred. (2) A high application percentage would provide a range of high and low ash concentrations to study. (3) The laboratory studies suggested that a 20% application of fly ash from the DJPP was required for maximum strength development in the test section. Two demonstration test sections were constructed. Fly ash from Unit 3 of the DJPP was used for the treatment. Also, water from the Dave Johnston recycle pond was used. The materials consisted of 240 tons of fly ash and 10,000 gallons of water. Based on calculations of the depth of treatment and the bulk density of the road material, a fly ash treatment of 20% and a water addition of 11 % were achieved. The laboratory design testing suggested that optimum moistures in the range of 11 to 13% were required for maximum compaction. Visual monitoring of the road showed that some areas required remedial attention. This was a result of inadequate mixing of the fly ash and soil, and insufficient water addition during construction. A soft spot in the road with a high fly ash content, was patched to reduce dusting and improve trafficability. The test sections were dusting because either insufficient water was added during construction or the fly ash mixtures dried out before sufficient curing could occur. The treated sections were covered with bottom ash to act as a moisture barrier and cover to the surface. The barrier was successful, but the bottom ash developed severe washboarding. As a result, the bottom ash was removed after the fly ash/soil achieved sufficient strength and · durability. Additional water applications helped develop a hard, upper 2- to 3-inch surface in the fly ash treated section of the road. Performance monitoring and evaluation of the construction techniques show that mixing was inadequate, whereas compaction appears to be satisfactory. Fly ash distribution via blade mixing did not produce a homogeneous mixture, although improvement may have been possible if additional passes had been performed. Evidence for both lateral variations in the test section from 15 to 50% fly ash and a vertical layering in the treated section have been documented. Inadequate water distribution due to improper mixing was also noted as evidenced by the fact that areas were found that appeared to have received little or no water. Compaction of the fly ash treated soil mixtures was in the range of 95% of the laboratory results and the estimated maximum dry density. The performance of the fly ash treated section is presently quite good, showing continued strength development and reduced potential for dusting. The mechanically treated section is developing cracks, which are expected to create problems by Spring 1992. The control section is already showing washboarding as it has in the past. The fly ash stabilization technology appears to be an environmentally acceptable technology that does not pose a threat to groundwater. The surface water and storm water runoff have not been assessed because rainfall in the area has been too low. However, WRI does not anticipate problems associated with surface water or storm water runoff quality. In addition, the level of radioactivity for the fly ash is too low to be a health concern. However, the application of the fly ash during the construction phase needs to be improved to prevent excessive fugitive dust emissions. Options for modifying the construction procedure are being addressed and will be incorporated into future test sections. The results of the phase I testing and demonstration activities show that the process of fly ash

stabilization of unpaved roads is promising. Although the strength development with the Dave Johnston fly ash is very slow, engineering performance of the road demonstration test sections is quite good. The fly ash treated test section has shown no evidence of washboarding, and the dust from the road has been reduced to levels comparable to the control section of the unpaved road.

Bloser, S. M. (2007). "Commonly Used Aggregate Materials and Placement Methods: Comparative Analysis for a Wearing Course on Low-Volume Roads in Pennsylvania." Transportation Research Record: Journal of the Transportation Research Board, 1989, 178-185.

Aggregate-surfaced roads are a viable component of the transportation network; they provide significant increases in road stability over earthen surfaced roads while avoiding the high placement and maintenance costs of pavements. The use of higher-quality, more stable aggregates will significantly reduce both the cost of maintaining gravel roads and the environmental concerns related to road runoff. This paper aims to provide a better understanding of wearing course aggregates by describing a comparative analysis experiment done as part of Pennsylvania's Dirt and Gravel Road Maintenance Program. Three aggregates commonly used in Pennsylvania were placed side by side under two different placement methods for each type of aggregate as part of a 3-year study to compare their long-term durability and cost-effectiveness. The two methods tested were the "dump and spread" method known as tailgating and the application of aggregate by a motor paver. Cross-sectional surveys were done on each aggregate section for 3 years following placement to determine elevation changes in the road surfaces. No significant difference in performance was found between aggregate sections placed with a paver and the same aggregate placed by tailgating. Driving surface aggregate was the only aggregate of the three tested that did not show a statistically significant change in road elevation during the 3-year course of study. Results illustrate the importance of selecting a properly graded aggregate containing minimal clay and soil material for use as surface aggregate on low-volume roads.

Christopher, B. R., Hayden, S. A., and Zhao, A. (2000). "Roadway base and subgrade geocomposite drainage layers." Testing and Performance of Geosynthetics in Subsurface Drainage, ASTM STP1390, L. D. Suits, J. B. Goddard, and J. S. Baldwin, eds., ASTM, West Conshohocken, PA.

The Maine Department of Transportation (DOT) in conjunction with the University of Maine and the U.S. Army Cold Regions Research Laboratory evaluated the use of a special geocomposite drainage net as a drainage layer and capillary barrier (to mitigate frost heave) on a section of road plagued with weak, frost-susceptible subgrade soils and poor pavement performance. The special geocomposite drainage net that is being used has a higher flow capacity than conventional geonets and, based on tests performed by the University of Illinois, does not deform significantly under heavy traffic loading. For the 425-m-long test section, the geonet drainage geocomposite was placed horizontally across the entire roadway but varied in vertical location to form three separate subsections for evaluating drainage of 1) the base coarse aggregate, 2) the asphaltic concrete pavement, and 3) the subgrade to allow for a capillary break in order to reduce frost action. An integral drainage collection system was installed to collect the water flowing in the geonet. This paper includes a project description, material and construction specifications, installation procedures, instrumentation, and test results based upon two seasons of monitoring. Laboratory characterization and performance testing initially used to evaluate the geocomposite are compared with the monitored results.

Christopher, B. R., Schwartz, C., and Boudreau, R. (2005). "Geotechnical Aspects of Pavements." FHWA NHI-05-037, National Highway Institute, Federal Highway Administration, U.S. Dept. of Transportation, Washington, D.C.

The manual covers the latest methods and procedures to address the geotechnical issues in pavement design, construction and performance for new construction, reconstruction, and rehabilitation projects. The manual includes details on geotechnical exploration and characterization of in place and constructed subgrades as well as unbound base/subbase materials. The influence and sensitivity of geotechnical inputs are reviewed with respect to the requirements in past and current AASHTO design guidelines and the mechanistic-empirical design approach developed under NCHRP 1-37A, including the three levels of design input quality. Design details for drainage features and base/subbase material requirements are covered along with the evaluation and selection of appropriate remediation measures for unsuitable subgrades. Geotechnical aspects in relation to construction, construction specifications, monitoring, and performance measurements are discussed.

Collings, D., Lindsay, R., and Shunmugam, R. "LTPP Exercise on a Foamed Bitumen Treated Base - Evaluation of Almost 10 Years of Heavy Trafficking on MR504 in Kwazulu-Natal." Proc., 8th Conference on Asphalt Pavements for Southern Africa (CAPSA'04), Document Transformation Technologies.

Situated halfway between the cities of Pietermaritzburg and Durban, Provincial Main Road (MR) 504 provides primary access to a large asphalt plant, a commercial quarry and a pre-cast concrete products factory. A 700m section of this road, located on a steep gradient (+10%), and was upgraded to blacktop standards during 1995 by constructing a single layer of foamed bitumen treated material on top of a prepared subbase layer. The single slurry seal that was applied soon after construction proved adequate for three years before requiring a competent surfacing. This road provides an ideal opportunity for assessing the performance of what was originally termed an "experimental" pavement. The relevant traffic that this pavement has carried is estimated from dispatch records at each of the plants. In addition to as-built data, information is available from investigations that were carried out in 1997 by the CSIR Transportek Division, commissioned by the Provincial Department of Transport to evaluate this and other pavements with foamed bitumen treated bases. This information is reviewed and supplemented by additional surveys and tests conducted in the first quarter of 2004. This paper portrays the change that has taken place in the pavement between the time it was constructed, two years after trafficking, and again six years later. Deflection data is used as a primary measure of changing conditions. Additional tests include those carried out on cores extracted from the foamed bitumen treated base, test pit excavations and a DCP survey. Prediction models that were compiled in 2002 from HVS trials on foamed bitumen treated materials are also reviewed. As the first LTPP exercise on a foamed bitumen treated material, this paper endeavours to portray the difference between the condition of a such material in a pavement subjected to continuous HVS loading over a short time period compared to heavy trafficking over an extended period of nine years.

Drake, A. (2012). "Gleann Mor Forest Road Argyll and Bute, Scotland." A ROADEX "Implementing Accessibility" Project, The Swedish Transport Administration, Northern Region, Sweden.

The ROADEX Project was a technical co-operation between road organisations across northern Europe that aimed to share road related information and research between the partners. The project was started in 1998 as a 3 year pilot co-operation between the districts of Finnish Lapland, Troms County of Norway, the Northern Region of Sweden and The Highland Council of Scotland and was subsequently followed and extended with a second project, ROADEX II, from 2002 to 2005, a third, ROADEX III from 2006 to 2007 and a fourth, ROADEX "Implementing Accessibility" from 2009 to 2012. The Partners in the ROADEX "Implementing Accessibility" project comprised public road administrations and forestry organisations from across the European Northern Periphery. These were The Highland Council, Forestry Commission Scotland and the Western Isles Council from Scotland, The Northern Region of The Norwegian Public Roads Administration, The Northern Region of The Swedish Transport Administration and the Swedish Forest Agency, The Centre of Economic Development, Transport and the Environment of Finland, The Government of Greenland, The Icelandic Road Administration and The National Roads Authority and The Department of Transport of Ireland. The aim of the project was to implement the road technologies developed by ROADEX on to the partner road networks to improve operational efficiency and save money. The lead partner for the project was The Swedish Transport Administration and the main project consultant was Roadscanners Oy of Finland. A main part of the project was a programme of 23 demonstration projects showcasing the ROADEX methods in the Local Partner areas supported by a new pan-regional "ROADEX Consultancy Service" and "Knowledge Centre". Three research tasks were also pursued as part of the project: D1 "Climate change and its consequences on the maintenance of low volume roads", D2 "Road Widening" and D3 "Vibration in vehicles and humans due to road condition". The following are lessons learned from the project: Most of the older Forestry Commission forest roads have had temporary repairs to keep the timber moving, and sections have been completely reconstructed following landslides etc. During these and subsequent maintenance operations, different sources and types of stone have been used which can make GPR interpretation of layer depths challenging. It is also true to say that although the performance specification of the FC timber haulage roads is the same throughout England, Scotland and Wales, ground conditions and materials are extremely variable so the structural composition of roads can be totally different from area to area. Therefore, the establishment of appropriate area parameters using local knowledge and ground truth is important. The FWD testing procedure is intended for hard road surfaces. URS Scott Wilson has confirmed that when the surface of a forest road is soft, it can be difficult to achieve a 50 kN load as some of the force is actually absorbed by the road. Consequently, FWD work should be carried out in dry conditions but this can only be aspirational in Scotland! (Note: In Sweden FWD measurements are carried out in the spring after the frost has gone. It has been found that if measurements are taken in the middle of a dry summer the values might be too good.) It is difficult to get consistent dielectric value readings from the sides of an excavated trench using the Adek Percometer. This survey and assessment method has subsequently been used to analyse a totally new forest road which was built to a carefully designed and monitored specification. The Stone Depth analysis procedure showed that no additional stone was required at any point. The Forestry Commission have also surveyed a road formation with no pavement at all. The same procedure showed that not only was stone required along the entire length of the alignment, but it also calculated the depths and volumes. These results were as expected and they have established an “envelope” within which all other survey data from existing forest roads should fall. Surveys to-date have given the Forestry Commission confidence in the efficacy of the technique and the next stage of the project will be to develop improved site procedures. The aim will be to devise a method of applying the survey outputs on future roads in a manner which not only closely relates to the calculated lengths, depths and volumes but which is also practical to set out and control.

Edil, T. B., Benson, C. H., Bin-Shafique, M. S., Tanyu, B. F., Kim, W.-H., and TSenol, A. (2002). "Field Evaluation of Construction Alternatives for Roadways over Soft Subgrade." Transportation Research Record: Journal of the Transportation Research Board, 1786, 36-48.

Alternative methods for providing a stable platform over soft subgrades were evaluated using a 1.4-km section along a Wisconsin State highway that incorporated 12 test sections to evaluate 9 different stabilization alternatives. A variety of industrial by-products and geosynthetics were evaluated for stabilization. The industrial by-products included foundry slag, foundry sand, bottom ash, and fly ash as subbase layer materials. The geosynthetics included geocells, a nonwoven geotextile, a woven geotextile, a drainage geocomposite, and a geogrid. The same pavement structure was used for all test sections except for the subbase layer, which varied depending on the properties of the alternative material being used. All test sections were designed to have approximately the same structural number as the conventional pavement structure used for the highway, which included a subbase of granular excavated rock. Observations made during and after construction indicated that all sections provided adequate support for the construction equipment and no distress was evident in any part of the highway. Each of the alternative stabilization methods, except a subbase prepared with foundry sand, appear to provide equivalent or greater stiffness than that provided by control sections constructed with excavated rock. However, the foundry sand subbase is providing adequate support. Analysis of leachate collected from the base of the test sections shows that the by-products discharge contaminants of concern at very low concentrations.

Fannin, R. J., and Sigurdsson, O. (1996). "Field observations on stabilization of unpaved roads with geosynthetics." Journal of Geotechnical Engineering, 122(7), 544-553.

The construction, instrumentation, and response to vehicle trafficking of an unpaved road on soft ground are described. The road is comprised of an unreinforced section, three sections with different geotextiles, and a section with geogrid. The performance of the unreinforced section compares reasonably well, at large rut depths, to prediction using the analytical approach most commonly used in current design practice. Inclusion of a geosynthetic between the base course layer and subgrade soil led to a significant improvement in trafficability. The improvement was greatest for the thinner base layer of 25 cm, and diminished with increasing layer thickness. Reasonable agreement was, again, observed between the field performance and analytical predictions at large rut depths. The analytical approach was found to significantly over predict the number of vehicle passes to develop a 5 cm rut. The lack of agreement at small to moderate rut depths is attributed to compaction of the base course layer in response to vehicle trafficking that is not accounted for in the analytical approach. Some implications of the field observations for selection of a geosynthetic are discussed, with reference to separation and reinforcement of gravel layers over soft soils.

Giroud, J. P. "An assessment of the use of geogrids in unpaved roads and unpaved areas." Proc., Jubilee Symposium on Polymer Geogrid Reinforcement, ARRB Group Limited, Vermonth South, Victoria.

This paper presents an assessment of the use of geogrids in unpaved roads and unpaved areas. Unpaved areas comprise working platforms, storage areas, parking lots, log yards, etc. The phrase “unpaved roads and trafficked areas”, sometimes used, is not used herein because it may be confusing (as it may imply that the areas are trafficked and the roads are not, and that the areas are not unpaved). The term “stabilisation structures” will be used to encompass these two types of structures; and the term “subgrade stabilisation” will refer to this application in general. This paper includes two main parts. In the first part, a technical analysis is presented where the relevant properties of geogrids in unpaved roads and unpaved areas are discussed. In the second part, the state of practice is reviewed and factors that have an impact on the use of geogrids in unpaved roads and unpaved areas are discussed, such as: the cost of geosynthetics and aggregate, competition with geotextiles, and experience of decision-makers. The paper ends with a discussion of challenges for the future, including research needs. This paper is written for readers who have a good knowledge of geotechnical engineering and geosynthetics and their applications. In particular, the readers are assumed to be knowledgeable about unpaved roads and unpaved areas, and to be familiar with the related terminology. Intentionally, the paper does not include any illustration in order to focus the attention of the readers on the analyses and discussions. The purpose of this paper is not to explain how to design and construct unpaved roads and unpaved areas, but to assess the use of geogrids in these structures.

Heath, A., Theyse, H., and Lea, J. (1999). "Use of ash in low-volume road construction in South Africa." Transportation Research Record: Journal of the Transportation Research Board, 1652, 196-202.

Sasol Chemical Industries produces large quantities of coarse clinker and fly ash as a by-product of the coal gasification process at their Sasolburg plant in South Af1ica. If this ash could be used as an aggregate in roads, the demand on natural reserves for aggregates would be reduced and an effective method of disposing of these materials would result. The ash is processed at a blending plant in Sasolburg and is marketed under the name Premamix. Trial sections were constructed using labor-based techniques with unstabilized and bitumen emulsion-treated Premamix as a base course material. As the Premamix is a lightweight material and is delivered at a specified moisture content (the optimum moisture content for compaction), it is ideal for labor-based construction of low-volume roads as only spreading and compaction of the layers are required. The trial sections were subjected to accelerated pavement testing with the heavy-vehicle simulator. Although high deflections were measured in the pavement structure, the Premamix performed well under trafficking, even after the base was soaked with water.

Henry, K. S., Olson, J. P., Farrington, S. P., and Lens, J. (2005). "Improved performance of unpaved roads during spring thaw." ERDC/CRREL TR-05-01, Engineer Research and Development Center Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Unpaved roads in Vermont are subject to deterioration from seasonal freezing and thawing, and many towns have roads that suffer chronic serviceability problems during the so-called “spring thaw,” or mud season. Several techniques thought to mitigate deterioration of unpaved roads during spring thaw were constructed on test sections of unpaved roads in two

towns. Each potential remedy was aimed at providing some combination of limiting the availability of moisture in the winter, improving drainage during spring, and strengthening the upper portion of the road. Each technique used local and/or commercially available materials, and all were easy to construct, i.e., a town road crew could build them. For two spring thaw seasons, we compared strength estimates based on dynamic cone penetrometer tests and the percentage of the road surface rutted for treated and control sections. Methods that permanently improved the strength of the top 12 inches of the road or decreased the water content of the upper 12 inches of the road resulted in significant performance improvement during spring thaw. Cement and cellular confinement systems worked well by improving the strength of the upper layers of the soil. Two new techniques— geowrap, comprising clean sand sandwiched by geotextile separators placed 12–18 inches deep, and the patented Geosynthetic Capillary Barrier Drain—provided benefit by keeping the upper layers of the soil relatively dry. Geogrid and geotextile separators placed 12 inch deep and trench drains parallel to the road provided no observable benefit.

Hoover, J. M., Moeller, D. T., Pitt, J. M., Smith, S. G., and Wainaina, N. W. (1982). "Performance of randomly oriented, fiber-reinforced roadway soils: A laboratory and field investigation." Iowa Highway Research Board Project HR-211, Engineering Research Institute, Iowa State University, Ames, Iowa.

The purpose of the study was to conduct a laboratory and field investigation into the potential of improving (a) soil-aggregate surfaced and subgrade materials, including those that are frost-prone and/or highly moisture susceptible, and (b) localized base course materials, by uniting such materials through fibrous reinforcement. The envisioned objective of the project was the development of a simple construction technique(s) that could be (a) applied on a selective basis to specific areas having a history of poor performance, or (b) used for improvement of potential base materials prior to surfacing. Little background information on such purpose and objective was available. Though the envisioned process had similarities to fibrous reinforced concrete, and to fibrous reinforced resin composites, the process was devoid of a cementitious binder matrix and thus highly dependent on the cohesive and frictional interlocking processes of a soil and/or aggregate with the fibrous reinforcement; a condition not unlike the introduction of reinforcing bars into a concrete sand/aggregate mixture without benefit of portland cement. Thus the study was also directed to answering some fundamental questions: (1) would the technique work; (2) what type or types of fibers are effective; (3) are workable fibers commercially available; and (4) can such fibers be effectively incorporated with conventional construction equipment, and employed in practical field applications? The approach to obtaining answers to these questions, was guided by the philosophy that an understanding of basic fundamentals was essential to developing a body of engineering knowledge that would serve as the basis for eventual development of design procedures with fibrous products for the applications previously noted.

Hoover, J. M., Pitt, J. M., Handfelt, L. D., and Stanley, R. L. (1981a). "Performance of soil-aggregate-fabric systems in frost-susceptible roads, Linn County, Iowa." Transportation Research Record: Journal of the Transportation Research Board, 827, 6-14.

Geotechnical construction fabric applied in soil-aggregate and granular-surfaced low-volume roadways indicate that fabric systems can, under certain circumstances, reduce thaw-induced deformations and improve field performance. Eleven test sections that involved different soil-aggregate-fabric systems were constructed on subgrades that displayed varying degrees of frost-related performance. Field evaluations were conducted over three cycles of spring thaw plus summer healing. Laboratory simulation of freeze-thaw action along with strength and deformation parameters obtained through the Iowa K-test were used on a fabric-reinforced, frost-susceptible soil to provide insight into soil fabric mechanisms and the potential for predicting field performance. Variation in the constructed soil-aggregate-fabric systems was achieved by locating fabric at different positions relative to layers of soil-aggregate or existing roadway materials, a choked macadam base course, and a thick granular backfill. Improvement was most noticeable where fabric was used as a reinforcement between a soil-aggregate surface and a frost-prone subgrade. Fabric used in conjunction with granular backfill, macadam base, and non-frost-susceptible subgrade did not appear justifiable.

Hopkins, T. C., Beckham, T. L., Sun, L., Ni, B., and Butcher, B. (2002). "Long-Term Benefits of Stabilizing Soil Subgrades." KTC-02-19/SPR196-99-1F, Kentucky Transportation Center, University of Kentucky, Lexington, Kentucky.

Chemical admixtures have been used extensively since the mid-eighties in Kentucky to improve bearing strengths of soil subgrades. Most pavements in Kentucky are constructed on clayey soils. Although short-term observations at a small number of sites showed that chemical stabilization worked very well, a need existed to perform a more comprehensive review and to assess the long-term benefits of this subgrade stabilization method. The main intent of this study was an attempt to address questions concerning bearing strengths, longevity, durability, structural credit, economics, and performance of pavements resting on soil subgrades mixed with chemical admixtures. In-depth field and laboratory studies were performed at fourteen roadway sites containing twenty different treated subgrade sections. Ages of the sites range from about 8 to 15 years. About 455 borings were made at the various sites. Air, instead of water, was used as the drilling media. In-situ CBR tests were performed on the treated subgrades and the untreated subgrades lying directly below the treated layers. Index tests and resilient modulus tests were performed on samples collected from the treated and untreated subgrades. Falling weight deflectometer (FWD) tests were performed. At the 85th percentile test value, the in situ CBR values of subgrades mixed with hydrated lime, Portland cement, a combination of hydrated lime and Portland cement, and a byproduct (MKD) obtained in the production of hydrated lime were 12 to 30 times greater than in CBR values of the untreated subgrades. In-situ CBR values of the treated layer ranged from 24 to 59 while the in-situ CBR of the untreated layer at the 85th percentile test value was only 2. Based on rating criteria of the Kentucky Transportation Cabinet, the conditions of the pavements at twelve sites could be rated “good” at the time of the study– pavement ages were 8 to 15 years– and “good” at the end of the twenty-year design period, based on projected data. At two sites, thin asphalt overlays had been constructed after 15 years. However, accumulated values of ESAL at those sites had exceeded or were near the values of ESAL assumed in the pavement designs. At the 20th percentile test value, rutting depths of the pavements resting on the treated subgrades were less than about 0.27 inches. Structural layer coefficients, a3, for use in pavement design of the different chemically stabilized subgrades were developed. The proposed values were verified at sites where reduced pavement thickness was used and “in service” structural coefficients could be observed. Back-calculated values of FWD modulus of the treated layers were about two times the values of modulus of the untreated subgrade. Resilient modulus of the treated subgrades was larger than the resilient modulus of the untreated subgrades. Moisture contents at the top of the untreated subgrade layers showed that a "soft" layer of material exists at the very top of the untreated subgrade. This soft zone did not exist at the top of the treated layer. This discovery has significant engineering implications. Future research will focus attention on an in-depth examination of this weak layer of soil. Chemical admixture stabilization is a good, durable and economical technique for improving subgrade strengths.

Hufenus, R., Rueegger, R., Banjac, R., Mayor, P., Springman, S. M., and Bronnimann, R. (2006). "Full-scale field tests on geosynthetic reinforced unpaved roads on soft subgrade." Geotextiles and Geomembranes, 24, 21-37.

A full-scale field test on a geosynthetic reinforced unpaved road was carried out, including compaction and trafficking, to investigate the bearing capacity and its performance on a soft subgrade. The test track was built with three layers of crushed, recycled fill material. The 1st layer was compacted statically, whereas the 2nd and 3rd were dynamically compacted. The geogrids were instrumented with strain gauges to measure the short- and long-term deformations and the ongoing formation of ruts was assessed from profile measurements. The various geosynthetics used for this reinforced unpaved road were found to have a relevant reinforcing effect only when used under a thin aggregate layer on a soft subgrade. Under such conditions, ruts can form in the subgrade, mobilizing strains and thus tensile forces in the geosynthetic. The achievable degree of reinforcement depends on the stiffness of the geosynthetic and is limited by finite lateral anchoring forces.

Hyvonen, L., Vuorimies, N., and Kolisoja, P. (2012a). "Road 16589 Saalahti - Mode 2 rutting site on a soft subgrade." The ROADEX "Implementing Accessibility" Project, The Swedish Transport Administration, Northern Region, Sweden.

Rutting of the road surface due to the development of permanent deformations, both in the road structure itself and in the underlying subgrade, is in most cases the dominant distress mechanism on low volume roads of the Northern Periphery area. From a road users' point of view rutting both lowers driving comfort and reduces traffic safety. This is particularly the case when surface water is trapped in ruts, thereby increasing the risk of aquaplaning in summertime and of icing in the wheel path in winter when temperatures fall below 0°C. In addition, rutting can also be very harmful to the structural condition of the road, as it speeds up water infiltration into the road structure, increasing the effects of dynamic wheel loads etc. Rutting can develop in a road for a number of reasons. It may develop in the structural layers due to poor quality material, or as a result of poor drainage making the material more susceptible to permanent deformations. It may also develop in a weak subgrade material if the overall thickness of the structural layers is low. This is a very typical situation on the low volume roads of the Northern Periphery area, particularly during the spring thaw where the subgrade material is frost susceptible. Rutting mechanisms are discussed in greater detail in the ROADEX reports available at www.roadex.org, together with a new method of classifying rutting modes. This report describes a ROADEX demonstration exercise carried out on a low volume road section of Road 16589 Saalahti in Jämsä, Central Finland. A geogrid reinforcement was used in the demonstration to retard the development of permanent deformations of a gravel road section located on a silty subgrade. The demonstration section had been suffering from deformations primarily taking place in the subgrade material that had become very soft during the spring thaw of the seasonal frost. This had also resulted in severe widening of the road cross-section and almost total clogging of the side ditches. According to the GPR profiles the total thickness of the

structural layers was much higher in the middle of the road than towards the edges of the road which was a clear indication of Mode 2 rutting. The reinforced structure consisted of two subsections in addition to which there was a reference section. One subsection was constructed with one layer of geogrid, rather than the standard rehabilitation solution of a geotextile. The second subsection was constructed with two layers of reinforcing geogrid 150 mm apart from each other. The standard rehabilitation structure of a geotextile was used in the reference structure. After one year of service it only can be concluded that both of the test structures and the reference structure have been performing equally well, and that the road is still in very good condition. Further monitoring of the settlement tubes installed in six cross sections of the road will reveal any differences in the development rate of permanent deformations between the test structure and reference structure. According to the life cycle analysis performed, the subsection reinforced with one layer of geogrid needs to last at least one year longer and the subsection reinforced with two layers of geogrid at least three years longer to be cost effective in comparison to the reference structure, if that is assumed to have a service life of 10 years. This is slightly longer than the typical assumption of 8 years life as in this case the reference structure was also about 50 mm thicker than would have been the standard solution.

Hyvonen, L., Vuorimies, N., and Kolisoja, P. (2012b). "Road 16583 Ehikki-Juikslahti - Mode 2 rutting site on peat." The ROADEX “Implementing Accessibility” Project, The Swedish Transport Administration, Northern Region, Sweden.

Rutting of the road surface due to the development of permanent deformations, both in the road structure itself and in the underlying subgrade, is in most cases the dominant distress mechanism on low volume roads of the Northern Periphery area. From a road users’ point of view rutting both lowers driving comfort and reduces traffic safety. This is particularly the case when surface water is trapped in ruts, thereby increasing the risk of aquaplaning in summertime and of icing in the wheel path in winter when temperatures fall below 0°C. In addition, rutting can also be very harmful to the structural condition of the road, as it speeds up water infiltration into the road structure, increasing the effects of dynamic wheel loads etc. Rutting can develop in a road for a number of reasons. It may develop in the structural layers due to poor quality material, or as a result of poor drainage making the material more susceptible to permanent deformations. It may also develop in a weak subgrade material if the overall thickness of the structural layers is low. This is a very typical situation on the low volume roads of the Northern Periphery area, particularly during the spring thaw where the subgrade material is frost susceptible. Rutting mechanisms are discussed in greater detail in the ROADEX reports available at www.roadex.org, together with a new method of classifying rutting modes. This report describes a ROADEX demonstration exercise carried out on a low volume road section of Road 16583 from Ehikki to Juokslahti in Jämsä, Central Finland. The section was located on a peat subgrade and was reinforced with a geogrid. The road had been deforming and widening significantly over the section mainly due to clogged side ditches, a low outlet ditch, and settlement of the road structure into the peat subgrade. As it was very difficult in practice to improve the operation of the outlet ditch, it was decided to reduce the further development of permanent deformations on the road by the addition of a new base course layer reinforced with a geogrid. As a reference structure, half of the test section was built with the addition of a new base course layer underlain by a geotextile, which could be considered as a standard solution in this type of problem site. After the first year of service, it only can be concluded that both the test structure and the reference structure have been performing equally well, and that the road is still in very good condition. Further monitoring of the settlement tubes installed in four cross sections of the road will reveal any differences in the development rate of permanent deformations between the test structure and the reference structure. According to the life cycle analysis performed, the section reinforced with geogrid needs to last at least 1.5 years longer to be cost effective in comparison to the reference structure, assuming that the reference structure will have a typical service life of 8 years. This had also resulted in severe widening of the road cross-section and almost total clogging of the side ditches. According to the GPR profiles the total thickness of the structural layers was much higher in the middle of the road than towards the edges of the road which was a clear indication of Mode 2 rutting. The reinforced structure consisted of two subsections in addition to which there was a reference section. One subsection was constructed with one layer of geogrid, rather than the standard rehabilitation solution of a geotextile. The second subsection was constructed with two layers of reinforcing geogrid 150 mm apart from each other. The standard rehabilitation structure of a geotextile was used in the reference structure. After one year of service it only can be concluded that both of the test structures and the reference structure have been performing equally well, and that the road is still in very good condition. Further monitoring of the settlement tubes installed in six cross sections of the road will reveal any differences in the development rate of permanent deformations between the test structure and reference structure. According to the life cycle analysis performed, the subsection reinforced with one layer of geogrid needs to last at least one year longer and the subsection reinforced with two layers of geogrid at least three years longer to be cost effective in comparison to the reference structure, if that is assumed to have a service life of 10 years. This is slightly longer than the typical assumption of 8 years life as in this case the reference structure was also about 50 mm thicker than would have been the standard solution.

Jobgen, M. C., Callahan, M., Harris, G., and Tymkowicz, S. (1994). "Low cost techniques of base stabilization." Project HR-312, Iowa Department of Transportation, Ames, Iowa.

The IHRB HR-312 research project (Jobgen et al. 1994) evaluated performance of four different stabilization methods for on unsurfaced roads. These stabilization methods included using: a) high float emulsion (HFE-300) to treat top 3 in. of base stone, b) a bio-chemical formula called as BIO CAT 300-1 to treat the base stone for different thicknesses (6 in., 8in., and 10 in.), c) Consolid System method in the top 10 in. of subgrade soil, wherein when the soil is dry a combination of two inverted emulsions are used and when the soil is wet a combination of an inverted emulsion and a lime hydrated base powder are used to treat the base stone, and d) 5 in. of macadam base and 2 in. of choke stone along with fabric under one of the sections. All test sections were sealed using a double seal coat and performance evaluation was conducted on these sections using Iowa Road Rater, Roughometer, and visual inspection annually from 1989 to 1992. Some key findings from the field testing were as follows: (a) Test sections stabilized with BIO CAT300-1 and Consolid system showed the highest average k-value (207 pci to 225+ pci) four years after construction. HFE-300 stabilized section showed an average k-value of 181 pci, macadam subbase section showed an average k-value of 172 pci, and macadam subbase with fabric section showed an average k-value of 116 pci, four years after construction. (b) Although the BIO CAT 300-1 and Consolid System stabilized sections showed high k-values, they showed poor performance with alligator cracking and rutting under traffic, and continued deterioration every year. It is speculated in the report that these failures could have been due to freeze-thaw cycles in the stabilized layers. (c) HFE-300 treated test sections showed some deterioration with alligator cracking. Macadam subbase test sections (with and without fabric) experienced minor

rutting and showed the best overall performance than all other sections. The use of fabric did not show noticeable improvement. (d) Use of macadam base and HFE-300 treatment showed cost effectiveness than other treatment options evaluated in this study.

Kendall, M., Baker, B., Evans, P., and Ramanujan, J. "Foamed Bitumen Stabilization - The Queensland Experience." Proc., 20th Australian Road Research Board (ARRB) Conference, Sydney, Australia.

This paper addresses: (a) the basics of foamed bitumen stabilization, (b) situations where foamed bitumen stabilization could be considered, (c) the design method used by the Queensland Department of Main Roads, (d) lessons learnt from the $2.5M, 17.6 km New England Highway Project, (e) what to look for when carrying out foamed bitumen stabilsation, and (f) the future of foamed bitumen stabilisation within the Queensland Department of Main Roads.

Kestler, M. A., Hanek, G., Truebe, M., and Bolander, P. (1999). "Removing spring thaw load restrictions from low volume roads: Development of a reliable, cost-effective method." Transportation Research Record: Journal of the Transportation Research Board, 1652, 188-197.

Low-volume roads in areas of seasonal freezing are highly susceptible to damage from trafficking during spring thaw. To minimize pavement damage, many agencies and states impose load restrictions during periods in which damage is most likely to occur. However, the magnitude and duration of reduced or prohibited hauling vary widely among agencies, and an optimal balance between maximizing local economy and minimizing road damage is rarely achieved. The U.S. Department of Agriculture Forest Service and the U.S. Army Cold Regions Research and Engineering Laboratory are evaluating a quantitative technique for removing load restrictions by developing correlations between pavement stiffness and soil moisture. Laboratory tests of the moisture sensors showed them to be accurate and repeatable under adverse freeze-thaw cycling. Preliminary analysis of field data showed that permanently installed time domain reftectometry and radio frequency soil moisture sensors strategically located throughout the forest road network will provide an affordable method for quantitatively determining when to remove load restrictions. Load restriction practices are reviewed, economic ramifications on the forest industry are briefly discussed, and laboratory and field test programs conducted to monitor soil moisture and pavement stiffness are outlined. In addition, instrumentation used for the study is described, observations from one of four national forest pavement test sites are presented, and the ongoing research to develop a method to remove load restrictions is discussed.

Koch, S., Ksaibati, K., and Huntington, G. (2011). "Performance of Recycled Asphalt Pavement in Gravel Roads." Transportation Research Record: Journal of the Transportation Research Board, 2204, 221-229.

Because more recycled asphalt pavement (RAP) has become available to use in roadways, the Wyoming Technology Transfer–Local Technical Assistance Program Center and two Wyoming counties saw a need to investigate the use of RAP in gravel roads. The Wyoming Department of Transportation along with the Mountain Plains Consortium funded this study. The investigation explored the use of RAP as a means of dust suppression while considering road serviceability. Test sections were constructed in the two counties and were monitored for dust loss by means of the Colorado State University dustometer. Surface distress evaluations of the test sections were performed following a technique developed by the U.S. Army Corps of Engineers in Unsurfaced Road Maintenance Management (Special Report 92-26). The data collected were statistically summarized and then analyzed. The performance of RAP sections was compared with that of gravel control sections. This comparison allowed fundamental conclusions and recommendations to be made for RAP and its ability to abate dust. It was found that RAP-incorporated gravel roads can reduce dust loss without adversely affecting the road's serviceability. Other counties and agencies can expand on this research to add to the toolbox for dust control on gravel roads.

Latha, G. M., Nair, A. M., and Hemalatha, M. S. (2010). "Performance of geosynthetics in unpaved roads." International Journal of Geotechnical Engineering, 2010(4), 337-349.

This paper presents results of field studies on unpaved low volume roads constructed over weak subgrade using geosynthetic reinforcement. The relative advantages of placing different reinforcing materials like geotextile, biaxial or uniaxial geogrid, geocell layer, and tire shreds at the interface of subgrade and base course are studied in terms of increase in load carrying capacity and reduction in rut depth. The rut depths measured in three different test sections when subjected moving vehicle load simulated by the passage of a scooter on the road at uniform speed for a maximum of 250 passes are compared to understand the relative efficiency of each of the reinforcing materials in reducing the rut formation in unpaved roads. Traffic benefit ratios were also compared for different reinforced test sections.

Less, R. A., and Paulson, C. K. (1977). "Experimental macadam stone base - Des Moines County." Project HR-175, Iowa Department of Transportation, Ames, Iowa.

The IHRB HR-175 research project evaluated the feasibility and economics of using macadam subbase material (with different thicknesses) with choke stone under PCC and asphalt pavements. The macadam subbase material used on this project had a typical gradation with 4 in. maximum particle size and 12 to 26% passing the 1 in. sieve. The choke stone had a typical gradation with 1 in. maximum particle size and 6 to 12% passing the No. 200 sieve. The study indicated that the macadam subbase performed well under both PCC and asphalt pavements, but the cost was relatively more. During construction, the finished macadam subbase showed a uniform structure with negligible amount of degradation during compaction. Production rates on placement of the macadam subbase material varied from about 2900 to 5000 tons per day. Lateral subdrain trenches backfilled with porous backfill was used on this project for drainage. This system performed well and minimized effects of frost boils, spring thaw, and other subsurface drainage issues.

Litzka, J., and Haslehner, W. "Cold In-Place Recycling on Low-Volume Roads in Austria." Proc., Sixth International Conference on Low-Volume Roads, Minneapolis, Minnesota.

Modern methods for road maintenance should involve used construction materials, take account of environmental compatibility, and eliminate road damage economically and durably. Regarding these basic requirements, attention should be paid to cold in-place recycling of damaged asphalt layers using cement stabilization. Within the last few years, cold in-place recycling has become an appropriate alternative for the rehabilitation of low-volume roads in Austria. In the course of documentation carried out at the Institute for Traffic and Transportation Engineering of the Vienna University of Bodenkultur, the individual steps of construction were analyzed. The advantage of the described procedure is that none of the old pavement need be hauled to a special repository. An innovative method for cold in-place recycling on low-volume roads using cement stabilization is described. The first step of this method contains a detailed

analysis of the section to be restored, including bearing capacity measurements and the determination of the grading curves of existing unbound layers. Grading curves are also determined for the existing asphalt layer after trial milling in order to consider refinement by milling. This analysis forms the basis for adding material before milling in order to achieve a well-graded aggregate. On the construction site, the necessary additional aggregate is spread over the existing pavement. In the next step, the cement binder is distributed on the road surface. A soil stabilizer breaks up the existing road structure and mixes it thoroughly with the aggregates and

Lynam, D., and Jones, K. (1979). "Pavement surfaced on macadam base - Adair County." Project HR-209, Iowa Department of Transportation, Ames, Iowa.

The IHRB HR-209 research project evaluated the feasibility and economics of using macadam subbase material (without choke stone) under PCC and asphalt pavements. The macadam subbase material used on this project had a typical gradation with 3 in. maximum particle size and < 1% passing the #8 sieve. Field testing was conducted using Road Rater testing and visual crack/distress surveys. Some key findings from this study were as follows: (a) Road Rater testing indicated that the structural rating of a PCC pavement is improved if macadam subbase is used under the pavement. However, the improvement structural rating from using 5 in. of macadam subbase is equivalent to about additional ½ or ¾ in. PCC. The macadam subbase served primarily as a drainage layer and therefore could be reduced to 3.5 to 4 in. thickness instead of 5 in. Asphalt treating the macadam stone could be of additional benefit for stability of the base. (b) 2 to 3 in. thick PCC pavements over 5 in. macadam subbase showed poor performance and low structural rating. It is indicated that a minimum 5.5 in. PCC pavement is required over macadam to obtain 20 year design life. (c) Macadam served as a good drainage layer and prevented D-cracking on PCC pavements (within the 5 years of evaluation), which was a common problem in the area with using Class 1 aggregate (which contained fines). (d) Significant allowance should be made for material overruns when placing either PCC or asphalt pavement on macadam without chokestone (215 cubic yards per mile for PCC). (E) The quarry must be in close proximity for the project (within 10 to 20 miles) for macadam stone base to be economically practical.

Maurer, G., Bemanian, S., and Polish, P. (2007). "Alternative Strategies for Rehabilitation of Low-Volume Roads in Neveda." Transportation Research Record: Journal of the Transportation Research Board, 1989, 309-320.

An overview of the attempt by the Nevada Department of Transportation (NDOT) to find alternative rehabilitation strategies to rehabilitate its low-volume road network effectively is provided. Because of Nevada's continuing growth, NDOT is faced with the challenge of how to balance its available funding between pavement preservation and capacity improvement projects. NDOT is responsible for 13,000 lane miles of roadway, of which 3,385 lane miles (26%) qualify as low-volume roads. The low-volume roads have a two-directional average daily traffic of 400 or less. Five roadway projects with a combined total of 111 centerline miles were rehabilitated with 29 combinations of structural and surface strategies. The rehabilitation strategies investigated included full-depth reclamation with lime, cement, asphalts, and foamed asphalt. Various cold-mix, cold-in-place recycling with millings and different rejuvenating agents, and surface treatment test sections were constructed. The constructability issues that were reported during construction are discussed. In addition, pavement condition is examined and laboratory

testing is reviewed. Results suggest that NDOT can use alternative rehabilitation strategies in place of its conventional method of 2-in. plant-mix bituminous surface overlay and chip seal to rejuvenate its low-volume roadway network. A cost saving of approximately $100,000 per centerline mile is anticipated.

Mekkawy, M. M., White, D. J., Suleiman, M. T., and Jahren, C. T. (2011). "Mechanically reinforced granular shoulders on soft subgrade: Laboratory and full scale studies." Geotextiles and Geomembranes, 29, 149-160.

A recently completed field study in Iowa showed that many granular shoulders overlie clayey subgrade layer with California Bearing Ratio (CBR) value of 10 or less. When subjected to repeated traffic loads, some of these sections develop considerable rutting. Due to costly recurring maintenance and safety concerns, the authors evaluated the use of biaxial geogrids in stabilizing a severely rutted 310 m tests section supported on soft subgrade soils. Monitoring the test section for about one year, demonstrated the application of geogrid as a relatively simple method for improving the shoulder performance. The field test was supplemented with a laboratory testing program, where cyclic loading was used to study the performance of nine granular shoulder models. Each laboratory model simulated a granular shoulder supported on soft subgrade with geogrid reinforcement at the interface between both layers. Based on the research findings, a design chart correlating rut depth and number of load cycles to subgrade CBR was developed. The chart was verified by field and laboratory measurements and used to optimize the granular shoulder design parameters and better predict the performance of granular shoulders.

Munro, R., Evans, R., and Saarenketo, T. (2007). "ROADEX II Project: Focusing on Low-Volume Roads in the European Northern Periphery." Transportation Research Record: Journal of the Transportation Research Board, 1989(2), 292-299.

The ROADEX Project is a living case study on the benefits of partnering across road districts to make the best use of available budgets. The ROADEX Project partners had an early shared vision of cooperation that has since materialized in great benefits to their respective areas through collaboration in research and development and enhancement of their in-house capabilities by direct access to experience within the other partners' organizations. This sharing of information and experience has enabled them to have cost-effective research programs on shorter time scales than would otherwise have been the case and has avoided "reinventing the wheel" in research and development in each national district. The ROADEX II Project addresses the specific problems that arise in dealing with low-volume road management across the northern periphery of Europe so that reliable and regular year-round road networks can be provided to remote communities there. The outputs delivered in the ROADEX II Project offer a range of sustainable fit-for-purpose solutions to local road problems that together compose a tool kit of solutions for local managers to enable them to give better public service to their areas year after year.

Saarenketo, T., and Aho, S. (2005). "Managing Spring Thaw Weakening on Low Volume Roads - Problem Description, Load Restriction Policies, Monitoring and Rehabilitation." The ROADEXII Project, The Swedish Road Administration, Northern Region, Sweden.

This is a final report from the Phase II subproject 2_3 survey of the Roadex II project, a technical transnational cooperation project between the Highland Council, the Western Isles

Council, and Forest Enterprise from Scotland; the Northern Region (formerly Troms district) of the Norwegian Public Roads Administration and the Norwegian Road Haulage Association; the Northern Region of the Swedish National Road Administration; and from Finland the Regions of Central Finland and Lapland of the Finnish Road Administration, as well as Metsähallitus Region of Eastern Lapland, the Forestry Centre of Lapland (Lapin Metsäkeskus), Stora Enso Metsä, and Metsäliitto, Procurement Area of Northern Finland. The Roadex project is partly financed by the ERDF IIIB Northern Periphery Programme. The lead partner in the project is the Highland Council from Scotland and project consultant is Roadscanners Oy from Finland. Roadex II project Chairman is Ron Munro from the Highland Council and project manager is Timo Saarenketo from Roadscanners. The report summarizes the work done on Task 2_3 "Spring Thaw Weakening" of the Roadex II project. The report will describe the theory behind spring thaw weakening and different load restriction policies used in the cold climate areas. It will also report the results of the field tests done in Scotland, Sweden and Norway and present some new structural solutions which have been found to work well at spring thaw weakening sites. Finally, new technologies for both road owners and/or road users that could be used in more effective spring thaw weakening management will be revealed.

Salour, F., and Erlingsson, S. (2012). "Pavement Structural Behavior during Spring Thaw - Interpretation of FWD measurements by monitoring environmental data from county road 126 at Torpsbruk." 2009/0572-29, Swedish National Road and Transport Research Institute (VTI), Linkoping, Sweden.

The present research report has been carried out based on the environmental data and Falling Weight Deflectometer (FWD) measurements from the county road Lv 126 in Southern Sweden during the year 2010. The Lv 126 county road has a relatively thin flexible pavement structure with unbound aggregate base and subbase layers. The major intention of this study was to investigate the behaviour of the pavement structure during spring thaw. Temperature and moisture content of the pavement structure profile were continuously monitored throughout the year 2010. Layer moduli backcalculation as well as deflection basin analyses were performed using the FWD measurements data. A comprehensive study on the effect of environmental factor variations and pavement structural capacity were carried out during the spring thaw and recovery period. The result showed a considerable decrease in the bearing capacity of the pavement structure during the spring thaw period when the highest annual moisture content was also registered. Both deflection basin indices and backcalculated layer modulus indicated that the pavement was weakest during the subgrade thawing phase. Backcalculation on the FWD measurements showed a 63% loss in stiffness of the subgrade soil and 48% in the granular base and subbase course during the spring thaw compared to the summer values. In addition, the compatibility of the analysis with a predictive stiffness moduli- moisture content model for unbound materials was studied. The measured field data from the test road pavement in Torpsbruk showed promising agreement with the resilient modulus predictive model, both for the granular layer and subgrade material. Similar models could be developed or calibrated for other soils and granular materials if sufficient data become available in the future.

Shoop, S., Kester, M., Stark, J., Ryerson, C., and Affleck, R. (2003). "Rapid stabilization of thawing soils: field experience and application." Journal of Terramechanics, 39, 181-194.

Thawing soils can severely restrict vehicle travel on unpaved surfaces. However, a variety of materials and construction techniques can be used to stabilize thawing soils to reduce

immobilization problems. The US Engineer Research and Development Center's Army Cold Regions Research and Engineering Laboratory (CRREL) and the Wisconsin National Guard evaluated several stabilization techniques in a field demonstration project during spring thaw at Fort McCoy, Wisconsin, in 1995. Additional tests on chemical stabilizing techniques were conducted at CRREL's Frost Effects Research Facility. The results of these test programs were reduced to a decision matrix for stabilizing thawing ground, and used during the deployment of US troops in Bosnia during January and February of 1996. The soil frost and moisture conditions expected during this time frame were predicted using MIDFROCAL (MIDwest FROst CALculator). This paper is an overview of the stabilization techniques evaluated and their recommended application based on the expected soil frost conditions and traffic requirements. Although the experiments were performed with military vehicles in mind, the techniques are suitable for many civilian applications such as forestry, construction, mining, and oil exploration.

Sigurdsson, O. (1991). "Geosynthetic stabilization of unpaved roads on soft ground: a field evaluation." MS, The University of British Columbia, British Columbia, Canada.

A full scale field trial was carried out to investigate the performance of different geosynthetics in unpaved road construction over soft ground. The test site comprises of five 16 m long by 4.5 m wide test sections, build on a subgrade of undrained shear strength approximately 40 kPa. One is unreinforced and serves as a control section in the study, three sections include a geotextile, and one includes a geogrid. Each test section incorporated a variable thickness of sandy gravel base course material, between 25 and 50 cm thick. They were trafficked in sequence by a vehicle of standard axle load. An important governing parameter for interpretation of behavior is the influence of base course thickness on the relationship between number of passes and rut depth, base course thickness, base course deformations, geosynthetic strain, and deformed profile of the geosynthetic, with increasing number of vehicle passes. Vehicle trafficking was continued to a rut depth of about 20 cm, which constitutes a serviceability failure. Results from the full scale field trial show a better performance in the reinforced sections than the unreinforced section. The performance of the unreinforced section shows good agreement with other well-documented field data at large rut depths, between 10 and 15 cm, but not at small ruts. Although the four geosynthetics exhibited a broad range of stiffness and material properties, the general performance of the four reinforced sections was similar on the thicker base course layers. This is attributed to a reinforced mechanism governed by stiffness and separation, and all materials appear adequately stiff for the site conditions and vehicle loading. On the thinner subgrades, a tensioned-membrane effect is mobilized and a significant difference is observed between the geosynthetics.

Sirivitmaitrie, C., Puppala, A. J., Saride, S., and Hoyos, L. (2011). "Combined lime–cement stabilization for longer life of low-volume roads." Transportation Research Record: Journal of the Transportation Research Board, 2204, 140-147.

Low-volume roads are an important part of the world's transportation infrastructure and a direct cause of the socioeconomic development of small city and rural communities. Construction, maintenance, and rehabilitation of these roads are major tasks and require a major part of the public works budget. Better design and construction methods can prolong pavement service life and result in lower maintenance and rehabilitation costs. This paper presents a research study done for the city of Arlington in north Texas to stabilize road subsoils with a combined lime and cement stabilizer, which in turn is expected to enhance service life of the roads. Both laboratory tests on stabilized soil mixtures and field performance data are analyzed and presented.

White, D. J., Ceylan, H., Jahren, C. T., Phan, T. H., Kim, S. H., Gopalakrishnan, K., and Suleiman, M. T. (2008). "Performance Evaluation of Concrete Pavement Granular Subbase—Pavement Surface Condition Evaluation." IHRB Project TR-554, Center for Transportation Research and Education, Iowa State University, Ames, Iowa.

This research project covered a wide range of activities that allowed researchers to understand the relationship between stability, pavement distress, and recycled portland cement concrete (RPCC) subbase aggregate materials. Detailed laboratory and field tests, including pavement distress surveys, were conducted at 26 sites in Iowa were conducted. Findings show that specific gravities of RPCC are lower than those of crushed limestone. RPCC aggregate material varies from poorly or well-graded sand to gravel. A modified Micro-Deval test procedure showed that abrasion losses of virgin aggregate materials were within the maximum Micro-Deval abrasion loss of 30% recommended by ASTM D6028-06. Micro-Deval abrasion loss of RPCC aggregate materials, however were much higher than those of virgin materials and exceeded 30% loss. Modulus of elasticity of RPCC subbase materials is high but variable. RPCC subbase layers normally have low permeability. The pavement surfaces for both virgin and RPCC subbase across Iowa were evaluated to fulfill the objectives of this study related to field evaluation. Visual distress surveys were conducted to gather the detailed current pavement condition information including the type, extent, and severity of the pavement distresses. The historical pavement condition information for the surveyed field sections was extracted from the Iowa DOT's Pavement Management Information System (PMIS). The current surface condition of existing field pavements with RPCC subbase was compared with the virgin aggregate subbase sections using two different approaches. The changes in pavement condition indices (PCI and IRI) with time for both types of pavements (subbases) were compared.

White, D. J., Harrington, D., Ceylan, H., and Rupnow, T. (2005b). "Fly Ash Soil Stabilization for Non-Uniform Subgrade Soils, Volume II: Influence of Subgrade Non-Uniformity on PCC Pavement Performance." IHRB Project TR-461; FHWA Project 4, Center for Transportation Research and Education, Iowa State University, Ames, Iowa.

To provide insight into subgrade non-uniformity and its effects on pavement performance, this study investigated the influence of non-uniform subgrade support on pavement responses (stress and deflection) that affect pavement performance. Several reconstructed PCC pavement projects in Iowa were studied to document and evaluate the influence of subgrade/subbase non-uniformity on pavement performance. In situ field tests were performed at 12 sites to determine the subgrade/subbase engineering properties and develop a database of engineering parameter values for statistical and numerical analysis. Results of stiffness, moisture and density, strength, and soil classification were used to determine the spatial variability of a given property. Natural subgrade soils, fly ash-stabilized subgrade, reclaimed hydrated fly ash subbase, and granular subbase were studied. The influence of the spatial variability of subgrade/subbase on pavement performance was then evaluated by modeling the elastic properties of the pavement and subgrade using the ISLAB2000 finite element analysis program. A major conclusion from this study is that non-uniform subgrade/subbase stiffness increases localized deflections and causes principal stress concentrations in the pavement, which can lead to fatigue cracking and other types of pavement distresses. Field data show that hydrated fly ash,

self-cementing fly ash-stabilized subgrade, and granular subbases exhibit lower variability than natural subgrade soils. Pavement life should be increased through the use of more uniform subgrade support. Subgrade/subbase construction in the future should consider uniformity as a key to long-term pavement performance.

White, D. J., Harrington, D., and Thomas, Z. (2005a). "Fly Ash Soil Stabilization for Non-Uniform Subgrade Soils, Volume I: Engineering Properties and Construction Guidelines." IHRB Project TR-461, FHWA Project 4, Center for Transportation Research and Education, Iowa State University, Ames, Iowa.

Soil treated with self-cementing fly ash is increasingly being used in Iowa to stabilize fine-grained pavement subgrades, but without a complete understanding of the short- and long-term behavior. To develop a broader understanding of fly ash engineering properties, mixtures of five different soil types, ranging from ML to CH, and several different fly ash sources (including hydrated and conditioned fly ashes) were evaluated. Results show that soil compaction characteristics, compressive strength, wet/dry durability, freeze-thaw durability, hydration characteristics, rate of strength gain, and plasticity characteristics are all affected by the addition of fly ash. Specifically, Iowa self-cementing fly ashes are effective at stabilizing fine-grained Iowa soils for earthwork and paving operations; fly ash increases compacted dry density and reduces the optimum moisture content; strength gain in soil-fly ash mixtures depends on cure time and temperature, compaction energy, and compaction delay; sulfur contents can form expansive minerals in soil–fly ash mixtures, which severely reduces the long-term strength and durability; fly ash increases the California bearing ratio of fine-grained soil–fly ash effectively dries wet soils and provides an initial rapid strength gain; fly ash decreases swell potential of expansive soils; soil-fly ash mixtures cured below freezing temperatures and then soaked in water are highly susceptible to slaking and strength loss; soil stabilized with fly ash exhibits increased freeze-thaw durability; soil strength can be increased with the addition of hydrated fly ash and conditioned fly ash, but at higher rates and not as effectively as self-cementing fly ash. Based on the results of this study, three proposed specifications were developed for the use of self-cementing fly ash, hydrated fly ash, and conditioned fly ash. The specifications describe laboratory evaluation, field placement, moisture conditioning, compaction, quality control testing procedures, and basis of payment.

Limitations

Ashmawy, A., McDonald, R., Carreon, D., and Atalay, F. (2006). "Stabilization of Marginal Soils Using Recycled Materials." BD-544-4, Department of Civil and Environmental Engineering, University of South Florida, Tallahassee, Florida.

Loose sand, soft clays, and organic deposits are often unsuitable for use in construction due to their less-than-desirable engineering properties. Traditional methods of stabilizing these soils through in-situ ground improvement or replacement techniques are costly. Recycled materials such as scrap tires, plastics, ash, slag, and construction debris provide a viable alternative both for their relatively lower cost and desirable engineering properties. Furthermore, use of recycled materials prevents their disposal into landfills, which are approaching capacity in Florida and across the nation. This report provides a comprehensive assessment of various recycled materials that can be used to stabilize marginal soils in Florida. Particular attention is given to material availability and environmental properties in addition to engineering properties.

A methodology is proposed to guide FDOT personnel in evaluating, testing, and approving any new material for use as a highway construction material.

Brandon, T. L., Brown, J. J., Daniels, W. L., DeFazio, T. L., Filz, G. M., Mitchell, J. K., Musselman, J., and Forsha, C. (2009). "Rapid stabilization/polymerization of wet clay soils - literature review." Airbase Technologies Division, Material and Manufacturing Directorate, Air Force Research Laboratory, Tyndall Air Force Base, Florida.

This report is written in response to a request from the Air Force Research Laboratory concerning research on rapid stabilization/polymerization of wet clay soils. The purpose of this report is to document the findings of a literature review (Phase I) carried out by the team assembled at Virginia Tech. The literature review covers approximately 200 papers, most of which deal with clay stabilization. This report contains the findings of this literature review, which are categorized by soil type, stabilization type, as well as other factors. This report also includes the recommendations of the Virginia Tech research team for a proposed research program for Phase II.

Jahren, C. T., White, D. J., Phan, T. H., Westercamp, C., and Becker, P. (2011). "Stabilization Procedures to Mitigate Edge Rutting for Granular Shoulders – Phase II." IHRB Project TR-591, Institute for Transportation, Iowa State University, Ames, Iowa.

A multifaceted investigation was undertaken to develop recommendations for methods to stabilize granular road shoulders with the goal of mitigating edge ruts. Included was reconnaissance of problematic shoulder locations, a laboratory study to develop a method to test for changes in granular material stability when stabilizing agents are used, and the construction of three sets of test sections under traffic at locations with problematic granular shoulders. Full results of this investigation are included in this report and its appendices. Based on the results of the investigation, the following was concluded: (1) Problematic shoulders are generally stiff enough to carry expected traffic loads for emergency pull-off and temporary parking. Material gradations are generally finer than specified for new construction and cross slopes are often steeper than called out on cross sections for new construction. However, such differences in what is expected for original construction are consistent with damage that would be expected during use and maintenance (degradation of size due to breakage and abrasion and loss of material through erosion and winter and summer maintenance). Therefore, it seems likely that edge ruts develop from a combination of vehicle offtracking and time elapsed between maintenance cycles, rather than defects regarding original geometry and material gradation or from structural weakness. Some effort to renew cross slope and material gradation may be helpful in mitigating edge ruts. In addition, a shorter maintenance cycle would most likely be required to mitigate edge ruts. (2) Calcium chloride, magnesium chloride, and Base One did not provide noticeable improvements on the US 20 shoulders. However, they were easily applied and have the potential to be applied with the Iowa DOT's own maintenance staff, using its own equipment that could be modified from winter use. These methods were attempted because it was hypothesized that an important failure mode was that fine particles near the pavement edge were being removed by wind erosion, leaving only large particles that are easily displaced by off-tracking vehicles. These products bind fine particles, mechanically with Base One and by attracting moisture with calcium chloride and magnesium chloride. Apparently, some other mechanism causes the edge ruts, despite the presence of fine particles near the pavement edge. (3) If full-depth reclamation is used to incorporate stabilizers, the Iowa DOT does not currently own and operate the necessary

equipment to compact and stabilize the reclaimed material. To provide the needed compaction effort, heavier equipment would have to be purchased or rented. In particular, it would be necessary to have a pneumatic compactor that could operate bi-directionally. Typically-available, pull-behind compactors do not allow enough passes to be made quickly enough when consideration is given to the time required to safely turn the units, especially on limited access highways. (4) DUSTLOCK appears to wear well in locations where the shoulder material provides a stable base and vehicles do not off-track to the extent that they do on the US 20 test section. In areas of heavy off-tracking, preliminary indications are that stabilizing the shoulders reduces the number of maintenance cycles to half of what they would be without the stabilizer. (5) The laboratory test method for investigating stabilizer performance appeared to be a reasonable effort that provided some information about stabilized material behavior in confined situations. However, the method would have to be combined with a test similar to an asphalt rut test to detect instability for unconfined circumstances.

Jobgen, M. C., Callahan, M., Harris, G., and Tymkowicz, S. (1994). "Low cost techniques of base stabilization." Project HR-312, Iowa Department of Transportation, Ames, Iowa.

The IHRB HR-312 research project (Jobgen et al. 1994) evaluated performance of four different stabilization methods for on unsurfaced roads. These stabilization methods included using: a) high float emulsion (HFE-300) to treat top 3 in. of base stone, b) a bio-chemical formula called as BIO CAT 300-1 to treat the base stone for different thicknesses (6 in., 8in., and 10 in.), c) Consolid System method in the top 10 in. of subgrade soil, wherein when the soil is dry a combination of two inverted emulsions are used and when the soil is wet a combination of an inverted emulsion and a lime hydrated base powder are used to treat the base stone, and d) 5 in. of macadam base and 2 in. of choke stone along with fabric under one of the sections. All test sections were sealed using a double seal coat and performance evaluation was conducted on these sections using Iowa Road Rater, Roughometer, and visual inspection annually from 1989 to 1992. Some key findings from the field testing were as follows: (a) Test sections stabilized with BIO CAT300-1 and Consolid system showed the highest average k-value (207 pci to 225+ pci) four years after construction. HFE-300 stabilized section showed an average k-value of 181 pci, macadam subbase section showed an average k-value of 172 pci, and macadam subbase with fabric section showed an average k-value of 116 pci, four years after construction. (b) Although the BIO CAT 300-1 and Consolid System stabilized sections showed high k-values, they showed poor performance with alligator cracking and rutting under traffic, and continued deterioration every year. It is speculated in the report that these failures could have been due to freeze-thaw cycles in the stabilized layers. (c) HFE-300 treated test sections showed some deterioration with alligator cracking. Macadam subbase test sections (with and without fabric) experienced minor rutting and showed the best overall performance than all other sections. The use of fabric did not show noticeable improvement. (d) Use of macadam base and HFE-300 treatment showed cost effectiveness than other treatment options evaluated in this study.

Lab Testing Results

Aiban, S. A., Al-Ahmadi, H. M., Asi, I. M., Siddique, Z. U., and Al-Amoudi, O. S. B. (2006). "Effect of geotextile and cement on the performance of sabkha subgrade." Building and Environment, 41, 807-820.

Many construction and post-construction problems have been reported in the literature when sabkha soils have been used without an understanding of their abnormal behavior, especially their inferior loading capability in their natural conditions. The strength of these soils can be further significantly decreased if the sabkha is soaked. The main objective of this study was to upgrade the load carrying capacity of pavements constructed on sabkha soils using geotextiles, and to assess the effect of geotextile grade, base thickness, loading type (static and dynamic) and moisture condition (as-molded and soaked) on the performance of soil-fabric aggregate (SFA) systems. In addition, the sabkha soil was treated with different dosages (5%, 7%, and 10%) of Portland cement and the performance of cement-stabilized sabkha was compared to that of the SFA system under different testing conditions. The ANOVA results indicated that the use of geotextile has a beneficial effect on sabkha soils, especially under wet conditions. Although the improvement in the load-carrying capacity of sabkha samples with high dosages of cement showed better results than the inclusion of geotextile, an economic analysis showed that the use of geotextiles would be superior. Moreover, mechanistic analysis was used to develop a prediction model for the percentage increase in the modulus of resilience.

Aiban, S. A., Wahhab, H. I. A., Al-Amoudi, O. S. B., and Ahmed, H. R. (1998). "Performance of a stabilized marl base: a case study." Construction and Building Materials, 12, 329-340.

The formation of depressions and settlement in roads shortly after being constructed is one of the major challenges facing the road authorities in the Arabian Gulf States. Such problems have been closely related to the nature of pavement materials and loading conditions as well as to the proximity of groundwater tables to the surface. A major road in eastern Saudi Arabia was reported for frequent deterioration even when the construction was properly carried out. A preliminary investigation was conducted to quantify the properties of the base course material i.e. marl soil and the cause of failure. The laboratory investigation indicated that the marl used in the construction, similar to other marls, has acute water sensitivity and loss of strength whenever the soil is inundated. A precautionary and immediate solution was proposed to stabilize the soil with cement. Consequently, a comprehensive laboratory program was carried out to assess the performance of cement-stabilized marl mixtures under different exposure conditions. Based on the laboratory results and the traffic data for the road under investigation, four sections were constructed, two of them being without any additive while in the other two the base course being treated with 4% cement. Continuous monitoring and evaluation of the four sections for 4 years indicated that the cement-treated road sections have exhibited superior performance over the untreated ones. Unlike the untreated sections, which have experienced various forms of deterioration within a few months after construction, the stabilized sections are still in an excellent condition.

Al-Kiki, I. M., Al-Atalla, M. A., and Al-Zubaydi, A. H. (2011). "Long Term Strength and Durability of Clayey Soil Stabilized With Lime." Engineering and Technology Journal, 29(4), 725-735.

This study deals with durability characteristics and unconfined compressive strength of clayey soil stabilized with lime. The tests comprises of unconfined compressive strength for samples stabilized with the optimum lime percent (4%), and subjected to cycles of the wet-dry, dry-wet and freeze-thaw durability tests as well as, long-term soaking and slake tests. The results indicated that, the efficiency of the lime in the improvement of unconfined compressive strength of clayey soil is of negative effect in the long term durability periods The wetting-drying cycles showed greater reduction in unconfined compressive strength than drying-wetting cycles, while the volume change of samples which subjected to drying at first, was greater than those conducted with wetting. On the other hand, freezing-thawing cycles causes a decreasing in the unconfined compressive strength values, and the reduction ratio was greater than wetting and drying cases. But, during soaking tests it was found that at early soaking periods, the lime stabilized samples continuously gaining strength, but beyond this the strength decreased with increasing soaking period. Finally, the stabilized samples with (4 and 6%) lime becomes more durable against the cycles of wetting and drying.

Behera, B., and Mishra, M. K. (2012). "California bearing ratio and Brazilian tensile strength of mine overburden-fly ash-lime mixtures for mine haul road construction." Geotechnical and Geological Engineering, 30, 449-459.

The production and utilization of coal is based on well-proven and widely used technologies. Fly ash, a coal combustion byproduct, has potential to produce a composite material with controlled and superior properties. The major challenges with the production of fly ash are in its huge land coverage, adverse impact on environment etc. It puts pressure on the available land particularly in a densely populated country like India. In India the ash utilization percentage has not been very encouraging in spite of many attempts. Stabilization of fly ash is one of the methods to transfer the waste material into a safe construction material. This investigation is a step in that direction. This paper presents the results of an investigation on compressive strength and bearing ratio characteristics of surface coal mine overburden material and fly ash mixes stabilized with lime for coal mine haul road construction. Tests were performed with different percentages of lime (2, 3, 6 and 9%). The effects of lime content and curing period on the bearing ratio and tensile strength characteristics of the stabilized overburden and fly ash mixes are highlighted. Unconfined compressive strength test results cured for 7, 28 and 56 days are presented to develop correlation between different tensile strengths and unconfined compressive strength. Empirical models are developed to estimate bearing ratio and tensile strength of mine overburden–fly ash–quick lime mixtures from unconfined compressive strength test results.

Benson, C. H., Edil, T. B., Tanyu, B. F., and Kim, W.-H. (2005). "Equivalency of Crushed Rock with Industrial By-Products and Geosynthetic-Reinforced Aggregates Used for Working Platforms during Pavement Construction." WHRP Final Report No. 0092-00-12, Department of Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, WI.

A study was conducted to define an equivalency criterion for five materials used for working platforms during pavement construction on a poor subgrade: conventional crushed rock (referred to as “breaker run”) and four alternatives (i.e. Grade 2 granular backfill (referred to as “Grade 2”), foundry slag, bottom ash, and foundry sand). Total deflection data for the equivalency assessment were obtained from a large-scale model experiment (LSME) simulating a prototype-scale pavement structure and in the field using a rolling wheel deflectometer (RWD). Design charts were developed for selecting the equivalent thickness of alternative working platform materials so that the alternative provides equal deflection as a layer of breaker run.

Another phase of the study was conducted to determine the equivalency of geosynthetic reinforced aggregate working platforms in providing support during pavement construction over soft subgrade. Four reinforcing geosynthetics (a geogrid, a woven geotextile, a non-woven geotextile, and drainage geocomposite) incorporated into two granular materials: Grade 2 and breaker run were used in this study. Design charts were developed for selecting the equivalent thickness of an alternative geosynthetic-reinforced working platform material so that the alternative provides equal deflection as a layer of breaker run.

Berg, K. C. (1998). "Durability and strength of activated reclaimed Iowa Class C fly ash aggregate in road bases." M.S. Thesis, Department of Civil Engineering, Iowa State University, Ames, Iowa.

The development of high-volume uses for coal-fired power plant waste creates both economic and environmental benefits. Approximately 90 million tons of coal combustion by-products are produced each year in the United States, including 70 to 80 million tons of fly ash. Only about 25% of the fly ash produced is utilized by other industries. Power plant waste such as fly ash, if not utilized in industrial or construction projects, must be disposed of in landfills or sluice ponds. Fly ash is commonly used as a partial replacement for Portland cement in concrete, where it has been shown to provide comparable strength for a significantly lower cost. A growing application for fly ash use is for the stabilization of soils that would otherwise be unsuitable construction materials. Fly ash has been economically used to increase strength, lower plasticity, and reduce the moisture content of soils that would have otherwise required Portland cement or lime stabilization. While both of these fly ash utilization methods provide clear economic and engineering benefits, only a relatively small portion of the fly ash produced can be utilized. Fly ash is usually limited to 15% replacement of Portland cement in concrete, and typical addition rates for soil stabilization are 5% to 15% by dry weight of soil. Higher volume uses for coal combustion products are necessary to significantly reduce the amount of waste that must be landfilled. The development of high-volume construction uses for a significant portion of this waste can reduce the landfilling costs as well as produce revenue from sale of the materials. A promising high-volume application of hydrated reclaimed Class C fly ash is as a replacement for aggregate in flexible pavement base courses. The focus of this research is to evaluate the properties of hydrated Iowa Class C fly ash aggregates reclaimed from sluice pond disposal sites. Bergeson and Barnes have recently developed a pavement thickness design method for the use of these aggregates in flexible pavement base courses based on the California Bearing Ratio (CBR) and unconfined compressive strength. To reinforce this strength-based pavement design, this research focuses on the freeze-thaw durability, volumetric stability, and long-term strength gain of hydrated reclaimed fly ash aggregate with different chemical activators. The main consideration for the prediction of the durability, strength, and volumetric stability of activator/reclaimed fly ash aggregate mixtures is the manner in which they will perform in field applications. The results of freeze-thaw durability testing, ASTM C 593 vacuum-saturated compressive strength testing, and unconfined compressive strength testing indicate that the untreated materials act as a granular material, while the lime-treated material develops higher strengths associated with a pozzolanic base material. The use of CKD, which is highly effective as an activator, was discontinued due to lowered availability and environmental concerns. CKD can contain high levels of lead, and changes in the manufacture of Portland cement have rendered it nearly unavailable in Iowa. Raw fly ash is somewhat effective as an activator, but fly ash/reclaimed fly ash aggregate mixtures break down when subjected to multiple freeze-thaw cycles. This may not be a large problem if high strengths are not required, because the base will probably function in a similar manner to a crushed stone base. This is evidenced by the good performance of the AFBC/reclaimed fly ash aggregate sections of the Ottumwa-Midland and Sutherland access roads. The surface courses of both roads remain intact and serviceable despite the deterioration of base into rough, angular aggregate-sized pieces. Although cores can no longer be extracted from these sections, aggregate interlock forces appear to provide adequate strength to the pavements. The use of fly ash aggregate without an activator is the obvious choice for low cost applications where high strengths are not required. The addition of 2.5% lime by dry weight of reclaimed ash aggregate provides significant gains in strength and durability for all the reclaimed fly ash aggregate sources tested in this project. The use of fly ash as an activator is preferred by vendors of reclaimed fly ash aggregate because they already possess it and do not need to purchase it from another source. This would not be the case with lime. The effectiveness of fly ash as an activator for reclaimed fly ash aggregate is definite, but it is not nearly as pronounced as the effect of lime activator. The addition of fly ash activator definitely results in a strength and durability increase, but as Barnes (11) has indicated, magnitude of this strength gain is questionable and the fast setting tendency of fly ash may raise concerns for road base construction. The additive level of 10% fly ash by dry weight of aggregate was selected as optimum. This level reduces keeps the workability concerns to a minimum, and 15% and 20% fly ash addition rates did not provide significantly different strength or durability than 10% fly ash in any of the materials tested for this project.

Bergeson, K. L., Kane, M. J., and Callen, D. O. (1990). "Crushed stone granular surfacing materials." Sponsored by the Iowa Limestone Produces Association and National Stone Association Research Program, Report by Engineering Research Institute, Iowa State University, Ames, Iowa.

The results of this research project indicate that crushed stone surfacing material graded on the fine side of IDOT Class A surfacing specifications provides lower roughness and better rideability; better braking and handling characteristics; and less dust generation than the coarser gradations. This is believed to be because there is sufficient fines (-#40 to - #200) available to act as a binder for the coarser material, which in turn promotes the formation of tight surface crust. This crust acts to provide a smooth riding surface, reduces dust generation, and improves vehicle braking and handling characteristics.

Bergeson, K. L., Waddingham, J. W., Brocka, S. G., and Lapke, R. K. (1995). "Bentonite treatment for economical dust reduction on limestone surface secondary roads." Iowa DOT Project HR-351, Engineering Research Institute, Iowa State University, Ames, Iowa.

This research project was directed at laboratory and field evaluation of sodium montmorillonite clay (Bentonite) as a dust palliative for limestone surfaced secondary roads. It was postulated that the electrically charged surfaces (negative) of the clay particles could interact with the charged surfaces (positive) of the limestone and act as a bonding agent to agglomerate fine (- #200) particulates, and also to bond the fine particulates to larger (+ #200) limestone panicles. One mile test roads were constructed in Tama, Appanoose, and Hancock counties in Iowa using Bentonite treatment levels (by weight of aggregate) ranging from 3.0 to 12.0 percent. Construction was accomplished by adding dry Bentonite to the surfacing material and then dry road mixing. The soda ash water solution (dispersing agent) was spray applied and the treated surfacing material wet mixed by motor graders to a consistency of 2 to 3 inch slump concrete.

Two motor graders working in tandem provided rapid mixing. Following wet mixing the material was surface spread and compacted by local traffic. Quantitative and qualitative periodic evaluations and testing of the test roads was conducted with respect to dust generation, crust development, roughness, and braking characteristics. As the Bentonite treatment level increased dust generation decreased. From a cost benefit standpoint, an optimum level of treatment is about 8 percent (by weight of aggregate). For roads with light traffic, one application at this treatment level resulted in a 60-70 percent average dust reduction in the first season, 40-50 percent in the second season, and 20-30 percent in the third season. Crust development was rated at two times better than untreated control sections. No discernible trend was evident with respect to roughness. There was no evident difference in any of the test sections with respect to braking distance and braking handling characteristics, under wet surface conditions compared to the control sections. Chloride treatments are more effective in dust reduction in the short term (3-4 months). Bentonite treatment is capable dust reduction over the lone: term (2-3 seasons). Normal maintenance blading operations can be used on Bentonite treated areas. Soda ash dispersed Bentonite treatment is conservatively estimated to be more than twice as cost effective per percent dust reduction than conventional chloride treatments, with respect to time. However, the disadvantage is that there is not the initial dramatic reduction in dust generation as with the chloride treatment. Although dust is reduced significantly after treatment there is still dust being generated. Video evidence indicates that the dust cloud in the Bentonite treated sections does not rise as high, or spread as wide as the cloud in the untreated section. It also settles faster than the cloud in the untreated section. This is considered important for driving safety of following traffic, and for nuisance dust invasion of residences and residential areas. The Bentonite appears to be functioning as a bonding agent to bind small limestone particulates to larger particles and is acting to agglomerate fine particles of limestone as evidenced by laboratory sieve analysis data, and by SEM micrographs. This bonding capability appears recoverable from environmental effects of winter, and from alternating wet and dry periods. The Bentonite is able to interact with new applications of limestone maintenance material and maintains a dust reduction capability.

Bhatty, J. I., Bhattacharja, S., and Todres, H. A. (1996). "Use of cement kiln dust in stabilizing clay soils." Portland Cement Association, Skokie, Illinois.

This report is part of an overall Portland Cement Association (PCA) project on the role of cement kiln dust (CKD), portland cement, and lime in the stabilization of clay soils. In this report, the term "clay soils" means soils having a variable clay content which normally manifests itself by causing the soil to have undesirable properties from an engineering point of view. The effect of the clay can thus be considered to be due to a combination of the clay's activity (plasticity, volume change, etc.) and its proportion of the whole. In a few special cases, non-clay soils have been stabilized using CKDs; clearly the mechanism of the stabilization is different for these soils. These cases are referenced in this report for completeness, and are differentiated from clay soils. Because of the (sometimes) high lime content and the fineness of CKD particles, the use of dust in stabilizing highly expansive clay soils for subbase and related applications is getting increased attention. Literature suggests that CKD enhances many of the engineering properties of the sub grade soils, and reduces the swelling potential of expansive clays. However, available information on the use of CKD for such applications is preliminary, isolated, and lacks quantitative data, as most of the work has been done only on selected soils and selected CKDs. It has been suggested that in order to have an insight on the stabilization potential of CKD and a complete understanding of the underlying mechanism, comprehensive and systematic studies on

CKD-soil stabilization are needed. This would require a selection of CKDs from different plant operations, and a selection of sub grade soils and expansive clays. The effect of CKD on the engineering properties needs to be optimized and compared with traditionally used stabilizing agents such as hydrated lime, fly ash, and portland cement.

Bin-Shafique, S., Rahman, K., Yaykiran, M., and Azfar, I. (2010). "The long-term performance of two fly ash stabilized fine-grained soil subbases." Resources, Conservation and Recycling, 54, 666-672.

An experimental study was conducted to investigate the long-term performance of fly ash stabilized two fine-grained soil subbases. One low plasticity clay soil and one high plasticity expansive clay soil were stabilized with a Class C fly ash with fly ash contents of 0%, 5%, 10%, and 20%, and compacted statically at the maximum dry density (standard Proctor) and at the optimum moisture content of the corresponding soil to prepare ten sets of replicates from each of the combinations. After curing all specimens for 7 days, the first set was subjected to plasticity index tests, unconfined compression tests, and vertical swell tests to estimate the improvement due to stabilization. Similar tests were also conducted on another nine sets of replicates in which six sets were subjected to 12 wet–dry cycles (three sets with tap water and the other three sets with saline water), and the other three sets were subjected to 12 freeze–thaw cycles in a laboratory controlled environment to simulate the weathering action. The effect of wet–dry cycles on stabilized soils was essentially insignificant; however, the fly ash stabilized soils lost up to 40% of the strength due to freeze–thaw cycles. Even after losing the strength significantly, the strength of stabilized soils was at least three times higher than that of the unstabilized soils. The swell potential of stabilized expansive soils also increased due to freeze–thaw cycles. The vertical swell increases rapidly for first four to five cycles and then increases very slowly.

Bland, A. E., Brown, T. H., and Sheesley, D. C. (1991). "Fly ash use for unpaved road stabilization - Phase I." Interim Technical Report WRI-92-R017, The University of Wyoming, Laramie, Wyoming.

Western Research Institute (WRI) has conducted both laboratory and field demonstrations of a relatively new nonstandard unpaved road stabilization technique burning Class C fly ash from coal-fired power generation plants using Wyoming subbituminous coals. The experimental construction technique uses lean fly ash/soil/water formulations for stabilizing unpaved road materials to reduce maintenance costs and to provide new expanded markets for coal fly ash. The experimental testing program was designed to evaluate different soil/fly ash conditions as well as different construction techniques. Laboratory testing was conducted using ash from the PacifiCorp Dave Johnston Power Plant (DJPP) near Glenrock, Wyoming and five different soil types from a road adjacent to the plant. The laboratory testing examined the geotechnical performance of the various amounts of fly ash treatment of the soils. Moisture-density relationships and moisture-strength relationships were determined. The Dave Johnston fly ash is a slow-reacting fly ash, and early strength development was low (less than 100 psi) for all mixtures tested up to 25% fly ash. A twofold increase in strength was noted between the low fly ash dosage rates (5%) and the high fly ash dosage (25%). Based on the results of the laboratory testing, it is recommended to use 20% fly ash and optimum moisture for compaction of 11 to 13% water. Two 1,000-ft experimental test sections demonstrating the fly ash stabilized unpaved road process were constructed in July 1991, near the DJPP. The unpaved road had a continued history of washboarding and required regular high levels of maintenance. Based on the laboratory testing and design, the experimental test road was constructed using Dave Johnston fly ash as a binder to stabilize the upper 9 inches of the road surface. The intent was to treat the road sections by scarifying\ adding fly ash, and thoroughly mixing these materials with water and compacting the mixture to a highly densified and stable road surface. It was intended that the road be immediately available to traffic and continue to improve in strength and durability with time. WRI decided to use a fly ash application of 20% to construct the test section for several reasons: (1) The fly ash source was adjacent to the road construction site, and no transportation costs would be incurred. (2) A high application percentage would provide a range of high and low ash concentrations to study. (3) The laboratory studies suggested that a 20% application of fly ash from the DJPP was required for maximum strength development in the test section. Two demonstration test sections were constructed. Fly ash from Unit 3 of the DJPP was used for the treatment. Also, water from the Dave Johnston recycle pond was used. The materials consisted of 240 tons of fly ash and 10,000 gallons of water. Based on calculations of the depth of treatment and the bulk density of the road material, a fly ash treatment of 20% and a water addition of 11 % were achieved. The laboratory design testing suggested that optimum moistures in the range of 11 to 13% were required for maximum compaction. Visual monitoring of the road showed that some areas required remedial attention. This was a result of inadequate mixing of the fly ash and soil, and insufficient water addition during construction. A soft spot in the road with a high fly ash content, was patched to reduce dusting and improve trafficability. The test sections were dusting because either insufficient water was added during construction or the fly ash mixtures dried out before sufficient curing could occur. The treated sections were covered with bottom ash to act as a moisture barrier and cover to the surface. The barrier was successful, but the bottom ash developed severe washboarding. As a result, the bottom ash was removed after the fly ash/soil achieved sufficient strength and · durability. Additional water applications helped develop a hard, upper 2- to 3-inch surface in the fly ash treated section of the road. Performance monitoring and evaluation of the construction techniques show that mixing was inadequate, whereas compaction appears to be satisfactory. Fly ash distribution via blade mixing did not produce a homogeneous mixture, although improvement may have been possible if additional passes had been performed. Evidence for both lateral variations in the test section from 15 to 50% fly ash and a vertical layering in the treated section have been documented. Inadequate water distribution due to improper mixing was also noted as evidenced by the fact that areas were found that appeared to have received little or no water. Compaction of the fly ash treated soil mixtures was in the range of 95% of the laboratory results and the estimated maximum dry density. The performance of the fly ash treated section is presently quite good, showing continued strength development and reduced potential for dusting. The mechanically treated section is developing cracks, which are expected to create problems by Spring 1992. The control section is already showing washboarding as it has in the past. The fly ash stabilization technology appears to be an environmentally acceptable technology that does not pose a threat to groundwater. The surface water and storm water runoff have not been assessed because rainfall in the area has been too low. However, WRI does not anticipate problems associated with surface water or storm water runoff quality. In addition, the level of radioactivity for the fly ash is too low to be a health concern. However, the application of the fly ash during the construction phase needs to be improved to prevent excessive fugitive dust emissions. Options for modifying the construction procedure are being addressed and will be incorporated into future test sections. The results of the phase I testing and demonstration activities show that the process of fly ash stabilization of unpaved roads is promising. Although the strength development with the Dave

Johnston fly ash is very slow, engineering performance of the road demonstration test sections is quite good. The fly ash treated test section has shown no evidence of washboarding, and the dust from the road has been reduced to levels comparable to the control section of the unpaved road.

Bolander, P. (1999). "Laboratory Testing of Nontraditional Additives for Stabilization of Roads and Trail Surfaces." Transportation Research Record: Journal of the Transportation Research Board, 1652, 24-31.

Recently the Pacific Northwest Region of the U.S. Department of Agriculture Forest Service conducted laboratory tests evaluating the expected field performance of various additives on dense-graded aggregate. Additives used in the laboratory analysis included chlorides, clay, enzymes, lignin sulfonate, synthetic polymer emulsions, and tall oil emulsions. Laboratory analysis included indirect tensile strength and durability testing on AASHTO T 99 fabricated samples. Durability was evaluated after a number of wet-dry and freeze-thaw cycles. Other variables in the study included the amount of additive and the cure (temperature and time) before testing. Findings and observations include the following: (a) Untreated dense-graded aggregate provides little tensile strength in warm dry climates. (b) Chlorides, clay additives, enzymes, and sulfonate provide some tensile strength in warm dry climates. With increasing moisture contents they lose their tensile strength. (c) Once cured, synthetic polymer and tall oil emulsions provide significant tensile strength in warm dry climates. In wet climates these additives would tend to break down with increased exposure to moisture or freezing. (d) Increasing the percent residual (solids) of the synthetic polymer emulsions and tall oil emulsions increases the tensile strength and durability of the treated material. (e) Cure temperature has a dramatic impact on tall oil emulsions' tensile strength and durability resistance. (f) The use of nontraditional additives can be cost-effective depending on the projects' objective, the type of in-place material, and the cost of the additive.

Castedo, L. H., and Wood, L. E. (1983). "Stabilization with foamed asphalt of aggregates commonly used in low-volume roads." Transportation Research Record: Journal of the Transportation Research Board, 898, 297-302.

Foamed asphalt, which is generated by combining asphalt cement and cold water through a foam nozzle, has been used worldwide as a means of stabilizing pavement construction materials. A review of the literature indicated a successful and broad use of foamed asphalt in low-volume-road construction. This relatively new concept appears to exhibit several characteristics that could lead to increased use of locally available materials as well as a more economical stabilization process without some detrimental features associated with other agents. The effects of different variables on foamed-asphalt mix design (Foamix) were investigated in this study. An AC-20 asphalt cement was used as the binder material. The aggregates included in the study were outwash sand, put-run gravel, and crushed stone. The variables studied were foamed-asphalt content (two levels), moisture content (three levels), and curing period (three levels). Foamix was found to be significantly affected by water infiltration. Water sensitivity results indicated that saturated strengths were much lower than corresponding cured strengths. Specimens fabricated at the highest bitumen content showed a greater resistance to water. In addition, moisture content (at mixing), bitumen content, and total fluid content all proved to have an effect on mixture performance. Foamix strengths increased with curing time, particularly from one to three days. It appears that foamed asphalt can be used as a stabilizing agent for commonly

available virgin aggregates as well as recycled material when adequate drainage and/or sealing is provided or when they are located in relatively dry environments.

Cerato, A. B., Miller, G. A., Snethen, D. S., and Hussey, N. (2011). "Validation and Refinement of Chemical Stabilization Procedures for Pavement Subgrade Soils in Oklahoma - Volume 1." FHWA-OK-11-02, School of Civil Engineering and Environmental Science, University of Oklahoma, Normal, OK.

Additions of byproduct chemicals, such as fly ash or cement kiln dust, have been shown to increase the unconfined compression strength (UCS) of soils. To be considered effective, the soil must exhibit a strength increase of at least 50 psi. Many current design methods base chemical additive percentage recommendations on the results of Atterberg Limit tests which do not always properly characterize the soil stabilization response. For example, Atterberg limit tests may reveal the same AASHTO classification of soil at two different sites, but one site may require more than twice the additive percentage of a chemical to achieve the desired UCS increase. This study examined the relationship between soil physico-chemical parameters and unconfined compression strength in various fine-grained soils to determine if other soil parameters have significant effects on predicting the strength of a soil treated with a given additive and additive content. The results of this study suggest that the surface area and shrinkage properties of the soil, combined with the Atterberg limit results, present a better picture of a given soil and will allow for better predictions of the amount of chemical stabilizer needed to adequately stabilize the soil.

Collins, R. W. (2011). "Stabilization of marginal soils using geofibers and nontraditional additives." MS Thesis, University of Alaska, Fairbanks, Alaska.

Western Alaska lacks gravel suitable for construction of roads and airports. As a result, gravel is imported, at a cost of between $200 and $600 per cubic yard, to fill transportation construction needs. In an effort to reduce these costs, the Alaska University Transportation Center (AUTC) began searching for methods to use local materials in lieu of imported gravel. The approach discussed in this thesis uses geofibers and chemical additives to achieve soil stabilization. Geofibers and chemical additives are commercially available products. The goal of the research presented in this thesis is to test the impact of addition of two geofiber types, six chemical additives, and combinations of geofibers with chemical additives on a wide variety of soil types. California Bearing Ratio (CBR) testing was used to measure the effectiveness of the treatments. Soils ranging from poorly graded sand (SP) to low plasticity silt (ML) were all effectively stabilized using geofibers, chemical additives, or a combination of the two. Through the research conducted a new method of soil stabilization was developed which makes use of curing accelerators in combination with chemical additives. This method produced CBR values above 300 for poorly graded sand after a seven day cure.

Consoli, N. C., Prietto, P. D. M., and Ulbrich, L. A. (1998). "Influence of fiber and cement addition on behavior of sandy soil." Journal of Geotechnical and Geoenvironmental Engineering, 124(12), 1211 to 1214.

Triaxial compression tests were carried out to evaluate the effect of randomly distributed fiber reinforcement and cement inclusion on the response of a sandy soil to load. Cemented specimens were prepared with cement contents of 0% and 1% by weight of dry soil and cured for seven days. Fiber length was of 12.8 mm, in the contents of 0% and 3% by weight of dry soil-cement mixture. Test results indicated that the addition of cement to soil increases stiffness, brittleness, and peak strength. The fiber reinforcement increases both the peak and residual triaxial strength, decreases stiffness, and changes the cemented soil's brittle behavior to a more ductile one. The triaxial peak strength increase due to fiber inclusion is more effective for uncemented soil. However, the increase in residual strength is more efficacious when fiber is added to cemented soil. Peak strength envelopes indicate that the friction angle is increased from 35° to 46° as a result of fiber inclusion. The cohesion intercept is affected slightly by fiber addition, being basically a function of cementation.

Consoli, N. C., Vendruscolo, M. A., and Prietto, P. D. M. (2003). "Behavior of plate load tests on soil layers improved with cement and fiber." Journal of Geotechnical and Geoenvironmental Engineering, 129(1), 96-101.

The load-settlement response from three plate load tests ~300 mm diameter, 25.4 mm thick carried out directly on a homogeneous residual soil stratum, as well as on a layered system formed by two different top layers ~300 mm thick!—sand-cement and sand-cement fiber—overlaying the residual soil stratum, is discussed in this technical note. The utilization of a cemented top layer increased bearing capacity, reduced displacement at failure, and changed soil behavior to a noticeable brittle behavior. After maximum load, the bearing capacity dropped towards approximately the same value found for the plate test carried out directly on the residual soil. The addition of fiber to the cemented top layer maintained roughly the same bearing capacity but changed the post failure behavior to a ductile behavior. A punching failure mechanism was observed in the field for the load test bearing on the sand-cement top layer, with tension cracks being formed from the bottom to the top of the layer. A completely distinct mechanism was observed in the case of the sand-cement-fiber top layer, the failure occurring through the formation of a thick shear band around the border of the plate, which allowed the stresses to spread through a larger area over the residual soil stratum.

Croft, J. B. (1968). "The problem in predicting the suitability of soils for cementitious stabilization." Engineering Geology, 2(6), 397-424.

The suitability of a soil for stabilization, the most appropriate stabilizing agent, and the quantity of agent are determined by the chemical and mineralogical compositions and texture of a soil. Soil classification based upon physical properties, compositional indices and genetic relationships are examined to determine their value for predicting successful stabilization. Chemical and physical properties do not characterize soils uniquely with regard to their response to cementitious stabilizing agents. The grouping of soils in an area according to their origins appears to be a practical solution. The object of the paper has been to draw attention to some of the factors influencing soil stabilization. It is not claimed that any of the procedures for predicting successful stabilization are infallible, and much depends upon personal judgment. However, once a knowledge of the soils in an area is accumulated, performance can be predicted with sufficient accuracy to eliminate much routine testing.

Daniels, J. L., and Janardhanam, R. (2007). "Cold-weather subgrade stabilization." GSP 172 Soil Improvement, V. R. Schaefer, G. M. Filz, P. M. Gallagher, A. L. Sehn, and K. J. Wissmann, eds., ASCE, Denver, Colorado.

This paper describes an approach to cold-weather subgrade stabilization. Background information was derived from the open literature, ongoing research and discussions with

stakeholders in industry, academia and the government. Traditional subgrade stabilization in road construction is defined herein as the use of unmodified lime, cement or fly ash in soil to improve the strength and overall performance of a pavement system. Many of the non-traditional additives currently on the market have been evaluated in recent years. Broadly, these may be categorized as asphalts, polymers, electrolytes, biochemical additives, FGD gypsum and lime/cement additives. Careful evaluation of each category in turn reveals that the most promising alternative to unmodified lime and cement is modified lime and cement. Specifically, rapidly maturing research in the field of cold weather concreting has demonstrated the ability for cementitious reactions to occur at low and sub-freezing temperatures when modified appropriately. Cementitious reactions are the same principle by which conventional lime and cement impart strength on subgrade soils. Naturally, straightforward research is required to transfer concreting technology to soil stabilization. To that end, an experimental campaign has been conducted. In particular, three chemical additives were selected and procured from the W.R. Grace Company, namely Polarset, Gilco, and Daraccel. As a preliminary metric of performance, unconfined compression strength testing was conducted on mixtures with and without the chemical additives. At the levels tested, the range of additives increase the cost of conventional stabilization from approximately 10 to 50%, although subsequent research may lower those values still. The control (unmodified) mixture of soil and cement resulted in an average 1-day strength of 487.1 kPa (70.6 psi) when cured at 2oC (35.6oF). For the same mixture at the same curing temperature, the average 1-day strength increased to 1286.9, 1394.5 and 1079.2 kPa (186.5, 202.1 and 156.4 psi) for the Polarset, Gilco and Daraccel additives, respectively. These increased strengths at 2^{o}C are also approximately double that of the unmodified samples cured at 20oC. These results are unique in that they represent the first application of cold-weather concreting technology to soil stabilization. While more work remains, these results suggest that the additives are promising.

DeJong, J. T., Frizges, M. B., and Nosslein, K. (2006). "Microbially Induced Cementation to Control Sand Response to Undrained Shear." Journal of Geotechnical and Geoenvironmental Engineering, 132(11), 1381-1392.

Current methods to improve the engineering properties of sands are diverse with respect to methodology, treatment uniformity, cost, environmental impact, site accessibility requirements, etc. All of these methods have benefits and drawbacks, and there continues to be a need to explore new possibilities of soil improvement, particularly as suitable land for development becomes more scarce. This paper presents the results of a study in which natural microbial biological processes were used to engineer a cemented soil matrix within initially loose, collapsible sand. Microbially induced calcite precipitation (MICP) was achieved using the microorganism Bacillus pasteurii, an aerobic bacterium pervasive in natural soil deposits. The microbes were introduced to the sand specimens in a liquid growth medium amended with urea and a dissolved calcium source. Subsequent cementation treatments were passed through the specimen to increase the cementation level of the sand particle matrix. The results of both MICP- and gypsum-cemented specimens were assessed nondestructively by measuring the shear wave velocity with bender elements. A series of isotropically consolidated undrained compression (CIUC) triaxial tests indicate that the MICP-treated specimens exhibit a noncollapse strain softening shear behavior, with a higher initial shear stiffness and ultimate shear capacity than untreated loose specimens. This behavior is similar to that of the gypsum-cemented specimens, which represent typical cemented sand behavior. SEM microscopy verified formation of a cemented sand matrix with a concentration of precipitated calcite forming bonds at particle-particle contacts. X-ray compositional mapping confirmed that the observed cement bonds were comprised of calcite.

DeJong, J. T., Mortenson, B. M., Martinez, B. C., and Nelson, D. C. (2010). "Bio-Mediated Soil Improvement." Ecological Engineering, 36(10), 197-210.

New, exciting opportunities for utilizing biological processes to modify the engineering properties of the subsurface (e.g. strength, stiffness, permeability) have recently emerged. Enabled by interdisciplinary research at the confluence of microbiology, geochemistry, and civil engineering, this new field has the potential to meet society's ever-expanding needs for innovative treatment processes that improve soil supporting new and existing infrastructure. This paper first presents an overview of bio-mediated improvement systems, identifying the primary components and interplay between different disciplines. Geometric compatibility between soil and microbes that restricts the utility of different systems is identified. Focus is then narrowed to a specific system, namely bio-mediated calcite precipitation of sands. Following an overview of the process, alternative biological processes for inducing calcite precipitation are identified and various microscopy techniques are used to assess how the pore space volume is altered by calcite precipitation, the calcite precipitation is distributed spatially within the pore space, and the precipitated calcite degrades during loading. Non-destructive geophysical process monitoring techniques are described and their utility explored. Next, the extent to which various soil engineering properties is identified through experimental examples. Potential advantages and envisioned applications of bio-mediated soil improvement are identified. Finally, the primary challenges that lie ahead, namely optimization and upscaling of the processes and the education/training of researchers/practitioners are briefly discussed.

Dempsey, B. J., and Thompson, M. R. (1972). "Effects of freeze-thaw parameters on the durability of stabilized materials." Highway Research Record, 379, 10-18.

A study was conducted to evaluate the effects of various frost-action parameters on the freeze-thaw durability of stabilized materials and to determine which parameters could be modified so that a characteristic freeze-thaw cycle could be adapted to laboratory use. The parameters studied were cooling rate, freezing temperature, length of freezing period, and thawing temperature. The cooling rate was found to be an important factor affecting the freeze-thaw durability of stabilized soils. Lower cooling rates (0. 2 to 2. 0 F/hr) that correlated best with quantitative field data were generally the most detrimental to durability. A sustained freezing study revealed that the length of the freezing period did not have to be greater than that required to accomplish complete freezing of the test specimen. The study further indicated that freezing and thawing temperatures should be representative of those for in-service pavement systems. Thawing temperatures for some stabilized materials are important because strength increase caused by a pozzolanic reaction is possible at high temperatures. The number of cycles used in a laboratory freeze-thaw test should be related to geographical location, climatic conditions, and position of the stabilized layer in the pavement system. For Illinois climatic conditions, a laboratory freeze-thaw cycle representative of field conditions would require a completion period of 48 hours.

Douglas, R. A., and Valsangkar, A. J. (1992). "Unpaved geosynthetic-built resource access roads: stiffness rather than rut depth as the key design criterion." Geotextiles and Geomembranes, 11, 45-49.

The economic significance of unpaved, resource access roads is enormous, contrary to widespread opinion, and their unique behaviour and requirements are in need of further study. It is pointed out that overall transportation costs and efficiencies are inextricably linked to the relationships between roads and vehicles. Because of the impact that road stiffness has on fuel consumption and therefore vehicle operating costs, it is contended that stiffness rather than permanent rut depth should be adopted as the key design criterion for resource access roads. In addition, carrying the rut depth criterion used in the design of sealed roads into the design of unsealed access roads is inappropriate, because for these roads, ruts can be eradicated by periodic maintenance operations. Because it is reasonable to expect that the stiffness of a low-standard access road structure could be significantly increased by the inclusion of a geogrid or geotextile, the range of road stiffness to be expected, and how it is affected by geosynthetic inclusions, was investigated by cycled-load testing of large-scale model pavement structures, consisting of granular bases provided with various geosynthetics placed on peat subgrades. Surprisingly, the improvement in model pavement stiffness over that for the subgrade itself was not great.

Ghazavi, M., and Roustaie, M. (2010). "The influence of freeze–thaw cycles on the unconfined compressive strength of fiber-reinforced clay." Cold Regions Science and Technology, 61, 125-131.

Freeze–thaw cycling is a weathering process that frequently occurs in cold climates. In the freeze state, thermodynamic conditions at temperatures just below 0 °C result in the translocation of water and ice. Consequently, the engineering properties of soils such as permeability, water content, stress–strain behavior, failure strength, elastic modulus, cohesion, and friction angle may be changed. Former studies have been focused on changes in physical and mechanical properties of soil due to freeze–thaw cycles. In this paper, the effect of freeze–thaw cycles on the compressive strength of fiber-reinforced clay is investigated. For this purpose, kaolinite clay reinforced by steel and polypropylene fibers is compacted in a laboratory and exposed to a maximum of 10 closed-system freezing and thawing cycles. The unconfined compressive strength of reinforced and unreinforced specimens is then determined. The results of the study show that for the soil investigated, the increase in the number of freeze–thaw cycles results in the decrease of unconfined compressive strength of clay samples by 20–25%. Moreover, inclusion of fiber in clay samples increases the unconfined compressive strength of soil and decreases the frost heave. Furthermore, the results of the study indicate that fiber addition does not decrease the soil strength against freeze–thaw cycles. Moreover, the study shows that the addition of 3% polypropylene fibers results in the increase of unconfined compressive strength of the soil before and after applying freeze–thaw cycles by 60% to 160% and decrease of frost heave by 70%.

Gopalakrishnan, K., Ceylan, H., and Kim, S. H. (2010). "Biofuel Co-Product Uses for Pavement Geo-Materials Stabilization." IHRB Project TR-582, Institute of Transportation, Iowa State University, Ames, Iowa.

The production and use of biofuels has increased in the present context of sustainable development. Biofuel production from plant biomass produces not only biofuel or ethanol but also co-products containing lignin, modified lignin, and lignin derivatives. This research investigated the utilization of lignin-containing biofuel co-products (BCPs) in pavement soil stabilization as a new application area. Laboratory tests were conducted to evaluate the performance and the moisture susceptibility of two types of BCP-treated soil samples compared to the performance of untreated and traditional stabilizer-treated (fly ash) soil samples. The two types of BCPs investigated were (1) a liquid type with higher lignin content (co-product A) and (b) a powder type with lower lignin content (coproduct B). Various additive combinations (co-product A and fly ash, co-products A and B, etc.) were also evaluated as alternatives to stand-alone co-products. Test results indicate that BCPs are effective in stabilizing the Iowa Class 10 soil classified as CL or A-6(8) and have excellent resistance to moisture degradation. Strengths and moisture resistance in comparison to traditional additives (fly ash) could be obtained through the use of combined additives (co-product A + fly ash; co-product A + co-product B). Utilizing BCPs as a soil stabilizer appears to be one of the many viable answers to the profitability of the bio-based products and the bioenergy business. Future research is needed to evaluate the freeze-thaw durability and for resilient modulus characterization of BCP modified layers for a variety of pavement subgrade and base soil types. In addition, the long-term performance of these BCPs should be evaluated under actual field conditions and traffic loadings. Innovative uses of BCP in pavement-related applications could not only provide additional revenue streams to improve the economics of biorefineries, but could also serve to establish green road infrastructures.

Gray, D. H., and Ohashi, H. (1983). "Mechanics of fiber reinforcement in sand." Journal of Geotechnical Engineering, 109(3), 335-353.

Direct shear tests were run on a dry sand reinforced with different types of fibers. Both natural and synthetic fibers plus metal wires were tested. Experimental behavior was compared with theoretical predictions based on a force equilibrium model of a fiber reinforced sand. Test results showed that fiber reinforcement increased the peak shear strength and limited post peak reductions in shear resistance. The fiber reinforcement model correctly predicted the influence of various sand-fiber parameters through shear strength increases that were: (1) Directly proportional to concentration or area ratio of fibers; (2) greatest for initial fiber orientations of 60° with respect to the shear surface; and (3) approximately the same for a reinforced sand tested in a loose and dense state, respectively. The findings of this study are relevant to such diverse problems as the contribution of roof reinforcement to the stability of sandy, coarse textured soils in granitic slopes, dune and beach stabilization by pioneer plants, tillage in root permeated soils, and soil stabilization with low modulus, woven fabrics.

Gullu, H., and Hazirbaba, K. (2010). "Unconfined compressive strength and post-freeze–thaw behavior of fine-grained soils treated with geofiber and synthetic fluid." Cold Regions Science and Technology, 62, 142-150.

This study focuses on a relatively new non-traditional stabilizer (synthetic fluid) used in conjunction with geofiber to improve the strength characteristics of a low-plasticity fine-grained soil. The investigation is based on unconfined compressive strength (UCS) tests. An efficient geofiber dosage was determined for the soil; treating it with geofiber only for the dosage rates varying from 0.2% to 1% by weight of dry soil. The individual contribution of the geofiber and synthetic fluid to the UCS gain was studied through testing each additive independently with the soil. Additionally, UCS tests were conducted on soil samples treated with geofiber and synthetic fluid together. All experiments were conducted for both unsoaked and soaked sample conditions. Strength developments were also investigated under freezing and thawing conditions. The treatment results are discussed in detail in terms of UCS and stress–strain response of the UCS test. The results demonstrate that the use of geofiber with synthetic fluid provided the highest UCS improvement (170% relative gain) in unsoaked samples when compared with the other treatment configurations. On the other hand, the synthetic fluid, when used alone, caused a relative decrease of 21% in the UCS of untreated soil in soaked conditions. The use of geofiber with synthetic fluid performed better in terms of the UCS under freezing and thawing conditions, while the synthetic fluid alone under the same conditions performed inadequately. The stress–strain responses of the soil treated with geofiber and synthetic fluid in terms of post-peak strength, strain hardening, and ductility were better than that of treated with synthetic fluid alone. Finally, the resilient modulus for the various treatment configurations was estimated from the UCS results. The findings indicate that the investigated soil stabilization technology appears to be promising for sites that can be represented by unsoaked conditions (i.e., where adequate drainage and unsaturated conditions can be ensured).

Hazirbaba, K., and Gullu, H. (2010). "California Bearing Ratio improvement and freeze–thaw performance of fine-grained soils treated with geofiber and synthetic fluid." Cold Regions Science and Technology, 63, 50-60.

This paper presents experimental results on the improvement of the California Bearing Ratio (CBR) performance of fine-grained soils by the addition of geofiber and synthetic fluid. CBR tests were conducted for freezing and thawing conditions in addition to non-freezing conditions. The improvement of soil was tested with the inclusion of: i) geofiber only, ii) synthetic fluid only, and iii) synthetic fluid and geofiber together. To represent unsaturated and saturated soil conditions for various field applications, both unsoaked and soaked samples were investigated. The results for unsoaked conditions indicated significant improvement in the CBR performance, particularly in samples treated with geofiber and synthetic together. For soaked conditions, the best performance was obtained from the samples treated with geofiber only. The CBR performance of samples subjected to a freeze–thaw cycle was also tested. Freezing and thawing tests on unsoaked samples showed that the addition of geofiber together with synthetic fluid was generally successful in providing resistance against freeze–thaw weakening, and that the addition of synthetic fluid alone was not very effective against the detrimental impact of freeze–thaw. The results from soaked samples subjected to a freeze–thaw cycle showed poor CBR performance for treatments involving synthetic fluid while samples improved with geofibers alone generally produced better performance.

Henry, K. S. (1990). "Laboratory investigation of the use of geotextiles to mitigate frost heave." CREEL Report 90-6, Cold Regions Research and Engineering Laboratory (CRREL), U.S. Army Corps of Engineers, Hanover, New Hampshire.

Frost action beneath pavements can lead to several problems, including thaw weakening, which leads to cracking and subsequent pumping of fine soil particles onto the surface, as well as hazardous conditions caused by differential heaving. This study utilized data and frost-susceptible soil collected at Ravalli County Airport, Hamilton, Montana, to study the use of geotextiles to mitigate frost heave. The ability of geotextiles to reduce frost heave in subgrade material by creating a capillary break was assessed by inserting disks of fabric in soil samples and subjecting them to laboratory frost heave tests. Frost heave tests were also conducted to classify the frost susceptibilities of soils at the airport. Soil moisture characteristics and unsaturated hydraulic conductivities were determined for soils tested as well as for one of the geotextiles used. Results of the laboratory investigation indicate that certain geotextiles show promise for use as capillary breaks. In laboratory tests, the presence of geotextiles led to the reduction of frost heave by amounts up to about 60%. It is speculated that the capillary break action provided by the geotextile is attributable to the pore size and structure of the material and the surface properties of the fibers.

Henry, K. S. (1996). "Geotextiles to mitigate frost effects in soils: A critical review." Transportation Research Record: Journal of the Transportation Research Board, 1534, 5-11.

The use of geotextiles to mitigate frost effects in soils has been studied, but few techniques have been developed. Guidelines developed for the placement of granular capillary barriers are presented to serve as preliminary guidelines for geotextile capillary barriers. Laboratory research shows that pore size distribution, wettability, and, for some geotextiles, thickness influence capillary barrier performance in a given soil. Geotextiles that easily wet do not reduce frost heave and may even exacerbate it. On the basis of the literature reviewed, guidance for selection of geotextile capillary barriers in field trials is given. If geotextiles function as capillary barriers during freezing and reinforce or separate and filter the subgrade at the base course interface during thaw, then the potential exists for their use in a combination of functions to reduce frost-related damage in geotechnical structures. It was found that properly designed geotextiles have the potential to reduce frost heave by functioning as capillary barriers, they can be filters for capillary barriers, and they can provide reinforcement or separation or filtration (or all of these) of the subgrade soil to reduce thaw-related damage.

Hoover, J. M. (1973). "Surface improvements and dust palliation of unpaved secondary roads and streets." Iowa Highway Research Board Project HR-151, Engineering Research Institute, Iowa State University, Ames, Iowa.

The report contains five parts:

(I) Project Summary by Hoover, J. M. - As of December 31, 1970 there were 57,270 miles of Local Secondary roads and 32,958 miles of Farm to Market roads in the Iowa secondary road system. The Local Secondary system carried a traffic load of 2,714,180 daily vehicle miles, accounting for 32% of all traffic in secondary system. For all Local Secondary roads having some form of surfacing, 98% were surfaced with gravel or crushed stone. During the 1970 construction year, 335 miles of surfaced roads were constructed in the Local Secondary system with 78% being surfaced with gravel or crushed stone. The total maintenance expenditure for all secondary roads in Iowa during 1970 amounted to $40,086,091. Of this, 42%, or $17,020,332, was spent for aggregate replacement on existing gravel or crushed stone roads with an additional 31% ($12,604,456) being spent on maintenance other than resurfacing. This amounts to 73% of the total maintenance budget and are the largest two maintenance expenditure items out of a list of 10 ranging from bridges to drainage assessments. The next largest item was 7%, for maintenance of existing flexible bases. Present costs of high-type flexible or rigid pavements range from $40,000 per mile up. Because of high cost, budget limitations, and low mileage of high traffic volume on Local Secondary roads, most Iowa counties are severely restricted as to the number of miles of roads that may be paved each year. Present design and construction standards provide adequate means for improvement of grade and cross section of secondary roads followed by: (a) immediate road metal surfacing, or (b) eventual high-type surfacing. There are, at present, no formal provisions for an intermediate type surfacing between these two extremes. Therefore, nearly all Iowa counties are in a situation in which they have only a few miles of high-type pavements with the bulk being surfaced with gravel or crushed stone. From the maintenance expenditures for 1970, it can be seen that the primary method of maintaining aggregate surfaced secondary roads remains, as it has in the past, as aggregate replacement. Roads continue to rut, washboard, ravel, pothole, and become the source for billowing clouds of dust. Loose aggregate makes driving hazardous, and results in cases of vehicle damage including cracked windshields, chipped paint, and dents, as well as increased fatalities. During the spring thaw and subsequent rains, many roads become extremely soft, slippery, and heavily rutted. As aggregate supplies decrease, inferior quality soft limestones and gravels are being used, resulting in faster degradation contributing to the dusting problem. Dust creates a safety hazard to both passing and oncoming traffic. It is also a definite household nuisance in rural areas, especially in heavily populated regions surrounding larger towns and cities where traffic on unpaved roads may range as high as 500 vehicles per day. The severity of these problems continues to increase as: (a) traffic volume increases, (b) more people move to rural areas surrounding larger towns and cities, and (c) the current concern over air pollution increases. The Iowa Air Pollution Control Commission has drafted guidelines with respect to "fugitive" dust, which ultimately will affect all unpaved state, county, and city roads and streets. Besides the above problems, most counties are faced with (a) rising costs of high-type pavement, (b) rising costs of maintenance, and (c) rising costs of replacement aggregates. The foregoing considerations dictated the need for finding a means to provide for low-cost surface improvement and dust control, using existing in-place materials, for immediate (and intermediate) use as a treated surface course on unpaved secondary roads - the objective of this research project. Three concurrent phases of study were included in the project: (1) laboratory screenings studies of various additives thought to have potential for long-lasting dust palliation, soil additive strength, durability, and additive retention potential; (2) test road construction using those additives that indicated promise for performance-serviceability usage; and (3) observations and tests of constructed sections for evaluation of the additive's contribution to performance and serviceability as well as the relationship to initial costs.

(II) Asphaltic products and elastometers as dust palliatives and surface improvement agents for unpaved secondary roads, by Bergeson, K. H. and Hoover, J. M.: Bituminous materials have long been used, with varying degrees of success, as soil stabilizers and waterproofing agents. With advancing technological developments many new asphaltic products, whose properties have been altered and supposedly enhanced by the addition of chemicals and selected emulsifying agents, are being marketed. Elastomers, which contain rubber in a modified form, have also been introduced. The beneficial effects of these products, as soil stabilizers and dust palliatives, can only be determined by laboratory evaluation and field trials. This investigation was conducted essentially as a three phase project consisting of (a) laboratory screenings of various asphaltic products and elastomers to evaluate their effectiveness as soil stabilizers and dust palliatives, (b) construction of a test road, based on the results of the laboratory screening phase, using those additives that appeared to be the most effective and economical, and (c) observation and tests of the various sections of the test road for evaluation of the additives' performance and serviceability with respect to dust palliation and surface improvement. The primary purpose of this study is to present the results of each of the above phases. The test road was constructed in September 1971 and had been in service only one year and three months at the time of termination of research. Therefore, phase 3 analyses are somewhat limited due to the period of time covered.

(III) Ammonium lignosulfonates as dust palliatives and surface improvement agents for unpaved secondary roads, by Fox, D. E., and Hoover, J. M.: At the time the research project was initiated in mid-1970, county engineer offices in Iowa were requested to propose locations for test roads within their respective counties. It was explained that all men, material, and equipment would be furnished by the individual counties. Laboratory screenings of additives and field testing of experimental roads would be carried out by the researchers, who would also be present to observe construction and provide technical assistance when and where needed. Four counties responded with interest in lignosulfonate stabilization. Lignosulfonates are available in almost unlimited quantities from paper mills. Ten years ago, lignosulfonates cost 6 cents per gallon at the mill and the price has not increased, although production has. Due to different pulping processes, the cation associated with lignosulfonate varies. Sodium, calcium, and ammonium lignosulfonates have all been used in soil stabilization and prices are similar. The study reported here utilized commercially-available lignosulfonate with ammonium as the associated cation. The following paragraphs explain the participation offered for lignosulfonate research by the corresponding county. The county engineer's office of Clinton County, Iowa made available a section of road 2620 ft long to which crushed limestone had been added at a rate of 2000 tons per mile. This length was naturally divided into three approximately equal sections, a flat upland location, a curve on a hill of about 6% grade, and a level bottomland section on a backwater area of the Mississippi River. The road was located between, and connected with, paved roads terminating at the Clinton and Camanche city limits. Two nearby industries contributed to a 1967 ADT (average daily traffic) of 500 vehicles per day, and maintenance was a problem. The researchers were invited to perform field tests on several roads within Floyd County, both prior to and following treatment with lignosulfonate. Construction was done by county personnel under the supervision of the lignosulfonate supplier. A dirt road near Marion, Linn County, was made available by the county engineer for research. Of 6000 ft length, the 1968 traffic survey showed an ADT of 44 vehicles. Prior to treatment, the grade was built up and improved by the ditch clean-out method typical of much secondary road construction. Using lignosulfonate from a local source, stabilization of nearly 150 miles of roads was begun in Lee County in the late 1950s and early 1960s. Treatment consisted of only light surface blading and occasional application of aggregate coupled with a lignosulfonate surface spray application. Over the years, an in-depth treatment was produced. Extensive cost and maintenance records on treated roads were kept and made available to the researchers.

(IV) Soil-chemical additives as surface improvement agents for unpaved roads, by Denny, C. K., and Hoover, J. M.: The use of polyester and plastic resins as soil stabilizers is relatively new and untried. The objective of this research was to investigate the capabilities of these resins and several other chemicals and commercial dust palliatives as potential low-cost dust palliatives and surface improvement agents. The investigation was conducted entirely in the laboratory but care was taken to approximate field conditions as accurately as possible. Various soil-chemical additives were evaluated on the basis of the following tests: (1) unconfined compressive strength, (2) durability and erosibility, (3) trafficability, (4) resistance to freezing and thawing, and (5) moisture retention and density. Some of the tests were standard while others were specifically modified, but in every case the treated specimens were compared with untreated control specimens.

(V) Appendix: Mineralogical analyses of dust samples, by Handy, R. L.: This part contains results of differential thermal-thermogravimetric analysis and petrographic analysis. Thermogravimetric analysis offers a rapid, accurate method for the measurement of carbonates and organic matter in 50 mg dust samples, and gives a reliable semi-quantitative indication of the amount of clay minerals. Analysis by petrographic microscope is less accurate but requires less sample, and therefore is a valuable supplemental technique for very small samples. Dust analyses show conclusively that selective sorting is operative, calcium carbonate dominating in dust samples collected near the road, and gradually decreasing to near zero several hundred feet away from the road. Simultaneously, the contents of clay and organic matter increase with distance from the road. The efficiency of the sorting indicates that it is size-selective rather than specific gravity-selective (i.e., carbonate contents are higher close to the road because the grains are larger and settle faster). Lignin treatment will drastically reduce the carbonate percentage in road dust, by more than a factor of 10, provided the added rock amount does not exceed 1000 T/mile. The total amount of dust is less drastically reduced, and the amount roughly coincides with the amounts of noncarbonate components in dusts from untreated roads. This suggests that lignin and clay build up a protective patina at the road surface, by migration upward due to evaporation. This patina protects the limestone and is worn off by traffic; however, it should renew so long as sufficient lignin remains in the road. (Alternatively, it probably can be renewed by surface treatments.) The existence of such a coating, while greatly reducing the limestone aggregate loss from the dry road, also may contribute some slipperiness on a wet road, and probably acts to reduce bonding between the road metal and a bituminous overlay. Rock added in excess of about 1000 T/mile is not effectively protected by a 1% lignin treatment, or lignin plus lime. In addition, at the higher rock application levels, added Ca(OH)* lime tends to further reduce the protective effect on carbonates, probably by flocculating the clay and reducing migration and development of a film.

Hoover, J. M. (Undated). "Factors influencing stability of granular base course mixes." Iowa Highway Research Board Project HR-99, Engineering Research Institute, Iowa State University, Ames, Iowa.

To evaluate the various factors influencing the stability of granular base course mixes, three primary goals were included in the project: (1) determination of a suitable and realistic laboratory method of compaction; (2) effect of gradation, density and mineralogy of the fines on shearing strength; and (3) possible improvement of the shear strength with organic and inorganic chemical stabilization additives.

Hoover, J. M., Moeller, D. T., Pitt, J. M., Smith, S. G., and Wainaina, N. W. (1982). "Performance of randomly oriented, fiber-reinforced roadway soils: A laboratory and field investigation." Iowa Highway Research Board Project HR-211, Engineering Research Institute, Iowa State University, Ames, Iowa.

The purpose of the study was to conduct a laboratory and field investigation into the potential of improving (a) soil-aggregate surfaced and subgrade materials, including those that are frost-prone and/or highly moisture susceptible, and (b) localized base course materials, by uniting such materials through fibrous reinforcement. The envisioned objective of the project was the development of a simple construction technique(s) that could be (a) applied on a selective basis to specific areas having a history of poor performance, or (b) used for improvement of potential base materials prior to surfacing. Little background information on such purpose and objective was available. Though the envisioned process had similarities to fibrous reinforced concrete, and to fibrous reinforced resin composites, the process was devoid of a cementitious binder matrix and thus highly dependent on the cohesive and frictional interlocking processes of a soil and/or aggregate with the fibrous reinforcement; a condition not unlike the introduction of reinforcing bars into a concrete sand/aggregate mixture without benefit of portland cement. Thus the study was also directed to answering some fundamental questions: (1) would the technique work; (2) what type or types of fibers are effective; (3) are workable fibers commercially available; and (4) can such fibers be effectively incorporated with conventional construction equipment, and employed in practical field applications? The approach to obtaining answers to these questions, was guided by the philosophy that an understanding of basic fundamentals was essential to developing a body of engineering knowledge that would serve as the basis for eventual development of design procedures with fibrous products for the applications previously noted.

Hoover, J. M., Pitt, J. M., Lusting, M. T., and Fox, D. E. (1981b). "Mission-oriented dust control and surface improvement processes for unpaved roads." Iowa DOT Project HR-194, Engineering Research Institute, Iowa State University, Ames, Iowa.

The study documented herein was implemented as a mission-oriented project designed to quantify and evaluate dust control and surface improvement processes for unpaved roads. In order to accomplish this mission, three levels of processing and treatment were established for comparison with untreated soil aggregate-surfaced roads utilizing only the existing in-place roadway materials: Category 1, surface applied dust palliation; Category 2, mixed-in-place dust palliation and surface improvement, without additional surfacing; and Category 3, mixed-in-place base stabilization with seal coat surfacing. Demonstration sections were developed in several representative geographic/geologic regions of the state including Plymouth, Pottawattamie, Story, Franklin, and Marion counties. Samples from these, as well as other possible sites, were subjected to laboratory tests including unconfined compression, freeze-thaw durability, Iowa K-Test, and trafficability testing, in both the untreated and treated conditions, as well as under varying forms of curing. The purpose of the laboratory testing was for evaluation of the subject material for potential use in one or more of the three categories of dust control and/or surface improvement processing. Field studies were initiated in each potential demonstration site for measurement of dust fall within, as well as to the exterior of the ROW. Such measurements were continued following Category 1 applications of selected palliation treatments. In-situ pre- and post-construction tests were conducted within each Category 3 demonstration section, including periodic plate-bearing, Benkelman beam, and moisture-density tests. During Category 3 construction, assistance was provided each county in construction coordination and moisture-density control. Specimens were field molded from each Category 3 mix prior to field compaction and returned to the laboratory for periodic testing of moisture-density and K-Test parameters. Dust fall testing included both quantity and particle-size distribution versus distance from roadway centerline. Through regression analyses of dust fall data, predictions were developed for quantity of dust at the ROW, as well as distance from roadway centerline at which ambient levels of dusting might be anticipated. Through such analyses, two potential control criteria for dust fall were developed. Based on comparison of pre- and post-Category 1 treatment applications, dust reduction effectiveness of several palliatives was evaluated. Such evaluations were coupled with estimated costs of each treatment as an approach to respective cost-benefits. Based on comparison of laboratory tests, pre- and post-construction in-situ tests, and visual examinations, each Category 3 stabilized base demonstration section was evaluated for structural integrity. The following generalized conclusions are thus founded on the various tests, investigations, and analyses presented within this report: (1) Unconfined compression tests of 2-in. by 2-in. cylindrical specimens can provide an initial method of trial mix suitability of various products for possible use as dust palliatives and/or surface improvement agents. Such trial mix testing should be followed by more refined testing on selected mixes. (2) Stability of various product and soil mixtures can be evaluated with freeze-thaw durability, trafficability, and the Iowa K-Test. Freeze-thaw elongation provides an indication of climatic stability as well as susceptibility to capillary moisture increases and heave potential. Trafficability tests provide a quantitative measure of waterproofing and resistance to an adverse traffic loading and environmental condition. The Iowa K-Test provides a quick measure of the undrained shear parameters: cohesion and angle of internal friction. In addition, the K-Test provides a qualitative measure of rutting potential of a mixture through the lateral stress ratio K and a measure of stress-strain relations through the vertical deformation modulus Ev. (3) Of the products evaluated through the various laboratory tests, only the combined Portland cement and fly ash appeared effective as a Category 3 stabilization process with most soil-aggregate classifications, though optimum quantities of the two products varied with each material. Variation of CSS asphalt emulsion zeta potential exhibited pronounced effects on mixture compatibility and required asphalt content, regardless of consideration of categorical usage. In a similar manner, the laboratory tests indicated categorical usage of ammonium lignosulfonate, Coherex, Polybind Acrylic DLR 81-03, and Amsco Res AB 1881 varied from negative to potentially effective depending on soil-aggregate type. (4) All demonstration sections, regardless of category level of processing, were constructed with conventional equipment. (5) Utilizing the measurement and analytical techniques described in this study, two recommendations of minimal roadway dust fall criteria were subjectively quantified. First, an ambient level should be achieved within a distance of 100 to 150 ft or less of an unpaved roadway centerline. Second, a quantity of 15 lbs/acre/day/100 vehicles, or less, should be achieved at the ROW. Such criteria should be considered as a reasonable starting point, with possible refinement with time. (6) Effective dust abatement as well as structural improvement may be obtained through Category 3 construction processing of an unpaved road using cement and fly ash or emulsified asphalt. (7) Only limited Category 1 dust palliation and cost effectiveness were obtained with Amsco Res AB 1881, Polybind Acrylic DLR 81-03, and cationic asphalt emulsion. Coherex appeared very effective as a dust palliative so long as it was not used with an absorptive aggregate. However, the cost of Coherex would limit its usage in Iowa. Calcium chloride and ammonium lignosulfonate appeared comparatively cost-effective as dust palliatives. Effectiveness of both the chloride and lignosulfonates might be enhanced if incorporated with a soil-aggregate surface using methods and/or specifications cited in preceding sections of this report.

Hopkins, T. C., Beckham, T. L., and Hunsucker, D. Q. (1995). "Modification of highway soil subgrades." Report KTC 94-11, Kentucky Transportation Center, University of Kentucky, Lexington, KY.

Major study objectives were to develop highway pavement subgrade stabilization guidelines, examine long-term benefits of chemical stabilizers, such as cement, hydrated lime, and two byproducts from industrial processes, and to establish a subgrade stabilization program in Kentucky. In developing a program, a number of design and construction issues had to be resolved. Factors affecting subgrade behavior are examined. Changes in moisture content and CBR strengths of untreated and chemically treated subgrades at three experimental highway routes were monitored over a 7-year period. CBR strengths of the untreated subgrades decreased dramatically while moisture contents increased. CBR strengths of subgrade sections treated with hydrated lime, cement and multicone kiln dust generally exceeded 12 and increased over the study period. At four other highway routs ranging in ages from 10 to 30 years, CBR strengths of soil-cement subgrades exceed 90. Knowing when subgrade stabilization is needed is critical to the development of an economical design and to insure the efficient construction of pavements. Bearing capacity analyses using a newly developed, stability model based on limit equilibrium and assuming a tire constant stress of 552 kPa show that stabilization should be considered when the CBR strength is less than 6.5. For other tire contact stresses, relationships corresponding to factors of safety of 1 and 1.5 are presented. Stability analysis of the first lifts of the paving materials showed that CBR strengths of untreated subgrade should be > 9. Guidelines for using geogrids as subgrade reinforcement are presented. Factors of safety of geogrid reinforced granular bases are approximately 10 to 25 percent larger than granular bases without reinforcement. As shown by strength tests and stability analysis, when the percent finer than the 0.002mm particle size of a soil increases to a value greater than about 15%, the factor of safety decreases significantly. Guidelines are also presented for this selection of the design strengths of untreated and treated subgrades with hydrated lime and cement. Based on a number of stabilization projects, recommended design undrained shear strengths of hydrated lime- and cement-treated subgrades are about 300 and 690 kPa, respectively. A laboratory testing procedure for determining the optimum percentage of chemical admixture is described. Correlations of dynamic cone penetrometer and Clegg impact hammer and in situ CBR strengths and unconfined compressive strengths are presented.

Hopkins, T. C., Beckham, T. L., Sun, L., Ni, B., and Butcher, B. (2002). "Long-Term Benefits of Stabilizing Soil Subgrades." KTC-02-19/SPR196-99-1F, Kentucky Transportation Center, University of Kentucky, Lexington, Kentucky.

Chemical admixtures have been used extensively since the mid-eighties in Kentucky to improve bearing strengths of soil subgrades. Most pavements in Kentucky are constructed on clayey soils. Although short-term observations at a small number of sites showed that chemical stabilization worked very well, a need existed to perform a more comprehensive review and to assess the long-term benefits of this subgrade stabilization method. The main intent of this study was an attempt to address questions concerning bearing strengths, longevity, durability, structural credit, economics, and performance of pavements resting on soil subgrades mixed with chemical admixtures. In-depth field and laboratory studies were performed at fourteen roadway sites containing twenty different treated subgrade sections. Ages of the sites range from about 8 to 15 years. About 455 borings were made at the various sites. Air, instead of water, was used as the drilling media. In-situ CBR tests were performed on the treated subgrades and the untreated subgrades lying directly below the treated layers. Index tests and resilient modulus tests were performed on samples collected from the treated and untreated subgrades. Falling weight deflectometer (FWD) tests were performed. At the 85th percentile test value, the in situ CBR values of subgrades mixed with hydrated lime, Portland cement, a combination of hydrated lime and Portland cement, and a byproduct (MKD) obtained in the production of hydrated lime were 12 to 30 times greater than in CBR values of the untreated subgrades. In-situ CBR values of the treated layer ranged from 24 to 59 while the in-situ CBR of the untreated layer at the 85th percentile test value was only 2. Based on rating criteria of the Kentucky Transportation Cabinet, the conditions of the pavements at twelve sites could be rated “good” at the time of the study– pavement ages were 8 to 15 years– and “good” at the end of the twenty-year design period, based on projected data. At two sites, thin asphalt overlays had been constructed after 15 years. However, accumulated values of ESAL at those sites had exceeded or were near the values of ESAL assumed in the pavement designs. At the 20th percentile test value, rutting depths of the pavements resting on the treated subgrades were less than about 0.27 inches. Structural layer coefficients, a3, for use in pavement design of the different chemically stabilized subgrades were developed. The proposed values were verified at sites where reduced pavement thickness was used and "in service" structural coefficients could be observed. Back-calculated values of FWD modulus of the treated layers were about two times the values of modulus of the untreated subgrade. Resilient modulus of the treated subgrades was larger than the resilient modulus of the untreated subgrades. Moisture contents at the top of the untreated subgrade layers showed that a "soft" layer of material exists at the very top of the untreated subgrade. This soft zone did not exist at the top of the treated layer. This discovery has significant engineering implications. Future research will focus attention on an in-depth examination of this weak layer of soil. Chemical admixture stabilization is a good, durable and economical technique for improving subgrade strengths.

Janoo, V. C., Barna, L. A., and Orchino, S. A. (1997). "Frost-Susceptibility Testing and Predictions for the Raymark Superfund Site." Special Report 97-31, US Army Corps of Engineers Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

This project was conducted to assist in predicting the effects of freeze–thaw cycling on Tilcon common granular fill during the freezing season. This material is being used as the subbase material in the proposed pavement structure at the Raymark Superfund site in Stratford, Connecticut. Based on the initial laboratory results of the Tilcon material performed at CRREL, the amount of fines passing the no. 200 sieve was found to be in the vicinity of 20%, of which approximately 14% was finer than 0.02 m. Results from the frost heave tests indicate that when the Tilcon material is saturated, based on the rate of heave, the material is classified a high to very high frost susceptible material. In the unsaturated condition, the material is classified as a low to medium frost-susceptible material. Computer simulations were run to predict the amount of frost heave and frost penetration that may be expected on this site during the freezing season. Results from the laboratory frost-susceptibility tests and computer simulations were then used to estimate the amount of cumulative damage to the pavement structure during its design life.

Johnson, A. (2012). "Freeze-thaw performance of pavement foundation materials." M.S. Thesis, Dept. of Civil Construction and Environmental Engineering, Iowa State University, Ames, Iowa.

Freezing and thawing processes damage pavement foundation systems; increase pavement and vehicle maintenance costs; reduce traveler comfort and safety; decrease fuel economy; and decrease pavement life spans. Current pavement design methods provide limited guidance characterizing frost-susceptible materials. A laboratory frost-heave and thaw-weakening test could be used to differentiate frost-susceptible materials from non-frost susceptible materials to reduce the effects of frost action. The goal of this research was to provide guidance for the selection of pavement foundation materials based on their freeze-thaw durability. The objectives of this study are to determine the effectiveness of ASTM D5918 Standard Test Methods for Frost Heave and Thaw Weakening Susceptibility of Soils by testing various soil types; study the effects of stabilizers on reducing frost-susceptibility; and determine seasonal changes of in situ pavement support conditions. The important outcomes of this research are that it is difficult to predict frost-heave susceptibility from USCS classifications;

when stabilizing loess with cement, increased cement content decreased the range of initial moisture contents that will result in maximum compressive strength; compared to unstabilized loess, cement-stabilized loess was found to be non-frost-susceptible, but fly ash-stabilized loess showed only slight improvement; and the coefficients of variation for ASTM D5918 test results were similar to published results. This research shows that using a test such as ASTM D5918 in the design phase to determine the relative frost-susceptibility of pavement foundation materials may ameliorate the effects of frost action.

Kalkan, E. (2009). "Effects of silica fume on the geotechnical properties of fine-grained soils exposed to freeze and thaw." Cold Regions Science and Technology, 58, 130-135.

Both the landfill liner and cover systems are the most important parts on a waste disposal landfill site. These systems are generally constructed using compacted fine-grained soils. It is known that the strength and permeability are particularly affected by freezing and thawing cycles in the cold regions. The aim of this study is to reduce the effects of freezing and thawing cycles on the strength and permeability. To modify the fine-grained soils, silica fume generated during silicon metal production as very fine dust of silica from a blast furnace and historically considered a waste product has been used as a stabilizer. The natural fine-grained soils and soil–silica fume mixtures have been compacted at the optimum moisture content and subjected to the laboratory tests. The test results show that the stabilized fine-grained soil samples containing silica fume exhibit high resistance to the freezing and thawing effects as compared to natural fine-grained soil samples. The silica fume decreases the effects of freezing and thawing cycles on the unconfined compressive strength and permeability. We have concluded that silica fume can be successfully used to reduce the effects of freezing and thawing cycles on the strength and permeability in landfill liner and cover systems constructed from compacted fine-grained soils.

Kaniraj, S. R., and Havanagi, V. G. (2001). "Behavior of cement-stabilized fiber-reinforced fly ash-soil mixtures." Journal of Geotechnical and Geoenvironmental Engineering, 2001, 574-584.

An experimental program was undertaken to study the individual and combined effects of randomly oriented fiber inclusions and cement stabilization on the geotechnical characteristics of fly ash-soil mixtures. An Indian fly ash was mixed with silt and sand in different proportions. The geotechnical characteristics of the raw fly ash-soil specimens and fly ash-soil specimens containing 1% randomly oriented polyester fiber inclusions were investigated. Unconfined compression tests were carried out on fly ash-soil specimens prepared with 3% cement content alone and also with 3% cement and 1% fiber contents, after different periods of curing. The study shows that cement stabilization increases the strength of the raw fly ash-soil specimens. The fiber inclusions increase the strength of the raw fly ash-soil specimens as well as that of the cement-stabilized specimens and change their brittle behavior to ductile behavior. Depending on the type of fly ash-soil mixture and curing period, the increase in strength caused by the combined action of cement and fibers is either more than or nearly equal to the sum of the increase caused by them individually.

Kettle, R. J., and McCabe, E. Y. (1985). "Mechanical Stabilization for the Control of Frost Heave." Canadian Journal of Civil Engineering, 12, 899-905.

This paper is concerned with the role of mechanical stabilization in controlling frost susceptibility. This has been assessed in terms of the heave, developed over a 250 h period, of cylindrical specimens subjected to the Transport and Road Research Laboratory (United

Kingdom) frost heave test. The basic soil matrix consisted of a highly susceptible mixture of sand and ground chalk. Three types of coarse particle (slag. basalt, limestone) were used as the stabilizing agent, and these were each subdivided into two particle groups: 20-3.35 mm and 37.5-20 mm. The introduction of up to 50% of the selected coarse aggregates produced various non-frost-susceptible mixtures. The influence of the coarse aggregate was very dependent on aggregate type but less dependent on aggregate size. The data have been examined to assess the role of these coarser particles in the freezing process, including the effects of their individual characteristics. This clearly demonstrated the possibility of using mechanical stabilization to control frost susceptibility and this was supported by the results of additional tests on natural soil. Heaving pressures are also reported and are examined in relation to the amount of aggregate added, nature of the aggregate, and particle size. The addition of coarse aggregate to the matrix is shown to reduce the measured heaving pressures.

Khoury, N., and Zaman, M. M. (2002). "Effect of Wet-Dry Cycles on Resilient Modulus of Class C Coal Fly Ash-Stabilized Aggregate Base." Transportation Research Record: Journal of the Transportation Research Board, 1787, 13-21.

A laboratory study was undertaken to investigate the effect of wet–dry (W-D) cycles on low-quality aggregates stabilized with Class C coal fly ash (CFA). Resilient modulus (Mr), unconfined compressive strength, and elastic modulus were used to evaluate this effect. Cylindrical specimens stabilized with 10% CFA, cured for 3 and 28 days, and subjected to different W-D cycles were tested. The Mr values of 28-day-cured specimens increased as W-D cycles increased up to 12, beyond which a reduction was observed. For 3-day-cured specimens, Mr increased with the number of W-D cycles. W-D action produced a greater detrimental effect on 28-day-cured specimens than on 3-day-cured specimens. The Mr values of 28-day-cured specimens subjected to 30 cycles were approximately 5% lower than the corresponding Mr values of specimens without any W-D cycles. The Mr values of 3-day-cured specimens subjected to 30 W-D cycles, however, increased approximately 55% compared with the corresponding Mr values of specimens with no W-D cycles. Also, it was found that 12 to 30 W-D cycles could be considered adequate to have a noticeable negative effect on 28-day-cured specimens; however, more than 30 cycles are needed for 3-day-cured specimens. Additionally, the positive effect of curing time was more dominant on 3-day-cured specimens, and the detrimental effect of W-D cycles was more influential on 28-day-cured specimens.

Khoury, N., and Zaman, M. M. (2007). "Durability of stabilized base courses subjected to wet–dry cycles." International Journal of Pavement Engineering, 8(4), 265-276.

A laboratory study was undertaken to evaluate the durability of cementitiously stabilized aggregate specimens subjected to wet–dry (W-D) cycles, representing a base course in a pavement structure. Specifically, cylindrical specimens of aggregates stabilized with 15% cement kiln dust (CKD), 10% class C fly ash, or 10% fluidized bed ash were prepared, cured for 28 days, and then subjected to W-D cycles prior to testing for resilient modulus (Mr). Four aggregates were selected in this experimental study: (1) Meridian, (2) Richard Spur, (3) Sawyer and (4) Hanson. Results showed that the Mr values decreased as W-D cycles increased up to 30, except for Sawyer specimens stabilized with 15% CKD. These specimens exhibited an increase in Mr values with W-D cycles up to 8, beyond which a reduction occurred. The performance of the stabilized specimens is believed to depend upon SAF (Silica, Alumina and Ferric Oxide compounds) and free lime of the stabilizing agents. Also, the optimum moisture content (OMC)

and maximum dry density (MDD), were found to be a good indicator of performance pertaining to stabilization and W-D action. A regression model correlating Mr with W-D cycles, SAF, free lime, OMC and MDD offered statistically promising results.

Khoury, N., and Zaman, M. M. (2007). "Environmental Effects on Durability of Aggregates Stabilized with Cementitious Materials." Journal of Materials in Civil Engineering, 19(1), 41-48.

The present study focuses on investigating the effect of freeze–thaw (FT) cycles, referred to as environmental effect in this paper, on aggregates stabilized with various stabilizing agents, namely, cement kiln dust (CKD), Class C fly ash (CFA), and fluidized bed ash (FBA). Cylindrical specimens were compacted and cured for 28 days in a moist room with a constant temperature and controlled humidity. After curing, specimens were subjected to 0, 8, 16, and 30 FT cycles, and then tested for resilient modulus (Mr). Results showed that Mr values of stabilized specimens decreased with increasing FT cycles up to 30. The reasons for such changes are explained by the increase in moisture content during thawing and the formation of ice lenses within the pores during freezing, causing distortion of the matrix of particles. It was also found that the decrease in Mr values varied with the type of stabilizing agents. The CKD-stabilized. Meridian and Richard Spur aggregates exhibited a higher reduction in Mr values than the corresponding values of CFA- and FBA stabilized specimens. The CFA-stabilized Sawyer specimens performed better than their CKD- and FBA-stabilized counterparts.

Latha, G. M., Nair, A. M., and Hemalatha, M. S. (2010). "Performance of geosynthetics in unpaved roads." International Journal of Geotechnical Engineering, 2010(4), 337-349.

This paper presents results of field studies on unpaved low volume roads constructed over weak subgrade using geosynthetic reinforcement. The relative advantages of placing different reinforcing materials like geotextile, biaxial or uniaxial geogrid, geocell layer, and tire shreds at the interface of subgrade and base course are studied in terms of increase in load carrying capacity and reduction in rut depth. The rut depths measured in three different test sections when subjected moving vehicle load simulated by the passage of a scooter on the road at uniform speed for a maximum of 250 passes are compared to understand the relative efficiency of each of the reinforcing materials in reducing the rut formation in unpaved roads. Traffic benefit ratios were also compared for different reinforced test sections.

Mathur, S., Koni, S., and Murty, A. (1999). "Utilization of industrial wastes in low-volume roads." Transportation Research Record: Journal of the Transportation Research Board, 1652, 246-256.

In recent years, applications of marginal materials, also called nontraditional (either natural or waste products), have been considered in road construction with great interest in many industrialized and developing countries. The use of nontraditional materials in road making is based on technical, economic, and ecological criteria. The lack of traditional road materials and the protection of the environment make it imperative to investigate marginal materials carefully. India has a large network of steel plants located in different parts of the country and many more are planned for the near future. Several million metric tons of iron and steel are produced in these plants. However, along with production of iron and steel, huge quantities of solid wastes like blast furnace slag and steel slag as well as other wastes such as flue dust, blast furnace sludge, and refractories are also being produced in these plants. The iron ores in India, although rich in iron content, are high in alumina content also and as such the volume of slag generated is very

high. Normally production of 1 metric ton (1 Mg) of steel generates 1 Mg of solid waste. Although the steel industry slags have their own unique properties and are exploitable for road works, they have never been put to use on Indian roads because of a lack of scientific studies conducted on these materials, nonavailability of proper design and construction standards on them, and the absence of data about the long-term behavior of these materials. In the absence other outlets, these solid wastes have occupied several acres of land around plants throughout the country. Keeping in mind the need for bulk use of these solid wastes in India, it was thought expedient to test these materials and to develop specifications to enhance the use of slags in road making, in which higher economic returns may be possible. Exhaustive and detailed laboratory investigations have been carried out at the Central Road Research Institute, New Delhi, India, to develop suitable specifications for construction of low-volume roads. Based on laboratory investigation results, specifications were developed for construction of low-volume roads in different parts of the country. While specifications were being formulated, attempts were made to maximize use of solid wastes in different layers of the road pavement. Post construction pavement performance studies have clearly indicated that these waste materials can be used for construction of low-volume roads with twofold benefits: (a) it will help clear valuable land of huge dumps of slags, and (b) it will also help preserve the natural reserves of aggregates, thus protecting the environment.

Mekkawy, M. M., White, D. J., Suleiman, M. T., and Jahren, C. T. (2011). "Mechanically reinforced granular shoulders on soft subgrade: Laboratory and full scale studies." Geotextiles and Geomembranes, 29, 149-160.

A recently completed field study in Iowa showed that many granular shoulders overlie clayey subgrade layer with California Bearing Ratio (CBR) value of 10 or less. When subjected to repeated traffic loads, some of these sections develop considerable rutting. Due to costly recurring maintenance and safety concerns, the authors evaluated the use of biaxial geogrids in stabilizing a severely rutted 310 m tests section supported on soft subgrade soils. Monitoring the test section for about one year, demonstrated the application of geogrid as a relatively simple method for improving the shoulder performance. The field test was supplemented with a laboratory testing program, where cyclic loading was used to study the performance of nine granular shoulder models. Each laboratory model simulated a granular shoulder supported on soft subgrade with geogrid reinforcement at the interface between both layers. Based on the research findings, a design chart correlating rut depth and number of load cycles to subgrade CBR was developed. The chart was verified by field and laboratory measurements and used to optimize the granular shoulder design parameters and better predict the performance of granular shoulders.

Mhaiskar, S. Y., and Mandal, J. N. (1992). "Soft Clay Subgrade Stabilisation using Geocells." Grouting, Soil Improvement, and Geosynthetics - GSP30, R. H. Borden, R. D. Holtz, and I. Juran, eds.

The present study is aimed at investigating the efficacy of the geocell structure on a soft clay and studying three important parameters affecting its performance. They are the width of geocell (a] and the height of the geocell (b], effect of strength of the geocell materia1 and relative density of the fill in the geocell. Experimental and Finite Element (F.E.] procedures have been adopted to study the above parameters. Soft saturated marine clay was used as subgrade while sand was used as backfill material. Monotonic loading using a plate to represent on-highway

loading conditions was used in plate load tests. The experimental results were simulated in a three dimensional F. E. procedure using ANSYS. (a general purpose F.E. package]. Considerable amount of improvement in the ultimate load and reduction in settlement was observed from the experimental results. Close agreement has been found between the experimental and F.E. results. The results of the F.E. analysis are used to study the improvement in stiffness.

Monlux, S. (2003). "Stabilizing Unpaved Roads with Calcium Chloride." Transportation Research Record: Journal of the Transportation Research Board, 1819, 52-56.

The U.S. Department of Agriculture Forest Service has stabilized unpaved road surfacing materials with relatively high concentrations of calcium chloride salt. The percentage of calcium chloride is higher than that traditionally used for dust abatement or aggregate base stabilization. Up to 2% pure salt by weight of aggregate was mixed into the top 2 in. (50 mm) of both aggregate and native road surfaces. The results were monitored for 2 to 4 years. The stabilized road surfaces resisted raveling and washboarding for several seasons and significantly reduced road blading and aggregate loss. As a result, calcium chloride stabilization may be a cost-effective treatment for roads with daily traffic volumes less than 200. Other benefits include reduced surface erosion and sedimentation; improved safety from reduced dust, raveling, and washboarding; and less frost penetration. Encouraged by these results, the Forest Service is conducting additional evaluations to determine the cost-effectiveness of surface stabilization with both magnesium chloride and calcium chloride in different environments and with different aggregate materials.

Monlux, S., and Mitchell, M. (2007). "Chloride Stabilization of Unpaved Road Aggregate Surfacing." Transportation Research Record: Journal of the Transportation Research Board, 1989(2), 50-58.

There are few alternatives for improving long-term performance of aggregate surfacing materials in dry climates other than annual dust abatement treatments. In-place stabilization of properly graded aggregate with chloride additives is cost-effective and provides performance and intangible benefits. Similar results are achieved by mixing additives with aggregate during crushing. This 2-year study identifies conditions in which chloride-stabilized roads have a projected life of 10 years or more if properly maintained. The greatest benefits are realized in projects with high aggregate surfacing replacement costs and average daily traffic volumes that exceed 100. Stabilization provides a higher standard of road surface performance by improving ride quality and reducing dust, corrugations (washboarding), and raveling (loose aggregate). Other intangible benefits include reduced sedimentation in streams, reduced aggregate resource depletion, reduced health hazards from dust, and increased road-user safety. This project developed guidelines for chloride stabilization of various aggregate surfacing materials in semiarid to arid environments. Performance and cost-effectiveness of chloride stabilization were measured on 12 projects and monitored for two seasons in four western states; monitoring included construction and maintenance costs, road surface deterioration, traffic, weather conditions, environmental effects, and materials testing. Treated surfaces needed blading after 25,500 vehicles, whereas untreated surfaces needed blading after only 3,200 vehicles. Environmental effects on trees, streams, and roadside soils were insignificant. Many tools were developed to assist in the proper implementation of chloride stabilization of road surface aggregates.

Muthen, K. M. (1999). "Foamed Asphalt Mixes - Mix Design Procedure." CR-98/077, CSIR Transportek, Pretoria, South Africa.

Foamed asphalt epitomizes the asphalt industry's drive towards energy efficient, environmentally friendly and cost-effective solutions for road-building. Foamed asphalt refers to a bituminous mixture of road-building aggregates and foamed bitumen, produced by a cold mix process. Although the foamed bitumen process was developed more than 40 years ago and lauded by researchers the world over, it is believed that the lack of standardized design procedures has contributed to the limited implementation of the technology in South Africa, with practitioners favouring more familiar and well documented products. Recently there has been significant interest in the product, especially in the in-situ method of construction, and hence the need for a standard mix design procedure has now become essential. One element of foamed asphalt technology which may prove to be an impediment to standardization is the emergence of various proprietary bitumen foaming techniques. This report focusses on the development of a mix design method for foamed asphalt mixes, based on research work conducted at CSIR Transportek on behalf of SABITA. An extensive survey was undertaken of the worldwide practice with regard to foamed asphalt mix design, which included literature surveys and liaison with recognized experts. A mix design procedure was developed, encompassing all the necessary elements from the selection of aggregates and binder to the determination of the optimum engineering properties of the mix. This was followed by a laboratory program designed to verify the proposed mix design procedure. It is believed that the proposed mix design procedure is independent of the type of bitumen foaming process used and should, therefore, be acceptable to practitioners.

Parsons, R. L., and Milburn, J. P. (2003). "Engineering Behavior of Stabilized Soils." Transportation Research Record: Journal of the Transportation Research Board, 1837, 20-29.

Stabilization of soils is an effective method for improving soil properties and pavement system performance. For many soils, more than one stabilization agent may be effective, and financial considerations or availability may be the determining factor on which to use. A series of tests was conducted to evaluate the relative performance of lime, cement, Class C fly ash, and an enzymatic stabilizer. These products were combined with a total of seven different soils with Unified Soil Classification System classifications of CH, CL, ML, and SM. Durability testing procedures included freeze–thaw, wet–dry, and leach testing. Atterberg limits and strength tests also were conducted before and after selected durability tests. Changes in pH were monitored during leaching. Relative values of soil stiffness were tracked over a 28-day curing period using the soil stiffness gauge. Lime- and cement-stabilized soils showed the most improvement in soil performance for multiple soils, with fly ash–treated soils showing substantial improvement. The results showed that for many soils, more than one stabilization option may be effective for the construction of durable subgrades. The enzymatic stabilizer did not perform as well as the other stabilization alternatives.

Pinilla, J., D., Miller, G. A., Cerato, A. B., and Snethen, D. S. (2011). "Influence of curing time on the resilient modulus of chemically stabilized soils." Geotechnical Testing Journal, 34(4), 364-372.

Research was conducted to investigate the influence of soil properties, additive type and curing time on the resilient modulus (MR) of chemically stabilized soils. Interest in characterizing the rate of MR improvement through curing time was the primary motivation for this study. Soils stabilized with cement kiln dust and Class C fly ash were collected at five construction sites in Oklahoma. Specimens were prepared at optimum compaction parameters and tested after various curing periods; a total of 58 MR tests were performed. Properties of both soils and admixtures were evaluated in order to correlate those with the enhanced behavior of the mixed soils measured as improved MR values. Regression equations were developed so that MR evolution with time could be quantitatively described. After 28 days of curing, tested soils showed improved MR values ranging from 7 to 46 times larger than those of untreated soil. Rates of improvement were characterized using a power type regression analysis. Although data are limited, correlations between improvement rate (Rt) and raw soil properties including fines fraction, pH, and to a lesser extent, specific surface area and cation exchange capacity, indicate these factors show promise as predictors of MR improvement with time.

Shoop, S. A., and Henry, K. S. (1991). "Effect of a geotextile on water migration and frost heave in a large-scale test basin." Transportation Research Record: Journal of the Transportation Research Board, 1307, 309-318.

The objective of this study was to examine the effect of a needle punched polyester geotextile on moisture migration and frost heave during freezing and thawing in a large test basin. In the past, nonwoven polypropylene geotextiles have been effective in reducing frost heave in laboratory tests. In this case, a needle punched polyester geotextile separator was monitored for its influence on frost heave and soil moisture tension for four freeze thaw cycles in a large test basin. Results from freezing tests in the test basin without a water table and with a water table present 12.7 cm below the fabric suggest that use of the fabric results in greater frost heave. When the water table was above the fabric, the fabric had no influence on frost heave or water distribution in the soil. Laboratory tests indicate that the separator had no effect on frost heave. Tensiometer data in the test basin indicate that lateral transmission of water through the fabric may have occurred, so transmission of water from thawed soil to freezing soil may have contributed to increased frost heave. It is concluded that if a geotextile is used in frost-susceptible soil, proper drainage and the correct fabric type must be used to prevent increased frost heave. The role of geotextile surface properties is important and their influence on moisture migration should be investigated further.

Simonsen, E., Janoo, V. C., and Isacsson, U. (2002). "Resilient Properties of Unbound Road Materials during Seasonal Frost Conditions." Journal of Cold Regions Engineering, 16(1), 28-50.

During recent decades, a considerable amount of research has been devoted to the resilient properties of unbound road materials. However, the severe effects of cold region climates on resilient behavior have been less exhaustibly -investigated. In this study, the results from extensive resilient modulus laboratory tests during full freeze-thaw cycling are presented. Various coarse and fine-grained subgrade soils were tested at selected temperatures from room temperature down to -10°C and back to room temperature. The soils are frozen and thawed inside a triaxial cell, thus eliminating external disturbances due to handling. The results indicate that all the soils exhibited a substantially reduced resilient modulus after the freeze-thaw cycle. A significant hysteresis for the clay soil in warming and cooling was also observed. This paper presents equations for different conditions. The equations may be used for selecting the appropriate resilient modulus value in current and future evaluation and design methods.

Solanki, P., Zaman, M., and Khalife, R. (2013). "Effect of freeze-thaw cycles on performance of stabilized subgrade." Sound Geotechnical Research to Practice: Honoring Robert D. Holtz II, Geotechnical Special Publication (GSP) No. 230, R. D. Holtz, A. W. Stuedlein, and B. R. Christoper, eds., ASCE, Reston, VA, 567-581.

A comparative laboratory study was conducted to evaluate the durability of three different subgrade soils stabilized with hydrated lime, class C fly ash (CFA), and cement kiln dust (CKD). Cylindrical specimens were compacted at optimum moisture content (OMC) and cured for 7 days in a moist room having a constant temperature and controlled humidity. Selected specimens were also compacted at a higher molding moisture content of OMC+4%. After curing, the specimens were subjected to different freeze-thaw (F-T) cycles and tested for unconfined compressive strength (UCS) or resilient modulus (Mr). The UCS and Mr values after F-T cycling were compared with those of the raw soil specimens to determine the influence of soil and additive type on durability. The UCS and Mr values revealed that the addition of cementitious additive increased the durability of stabilized specimens against F-T cycles. The extent of improvement in durability, however, was dependent on the characteristics of both soil and additive and number of F-T cycles.

Stormont, J. C., Ramos, R., and Henry, K. S. (2001). "Geocomposite capillary barrier drain systems with fiberglass transport layer." Transportation Research Record: Journal of the Transportation Research Board, 1772, 131-136.

A geocomposite capillary barrier drain (GCBD) removes water from soil while pore pressures remain negative, that is, the soil to be drained does not need to be saturated. GCBDs are being evaluated for inclusion in pavement systems, particularly between the base course and subgrade layer. The GCBD system comprises a capillary barrier layer (a geonet) sandwiched between transport layers (certain geotextiles). Improved GCBD performance is expected with a transport layer that has a greater affinity for water compared with conventional geotextiles. After many materials were evaluated, a woven fiberglass product was selected for further evaluation as a transport layer. A GCBD with a fiberglass transport layer was placed between a subgrade and a base course in a 3-m-long sloped test device used to measure lateral drainage. Water was infiltrated on the top of the base course, and drainage from the GCBD and the soil layers was collected. Measurements of soil suction were made within the soil layers. The GCBD performance was evaluated during three test phases: constant rate infiltration, subsequent drainage with no infiltration, and transient infiltration corresponding to a design storm. The GCBD was successful in draining sufficient water under suction to prevent positive pore water pressures from developing in the base course and to limit water movement into the underlying subgrade soil.

Stormont, J. C., and Stockton, T. B. (2000). "Preventing positive pore water pressures with a geocomposite capillary barrier drain." Testing and Performance of Geosynthetics in Subsurface Drainage, ASTM STP 1390, L. D. Suits, J. B. Goddard, and J. S. Baldwin, eds., ASTM, West Conshohocken, PA, 15-31.

The Geocomposite Capillary Barrier Drain (GCBD) has been developed and tested to prevent positive pore water pressures from developing by laterally draining water while it is still in tension. The GCBD consists of two key layers that function as long as the water pressures in the system remain negative: (I) a transport layer that laterally drains water and (2) a capillary barrier layer that prevents water from moving downward. Prototype GCBD systems have been tested in a 3 m long lateral drainage test apparatus. For most test conditions, the GCBD systems drained water under negative pressures at a rate sufficient to prevent any positive water pressures from developing in the overlying soil. Further, the drain system served as a barrier as it prevented downward flowing water from moving into the underlying soil.

Velasquez, R., Marasteanu, M. O., Hozalski, R., and Clyne, T. (2005). "Preliminary laboratory investigation of enzyme solutions as a soil stabilizer." Work Order 79, Minnesota Department of Transportation, St. Paul, MN.

Enzymes as soil stabilizer has been used to improve the strength of subgrades due to low cost and relatively wide applicability compare to standard stabilizers. The use of enzymes as stabilizer has not been subjected to any technical development and is presently carried out using empirical guidelines based on previous experience. It is not clear how and under what conditions these products work. Therefore, it becomes an important priority to study and determine the effects of different types of enzymes on the strength of different soils. The chemical composition and mode of action of two commercial soil stabilizers were evaluated using standard and innovative analytical techniques. The product studied shows a high concentration of protein, but did not appear to contain active enzymes based on standard enzymatic activity tests. Results from quantitative surface tension testing and qualitative observations suggest that the enzymes behave like a surfactant, which may play a role in its soil stabilization performance. Two types of soils (soil I and II) and two enzyme products (A and B) were studied in this research. The “three kneading feet tool” was used as a laboratory compaction device for the specimen preparation; the target density was 95% of the maximum dry density obtained in laboratory conditions using T99 procedure. The target moisture was the optimum water content, the enzyme was considered part of the water needed to obtain the optimum moisture content, and the enzyme application rate was 1 cc of enzyme per 5 liters of water. All the specimens were subject to resilient modulus testing and shear strength testing. The resilient modulus testing was performed according to specification described in NCHRP report 1-28A. The effect of time on the performance was also evaluated by running tests on specimens cured for various times. A program developed in visual basic which is based on the recommendations for the analysis of resilient modulus data as part of NCHRP 1-28A protocol was used to analyze the resilient modulus data. The limited data obtained in this project showed that the addition of enzyme A does not improve substantially the resilient modulus of soil I. but increases by 54% the resilient modulus of soil II. In the other hand the addition of enzyme B to soil I and II had a pronounced effect on the resilient modulus. The stiffness of soil I was increased in average by 69% and by 77% for soil II. The type of soil had an effect on the effectiveness of the treatments. Percentages of fines, chemical composition among other are properties that affect the stabilization mechanism. It was found that the resilient modulus increased as the curing time increases for all mixtures of soils and enzymes. It was also noticed that an increment in the application rate suggested by the manufacturers does not improve the effectiveness of the stabilization process. Shear strength tests were performed on 26 specimens following the NCHRP 1-28A protocol. Two different confining pressures were used; 4 and 8 psi. The limited number of specimens tested show that at least 4 months of curing time are needed to observe improvement in the shear strength. It was observed that enzyme A increases the shear strength of soil I by 9%, and by 23% for soil II. In the other hand enzyme B increases the shear strength by 31% for soil I and 39% for soil II. Recommendations for further study include testing more mixtures of soils and enzymes to encompass a wider range of materials and comparing laboratory test data with data obtain in field.

White, D. J., Ceylan, H., Jahren, C. T., Phan, T. H., Kim, S. H., Gopalakrishnan, K., and Suleiman, M. T. (2008). "Performance Evaluation of Concrete Pavement Granular Subbase—Pavement Surface Condition Evaluation." IHRB Project TR-554, Center for Transportation Research and Education, Iowa State University, Ames, Iowa.

This research project covered a wide range of activities that allowed researchers to understand the relationship between stability, pavement distress, and recycled portland cement concrete (RPCC) subbase aggregate materials. Detailed laboratory and field tests, including pavement distress surveys, were conducted at 26 sites in Iowa were conducted. Findings show that specific gravities of RPCC are lower than those of crushed limestone. RPCC aggregate material varies from poorly or well-graded sand to gravel. A modified Micro-Deval test procedure showed that abrasion losses of virgin aggregate materials were within the maximum Micro-Deval abrasion loss of 30% recommended by ASTM D6028-06. Micro-Deval abrasion loss of RPCC aggregate materials, however were much higher than those of virgin materials and exceeded 30% loss. Modulus of elasticity of RPCC subbase materials is high but variable. RPCC subbase layers normally have low permeability. The pavement surfaces for both virgin and RPCC subbase across Iowa were evaluated to fulfill the objectives of this study related to field evaluation. Visual distress surveys were conducted to gather the detailed current pavement condition information including the type, extent, and severity of the pavement distresses. The historical pavement condition information for the surveyed field sections was extracted from the Iowa DOT's Pavement Management Information System (PMIS). The current surface condition of existing field pavements with RPCC subbase was compared with the virgin aggregate subbase sections using two different approaches. The changes in pavement condition indices (PCI and IRI) with time for both types of pavements (subbases) were compared.

White, D. J., Harrington, D., and Thomas, Z. (2005a). "Fly Ash Soil Stabilization for Non-Uniform Subgrade Soils, Volume I: Engineering Properties and Construction Guidelines." IHRB Project TR-461, FHWA Project 4, Center for Transportation Research and Education, Iowa State University, Ames, Iowa.

Soil treated with self-cementing fly ash is increasingly being used in Iowa to stabilize fine-grained pavement subgrades, but without a complete understanding of the short- and long-term behavior. To develop a broader understanding of fly ash engineering properties, mixtures of five different soil types, ranging from ML to CH, and several different fly ash sources (including hydrated and conditioned fly ashes) were evaluated. Results show that soil compaction characteristics, compressive strength, wet/dry durability, freeze-thaw durability, hydration characteristics, rate of strength gain, and plasticity characteristics are all affected by the addition of fly ash. Specifically, Iowa self-cementing fly ashes are effective at stabilizing fine-grained Iowa soils for earthwork and paving operations; fly ash increases compacted dry density and reduces the optimum moisture content; strength gain in soil-fly ash mixtures depends on cure time and temperature, compaction energy, and compaction delay; sulfur contents can form expansive minerals in soil–fly ash mixtures, which severely reduces the long-term strength and durability; fly ash increases the California bearing ratio of fine-grained soil–fly ash effectively dries wet soils and provides an initial rapid strength gain; fly ash decreases swell potential of expansive soils; soil-fly ash mixtures cured below freezing temperatures and then soaked in water are highly susceptible to slaking and strength loss; soil stabilized with fly ash exhibits increased freeze-thaw durability; soil strength can be increased with the addition of hydrated fly ash and conditioned fly ash, but at higher rates and not as effectively as self-cementing fly ash.

Based on the results of this study, three proposed specifications were developed for the use of self-cementing fly ash, hydrated fly ash, and conditioned fly ash. The specifications describe laboratory evaluation, field placement, moisture conditioning, compaction, quality control testing procedures, and basis of payment.

Yarbasi, N., Kalkan, E., and Akbulut, S. (2007). "Modification of the geotechnical properties, as influenced by freeze-thaw, of granular soils with waste additives." Cold Regions Science and Technology, 48, 44-54.

This paper evaluates the use of waste materials such as silica fume, fly ash, and red mud in the modification of granular soils in order to remove the effects of freezing–thawing cycles. In this study, two granular soils obtained from primary rock were stabilized by silica fume–lime, fly ash–lime, and red mud–cement additive mixtures. Natural and stabilized soil samples were subjected to freezing–thawing cycles after curing for 28 days. After the freezing–thawing cycles, compressive strength, California bearing ratio, freezing–thawing, ultrasonic wave, and resonant frequency tests were performed to investigate effects of additive mixtures on the freezing–thawing properties of natural and stabilized soil samples. The experimental results show that stabilized samples with silica fume–lime, fly ash–lime, and red mud–cement additive mixtures have high freezing–thawing durability as compared to unstabilized samples. These additive mixtures have also improved the dynamic behaviors of the soil samples. Consequently, we conclude that silica fume–lime, fly ash–lime, and red mud–cement additive mixtures, particularly silica fume–lime mixture, can be successfully used as an additive material to enhance the freezing–thawing durability of granular soils for road constructions and earthwork applications.

Zaimoglu, S. A. (2010). "Freezing-thawing behavior of fine-grained soils reinforced with polypropylene fibers." Cold Regions Science and Technology, 60, 63-65.

A number of studies have been conducted recently to investigate the influence of randomly oriented fibers on some engineering properties of cohesive and cohesionless soils. However, very few studies have been carried out on freezing–thawing behavior of soils reinforced with discrete fiber inclusions. This experimental study was performed to investigate the effect of randomly distributed polypropylene fibers on strength and durability behavior of a fine-grained soil subjected to freezing–thawing cycles. For strength behavior, a series of unconfined compression tests were conducted. Mass losses were also calculated after freezing–thawing cycles as criteria for durability behavior. The content of polypropylene fiber was varied between 0.25% and 2% by dry weight of soil in the tests. The test results for the reinforced specimens were compared with that for the unreinforced sample. It was observed that the mass loss in reinforced soils was almost 50% lower than that in the unreinforced soil. It was also found that the unconfined compressive strength of specimens subjected to freezing–thawing cycles generally increased with an increasing fiber content. On the other hand, the results indicated that the initial stiffness of the stress–strain curves was not affected significantly by the fiber reinforcement in the unconfined compression tests.

Field Study (Unpaved Roads)

Bassel, J. R., Edwards, A., Leibbrand, L., Keller, G. R., and Dauer, W. (1999). "Three road-crushing demonstration projects." Transportation Research Record: Journal of the Transportation Research Board, 1652.

At the Sixth International Conference on Low-Volume Roads Yves Provencher, Forest Engineering Research Institute of Canada, presented a paper on the F.A.H.R. rock crusher mounted to a front-end loader. At the same time the Coronado National Forest in Arizona was renting a F.A.H.R. rock crusher for an in-place road-crushing project. In 1997 San Dimas Technology and Development Center, in partnership with the Coronado National Forest, sponsored two demonstration projects to further test the crusher at unique locations to gain additional information from actual field trials. These projects were located on the Rio Grande National Forest in Colorado and the Plumas National Forest in California. The three projects are described here, with results and conclusions gained from the demonstration projects. The concentration is on the characteristics of the processed material. Samples taken from windrows during the crushing operation were tested to determine hardness and gradations before and after crushing. Cost varied from $8 to $26 per m3 including roadbed preparation, crushing, and blading. Rocks and boulders to 405-mm maximum size were crushed. The processed material has a maximum size of 50 to 75 mm. The product produced by the crusher offers a viable alternative for aggregate on a road surface, particularly as a road surface cushion material, where the quality and expense of standard crushed aggregate, such as base course material, are not needed on low-volume roads.

Behak, L. (2011). "Performance of Full-Scale Test Section of Low-Volume Road with Reinforcing Base Layer of Soil–Lime." Transportation Research Record: Journal of the Transportation Research Board, 2204, 158-164.

The roads of the rice region of Merin Lake in Uruguay are subjected to low annual average traffic. However, the average daily traffic is approximately 100 trucks during harvest time. The local soils, characterized as clayey silts, are unsuitable for such traffic demands and are generally replaced or reinforced by materials found more than 70 km away, with high transportation costs. An investigation of the performance of a full-scale test section of pavement with a base layer of local silty clay soil stabilized with lime was conducted. The design of the test section consisted of soil selection, determination of lime content for stabilization, compaction, and California bearing ratio laboratory tests. Two test sections, each 50 m, were built, with a base layer of selected soil mixed with 3% lime in one section and with 5% lime in the other. After the rice harvest, the performance of the test sections was evaluated by visual observation of the base layer and deflection measures with a Benkelman beam. Despite some construction difficulties, the deflection average values changed from 244 x 10−2 cm immediately after the section was built to 77 x 10−2 cm 4 months later. The use of soil–lime material for base layers of low-volume roads is a technical and economical alternative that provides a significant improvement of the rural road network with socioeconomic benefits.

Bergeson, K. L., Kane, M. J., and Callen, D. O. (1990). "Crushed stone granular surfacing materials." Sponsored by the Iowa Limestone Produces Association and National Stone Association Research Program, Report by Engineering Research Institute, Iowa State University, Ames, Iowa.

The results of this research project indicate that crushed stone surfacing material graded on the fine side of IDOT Class A surfacing specifications provides lower roughness and better rideability; better braking and handling characteristics; and less dust generation than the coarser gradations. This is believed to be because there is sufficient fines (-#40 to - #200) available to act as a binder for the coarser material, which in turn promotes the formation of tight surface crust. This crust acts to provide a smooth riding surface, reduces dust generation, and improves vehicle braking and handling characteristics.

Bergeson, K. L., Waddingham, J. W., Brocka, S. G., and Lapke, R. K. (1995). "Bentonite treatment for economical dust reduction on limestone surface secondary roads." Iowa DOT Project HR-351, Engineering Research Institute, Iowa State University, Ames, Iowa.

This research project was directed at laboratory and field evaluation of sodium montmorillonite clay (Bentonite) as a dust palliative for limestone surfaced secondary roads. It was postulated that the electrically charged surfaces (negative) of the clay particles could interact with the charged surfaces (positive) of the limestone and act as a bonding agent to agglomerate fine (- #200) particulates, and also to bond the fine particulates to larger (+ #200) limestone panicles. One mile test roads were constructed in Tama, Appanoose, and Hancock counties in Iowa using Bentonite treatment levels (by weight of aggregate) ranging from 3.0 to 12.0 percent. Construction was accomplished by adding dry Bentonite to the surfacing material and then dry road mixing. The soda ash water solution (dispersing agent) was spray applied and the treated surfacing material wet mixed by motor graders to a consistency of 2 to 3 inch slump concrete. Two motor graders working in tandem provided rapid mixing. Following wet mixing the material was surface spread and compacted by local traffic. Quantitative and qualitative periodic evaluations and testing of the test roads was conducted with respect to dust generation, crust development, roughness, and braking characteristics. As the Bentonite treatment level increased dust generation decreased. From a cost benefit standpoint, an optimum level of treatment is about 8 percent (by weight of aggregate). For roads with light traffic, one application at this treatment level resulted in a 60-70 percent average dust reduction in the first season, 40-50 percent in the second season, and 20-30 percent in the third season. Crust development was rated at two times better than untreated control sections. No discernible trend was evident with respect to roughness. There was no evident difference in any of the test sections with respect to braking distance and braking handling characteristics, under wet surface conditions compared to the control sections. Chloride treatments are more effective in dust reduction in the short term (3-4 months). Bentonite treatment is capable dust reduction over the lone: term (2-3 seasons). Normal maintenance blading operations can be used on Bentonite treated areas. Soda ash dispersed Bentonite treatment is conservatively estimated to be more than twice as cost effective per percent dust reduction than conventional chloride treatments, with respect to time. However, the disadvantage is that there is not the initial dramatic reduction in dust generation as with the chloride treatment. Although dust is reduced significantly after treatment there is still dust being generated. Video evidence indicates that the dust cloud in the Bentonite treated sections does not rise as high, or spread as wide as the cloud in the untreated section. It also settles faster than the cloud in the untreated section. This is considered important for driving safety of following traffic, and for nuisance dust invasion of residences and residential areas. The Bentonite appears to be functioning as a bonding agent to bind small limestone particulates to larger particles and is acting to agglomerate fine particles of limestone as evidenced by laboratory sieve analysis data, and by SEM micrographs. This bonding capability appears recoverable from environmental effects of winter, and from alternating wet and dry periods. The Bentonite is able to interact with new applications of limestone maintenance material and maintains a dust reduction capability.

Bland, A. E., Brown, T. H., and Sheesley, D. C. (1991). "Fly ash use for unpaved road stabilization - Phase I." Interim Technical Report WRI-92-R017, The University of Wyoming, Laramie, Wyoming.

Western Research Institute (WRI) has conducted both laboratory and field demonstrations of a relatively new nonstandard unpaved road stabilization technique burning Class C fly ash from coal-fired power generation plants using Wyoming subbituminous coals. The experimental construction technique uses lean fly ash/soil/water formulations for stabilizing unpaved road materials to reduce maintenance costs and to provide new expanded markets for coal fly ash. The experimental testing program was designed to evaluate different soil/fly ash conditions as well as different construction techniques. Laboratory testing was conducted using ash from the PacifiCorp Dave Johnston Power Plant (DJPP) near Glenrock, Wyoming and five different soil types from a road adjacent to the plant. The laboratory testing examined the geotechnical performance of the various amounts of fly ash treatment of the soils. Moisture-density relationships and moisture-strength relationships were determined. The Dave Johnston fly ash is a slow-reacting fly ash, and early strength development was low (less than 100 psi) for all mixtures tested up to 25% fly ash. A twofold increase in strength was noted between the low fly ash dosage rates (5%) and the high fly ash dosage (25%). Based on the results of the laboratory testing, it is recommended to use 20% fly ash and optimum moisture for compaction of 11 to 13% water. Two 1,000-ft experimental test sections demonstrating the fly ash stabilized unpaved road process were constructed in July 1991, near the DJPP. The unpaved road had a continued history of washboarding and required regular high levels of maintenance. Based on the laboratory testing and design, the experimental test road was constructed using Dave Johnston fly ash as a binder to stabilize the upper 9 inches of the road surface. The intent was to treat the road sections by scarifying\ adding fly ash, and thoroughly mixing these materials with water and compacting the mixture to a highly densified and stable road surface. It was intended that the road be immediately available to traffic and continue to improve in strength and durability with time. WRI decided to use a fly ash application of 20% to construct the test section for several reasons: (1) The fly ash source was adjacent to the road construction site, and no transportation costs would be incurred. (2) A high application percentage would provide a range of high and low ash concentrations to study. (3) The laboratory studies suggested that a 20% application of fly ash from the DJPP was required for maximum strength development in the test section. Two demonstration test sections were constructed. Fly ash from Unit 3 of the DJPP was used for the treatment. Also, water from the Dave Johnston recycle pond was used. The materials consisted of 240 tons of fly ash and 10,000 gallons of water. Based on calculations of the depth of treatment and the bulk density of the road material, a fly ash treatment of 20% and a water addition of 11 % were achieved. The laboratory design testing suggested that optimum moistures in the range of 11 to 13% were required for maximum compaction. Visual monitoring of the road showed that some areas required remedial attention. This was a result of inadequate mixing of the fly ash and soil, and insufficient water addition during construction. A soft spot in the road with a high fly ash content, was patched to reduce dusting and improve trafficability. The test sections were dusting because either insufficient water was added during construction or the fly ash mixtures dried out before sufficient curing could occur. The treated sections were covered with bottom ash to act as a moisture barrier and covering the surface. The barrier was successful, but the bottom ash developed severe washboarding. As a result, the bottom ash was removed after the fly ash/soil achieved sufficient strength and · durability. Additional water applications helped develop a hard, upper 2- to 3-inch surface in the fly ash treated section of the road. Performance monitoring and evaluation of the construction techniques show that mixing was inadequate, whereas compaction appears to be satisfactory. Fly ash distribution via blade mixing did not produce a homogeneous mixture, although improvement may have been possible if additional passes had been performed. Evidence for both lateral variations in the test section from 15 to 50% fly ash and a vertical layering in the treated section have been documented. Inadequate water distribution due to improper mixing was also noted as evidenced by the fact that areas were found that appeared to have received little or no water. Compaction of the fly ash treated soil mixtures was in the range of 95% of the laboratory results and the estimated maximum dry density. The performance of the fly ash treated section is presently quite good, showing continued strength development and reduced potential for dusting. The mechanically treated section is developing cracks, which are expected to create problems by Spring 1992. The control section is already showing washboarding as it has in the past. The fly ash stabilization technology appears to be an environmentally acceptable technology that does not pose a threat to groundwater. The surface water and storm water runoff have not been assessed because rainfall in the area has been too low. However, WRI does not anticipate problems associated with surface water or storm water runoff quality. In addition, the level of radioactivity for the fly ash is too low to be a health concern. However, the application of the fly ash during the construction phase needs to be improved to prevent excessive fugitive dust emissions. Options for modifying the construction procedure are being addressed and will be incorporated into future test sections. The results of the phase I testing and demonstration activities show that the process of fly ash stabilization of unpaved roads is promising. Although the strength development with the Dave Johnston fly ash is very slow, engineering performance of the road demonstration test sections is quite good. The fly ash treated test section has shown no evidence of washboarding, and the dust from the road has been reduced to levels comparable to the control section of the unpaved road.

Bloser, S. M. (2007). "Commonly Used Aggregate Materials and Placement Methods: Comparative Analysis for a Wearing Course on Low-Volume Roads in Pennsylvania." Transportation Research Record: Journal of the Transportation Research Board, 1989, 178-185.

Aggregate-surfaced roads are a viable component of the transportation network; they provide significant increases in road stability over earthen surfaced roads while avoiding the high placement and maintenance costs of pavements. The use of higher-quality, more stable aggregates will significantly reduce both the cost of maintaining gravel roads and the environmental concerns related to road runoff. This paper aims to provide a better understanding of wearing course aggregates by describing a comparative analysis experiment done as part of Pennsylvania's Dirt and Gravel Road Maintenance Program. Three aggregates commonly used in Pennsylvania were placed side by side under two different placement methods for each type of aggregate as part of a 3-year study to compare their long-term durability and cost-effectiveness. The two methods tested were the "dump and spread" method known as tailgating and the application of aggregate by a motor paver. Cross-sectional surveys were done on each aggregate section for 3 years following placement to determine elevation changes in the road surfaces. No significant difference in performance was found between aggregate sections placed with a paver and the same aggregate placed by tailgating. Driving surface aggregate was the only aggregate of the three tested that did not show a statistically significant change in road elevation during the 3-year course of study. Results illustrate the importance of selecting a properly graded aggregate containing minimal clay and soil material for use as surface aggregate on low-volume roads.

Brandon, T. L., Al-Qadi, I. L., Lacina, B. A., and Bhutta, S. A. (1996). "Construction and Instrumentation of Geosynthetically Stabilized Secondary Road Test Sections." Transportation Research Record: Journal of the Transportation Research Board, 1534, 50-57.

Nine instrumented flexible pavement test sections were constructed in a rural secondary road in southwest Virginia. The nine test sections, each 15 m (50 ft) long, were built to examine the effects of geogrid and geotextile stabilization. Three lest sections were constructed with a geogrid, three were built with a geotextile, and three were nonstabilized. The test section base course thicknesses ranged from 10,2 cm (4.0 in.) to 20.3 cm (8.0 in.), and the hot-mix asphalt (HMA) thickness averaged 8.9 cm (3.5 in.). Geosynthetic stabilization was placed on top of the subgrade layer. The pavement test sections were heavily instrumented with two types of pressure cells, soil and HMA strain gauges, thermocouples, and soil moisture cells. In addition, strain gauges were installed directly on the geogrid and geotextile. An extensive instrumentation infrastructure was constructed to locate all instrumentation, cabling, and data acquisition facilities underground. Instrument survivability has ranged from 6 percent for the strain gauges mounted on the geotextile to 100 percent for the soil moisture blocks after 8 months of operation. The majority of instrument failures occurred either during construction or the first few weeks of operation. The data acquisition system is triggered by traffic passing over piezoelectric sensors and operates remotely. The corresponding data are transferred via modem to Virginia Polytechnic Institute and State University for processing. It is planned that the performance of the pavement test sections will be monitored for a minimum of 3 years.

Campbell, A. E., and Jones, D. (2011). "Soil Stabilization in Low-Volume Roads - Obstacles to Product Implementation from Additive Supplier's Standpoint." Transportation Research Record: Journal of the Transportation Research Board (2204), 172-178.

Overwhelming evidence supports the importance of gravel roads. However, road agencies are increasingly faced with the necessity of relying on marginal materials in construction of low-volume roads. Use of these materials necessitates that stabilization be used to alter the engineering parameters to ensure that corrugation, erosion, rutting, poor passability, dust, and low-bearing capacity are avoided. Soil stabilization is increasingly being used as an unsealed-road asset management tool in an attempt to reduce the impacts of these issues, and nontraditional soil stabilizers have been a primary area of focus. Yet few such products have gained widespread acceptance. This paper looks at the lack of usage of alternative stabilizers in the marketplace today from the viewpoint of the product supplier. It aims to identify the issues facing the supplier in introducing a competent nontraditional soil stabilizer product to road agencies and to identify the measures such suppliers can take to advance those products that show good potential. Measures that could be introduced to better manage the field of soil stabilization for unsealed and low-volume sealed roads have been suggested. These measures include the following: established guidelines, specifications, test methods, and management principles, all prepared in a format that is readily acceptable and adoptable by industry engineers;

an industry association; and the adoption of a dedicated research protocol establishing minimum requirements for research on such additives.

Drake, A. (2012). "Gleann Mor Forest Road Argyll and Bute, Scotland." A ROADEX "Implementing Accessibility" Project, The Swedish Transport Administration, Northern Region, Sweden.

The ROADEX Project was a technical co-operation between road organisations across northern Europe that aimed to share road related information and research between the partners. The project was started in 1998 as a 3 year pilot co-operation between the districts of Finnish Lapland, Troms County of Norway, the Northern Region of Sweden and The Highland Council of Scotland and was subsequently followed and extended with a second project, ROADEX II, from 2002 to 2005, a third, ROADEX III from 2006 to 2007 and a fourth, ROADEX "Implementing Accessibility" from 2009 to 2012. The Partners in the ROADEX "Implementing Accessibility" project comprised public road administrations and forestry organisations from across the European Northern Periphery. These were The Highland Council, Forestry Commission Scotland and the Western Isles Council from Scotland, The Northern Region of The Norwegian Public Roads Administration, The Northern Region of The Swedish Transport Administration and the Swedish Forest Agency, The Centre of Economic Development, Transport and the Environment of Finland, The Government of Greenland, The Icelandic Road Administration and The National Roads Authority and The Department of Transport of Ireland. The aim of the project was to implement the road technologies developed by ROADEX on to the partner road networks to improve operational efficiency and save money. The lead partner for the project was The Swedish Transport Administration and the main project consultant was Roadscanners Oy of Finland. A main part of the project was a programme of 23 demonstration projects showcasing the ROADEX methods in the Local Partner areas supported by a new pan-regional "ROADEX Consultancy Service" and "Knowledge Centre". Three research tasks were also pursued as part of the project: D1 "Climate change and its consequences on the maintenance of low volume roads", D2 "Road Widening" and D3 "Vibration in vehicles and humans due to road condition". The following are lessons learned from the project: Most of the older Forestry Commission forest roads have had temporary repairs to keep the timber moving, and sections have been completely reconstructed following landslides etc. During these and subsequent maintenance operations, different sources and types of stone have been used which can make GPR interpretation of layer depths challenging. It is also true to say that although the performance specification of the FC timber haulage roads is the same throughout England, Scotland and Wales, ground conditions and materials are extremely variable so the structural composition of roads can be totally different from area to area. Therefore, the establishment of appropriate area parameters using local knowledge and ground truth is important. The FWD testing procedure is intended for hard road surfaces. URS Scott Wilson has confirmed that when the surface of a forest road is soft, it can be difficult to achieve a 50 kN load as some of the force is actually absorbed by the road. Consequently, FWD work should be carried out in dry conditions but this can only be aspirational in Scotland! (Note: In Sweden FWD measurements are carried out in the spring after the frost has gone. It has been found that if measurements are taken in the middle of a dry summer the values might be too good.) It is difficult to get consistent dielectric value readings from the sides of an excavated trench using the Adek Percometer. This survey and assessment method has subsequently been used to analyse a totally new forest road which was built to a carefully designed and monitored specification. The Stone Depth analysis procedure showed that no additional stone was required at any point. The Forestry Commission have also surveyed a road formation with no pavement at all. The same procedure showed that not only was stone required along the entire length of the alignment, but it also calculated the depths and volumes. These results were as expected and they have established an “envelope” within which all other survey data from existing forest roads should fall. Surveys to-date have given the Forestry Commission confidence in the efficacy of the technique and the next stage of the project will be to develop improved site procedures. The aim will be to devise a method of applying the survey outputs on future roads in a manner which not only closely relates to the calculated lengths, depths and volumes but which is also practical to set out and control.

Embacher, R. A. (2006). "Duration of Spring-Thaw Recovery for Aggregate-Surfaced Roads." MN/RC-2006-12, Minnesota Department of Transportation, St. Paul, Minnesota.

Low-volume roads constructed in regions susceptible to freezing and thawing periods are often at risk of load-related damage during the spring-thaw period. The reduced support capacity during the thawing period is a result of excess melt water that becomes trapped above the underlying frozen layers. Many agencies place spring load restrictions (SLR) during the thaw period to reduce unnecessary damage to the roadways. The period of SLR set forth by the Minnesota Department of Transportation is effective for all flexible pavements; however, experience suggests that many aggregate-surfaced roads require additional time relative to flexible pavements to recover strength sufficient to carry unrestricted loads. An investigation was performed to improve local agencies’ ability to evaluate the duration of SLR on aggregate-surfaced roadways. This was accomplished through seasonal measurements of in situ shear strengths, measured using the dynamic cone penetrometer (DCP), on various Minnesota county routes. In situ strength tests were conducted on selected county gravel roads over the course of three years. Strength levels recorded during the spring-thaw weakened period were compared to fully recovered periods that typically occur in late spring/summer. The results indicate that aggregate-surfaced roads generally require 1 to 3 additional weeks, over that of flexible pavements, to reach recovered bearing capacity. Additionally, a strong correlation was found between duration required to attain given strength recovery values and climatic and grading inputs.

Fannin, R. J., and Sigurdsson, O. (1996). "Field observations on stabilization of unpaved roads with geosynthetics." Journal of Geotechnical Engineering, 122(7), 544-553.

The construction, instrumentation, and response to vehicle trafficking of an unpaved road on soft ground are described. The road is comprised of an unreinforced section, three sections with different geotextiles, and a section with geogrid. The performance of the unreinforced section compares reasonably well, at large rut depths, to prediction using the analytical approach most commonly used in current design practice. Inclusion of a geosynthetic between the base course layer and subgrade soil led to a significant improvement in trafficability. The improvement was greatest for the thinner base layer of 25 cm, and diminished with increasing layer thickness. Reasonable agreement was, again, observed between the field performance and analytical predictions at large rut depths. The analytical approach was found to significantly over predict the number of vehicle passes to develop a 5 cm rut. The lack of agreement at small to moderate rut depths is attributed to compaction of the base course layer in response to vehicle trafficking that is not accounted for in the analytical approach. Some implications of the field

observations for selection of a geosynthetic are discussed, with reference to separation and reinforcement of gravel layers over soft soils.

Henry, K. S., Olson, J. P., Farrington, S. P., and Lens, J. (2005). "Improved performance of unpaved roads during spring thaw." ERDC/CRREL TR-05-01, Engineer Research and Development Center Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Unpaved roads in Vermont are subject to deterioration from seasonal freezing and thawing, and many towns have roads that suffer chronic serviceability problems during the so-called “spring thaw,” or mud season. Several techniques thought to mitigate deterioration of unpaved roads during spring thaw were constructed on test sections of unpaved roads in two towns. Each potential remedy was aimed at providing some combination of limiting the availability of moisture in the winter, improving drainage during spring, and strengthening the upper portion of the road. Each technique used local and/or commercially available materials, and all were easy to construct, i.e., a town road crew could build them. For two spring thaw seasons, we compared strength estimates based on dynamic cone penetrometer tests and the percentage of the road surface rutted for treated and control sections. Methods that permanently improved the strength of the top 12 inches of the road or decreased the water content of the upper 12 inches of the road resulted in significant performance improvement during spring thaw. Cement and cellular confinement systems worked well by improving the strength of the upper layers of the soil. Two new techniques— geowrap, comprising clean sand sandwiched by geotextile separators placed 12–18 inches deep, and the patented Geosynthetic Capillary Barrier Drain—provided benefit by keeping the upper layers of the soil relatively dry. Geogrid and geotextile separators placed 12 inch deep and trench drains parallel to the road provided no observable benefit.

Hoover, J. M. (1973). "Surface improvements and dust palliation of unpaved secondary roads and streets." Iowa Highway Research Board Project HR-151, Engineering Research Institute, Iowa State University, Ames, Iowa.

The report contains five parts:

(I) Project Summary by Hoover, J. M. - As of December 31, 1970 there were 57,270 miles of Local Secondary roads and 32,958 miles of Farm to Market roads in the Iowa secondary road system. The Local Secondary system carried a traffic load of 2,714,180 daily vehicle miles, accounting for 32% of all traffic in secondary system. For all Local Secondary roads having some form of surfacing, 98% were surfaced with gravel or crushed stone. During the 1970 construction year, 335 miles of surfaced roads were constructed in the Local Secondary system with 78% being surfaced with gravel or crushed stone. The total maintenance expenditure for all secondary roads in Iowa during 1970 amounted to $40,086,091. Of this, 42%, or $17,020,332, was spent for aggregate replacement on existing gravel or crushed stone roads with an additional 31% ($12,604,456) being spent on maintenance other than resurfacing. This amounts to 73% of the total maintenance budget and are the largest two maintenance expenditure items out of a list of 10 ranging from bridges to drainage assessments. The next largest item was 7%, for maintenance of existing flexible bases. Present costs of high-type flexible or rigid pavements range from $40,000 per mile up. Because of high cost, budget limitations, and low mileage of high traffic volume on Local Secondary roads, most Iowa counties are severely restricted as to the number of miles of roads that may be paved each year. Present design and construction

standards provide adequate means for improvement of grade and cross section of secondary roads followed by: (a) immediate road metal surfacing, or (b) eventual high-type surfacing. There are, at present, no formal provisions for an intermediate type surfacing between these two extremes. Therefore, nearly all Iowa counties are in a situation in which they have only a few miles of high-type pavements with the bulk being surfaced with gravel or crushed stone. From the maintenance expenditures for 1970, it can be seen that the primary method of maintaining aggregate surfaced secondary roads remains, as it has in the past, as aggregate replacement. Roads continue to rut, washboard, ravel, pothole, and become the source for billowing clouds of dust. Loose aggregate makes driving hazardous, and results in cases of vehicle damage including cracked windshields, chipped paint, and dents, as well as increased fatalities. During the spring thaw and subsequent rains, many roads become extremely soft, slippery, and heavily rutted. As aggregate supplies decrease, inferior quality soft limestones and gravels are being used, resulting in faster degradation contributing to the dusting problem. Dust creates a safety hazard to both passing and oncoming traffic. It is also a definite household nuisance in rural areas, especially in heavily populated regions surrounding larger towns and cities where traffic on unpaved roads may range as high as 500 vehicles per day. The severity of these problems continues to increase as: (a) traffic volume increases, (b) more people move to rural areas surrounding larger towns and cities, and (c) the current concern over air pollution increases. The Iowa Air Pollution Control Commission has drafted guidelines with respect to "fugitive" dust, which ultimately will affect all unpaved state, county, and city roads and streets. Besides the above problems, most counties are faced with (a) rising costs of high-type pavement, (b) rising costs of maintenance, and (c) rising costs of replacement aggregates. The foregoing considerations dictated the need for finding a means to provide for low-cost surface improvement and dust control, using existing in-place materials, for immediate (and intermediate) use as a treated surface course on unpaved secondary roads - the objective of this research project. Three concurrent phases of study were included in the project: (1) laboratory screenings studies of various additives thought to have potential for long-lasting dust palliation, soil additive strength, durability, and additive retention potential; (2) test road construction using those additives that indicated promise for performance-serviceability usage; and (3) observations and tests of constructed sections for evaluation of the additive's contribution to performance and serviceability as well as the relationship to initial costs.

(II) Asphaltic products and elastometers as dust palliatives and surface improvement agents for unpaved secondary roads, by Bergeson, K. H. and Hoover, J. M.: Bituminous materials have long been used, with varying degrees of success, as soil stabilizers and waterproofing agents. With advancing technological developments many new asphaltic products, whose properties have been altered and supposedly enhanced by the addition of chemicals and selected emulsifying agents, are being marketed. Elastomers, which contain rubber in a modified form, have also been introduced. The beneficial effects of these products, as soil stabilizers and dust palliatives, can only be determined by laboratory evaluation and field trials. This investigation was conducted essentially as a three phase project consisting of (a) laboratory screenings of various asphaltic products and elastomers to evaluate their effectiveness as soil stabilizers and dust palliatives, (b) construction of a test road, based on the results of the laboratory screening phase, using those additives that appeared to be the most effective and economical, and (c) observation and tests of the various sections of the test road for evaluation of the additives’ performance and serviceability with respect to dust palliation and surface improvement. The primary purpose of this study is to present the results of each of the above phases. The test road was constructed in September 1971 and had been in service only one year and three months at the time of termination of research. Therefore, phase 3 analyses are somewhat limited due to the period of time covered.

(III) Ammonium lignosulfonates as dust palliatives and surface improvement agents for unpaved secondary roads, by Fox, D. E., and Hoover, J. M.: At the time the research project was initiated in mid-1970, county engineer offices in Iowa were requested to propose locations for test roads within their respective counties. It was explained that all men, material, and equipment would be furnished by the individual counties. Laboratory screenings of additives and field testing of experimental roads would be carried out by the researchers, who would also be present to observe construction and provide technical assistance when and where needed. Four counties responded with interest in lignosulfonate stabilization. Lignosulfonates are available in almost unlimited quantities from paper mills. Ten years ago, lignosulfonates cost 6 cents per gallon at the mill and the price has not increased, although production has. Due to different pulping processes, the cation associated with lignosulfonate varies. Sodium, calcium, and ammonium lignosulfonates have all been used in soil stabilization and prices are similar. The study reported here utilized commercially-available lignosulfonate with ammonium as the associated cation. The following paragraphs explain the participation offered for lignosulfonate research by the corresponding county. The county engineer's office of Clinton County, Iowa made available a section of road 2620 ft long to which crushed limestone had been added at a rate of 2000 tons per mile. This length was naturally divided into three approximately equal sections, a flat upland location, a curve on a hill of about 6% grade, and a level bottomland section on a backwater area of the Mississippi River. The road was located between, and connected with, paved roads terminating at the Clinton and Camanche city limits. Two nearby industries contributed to a 1967 ADT (average daily traffic) of 500 vehicles per day, and maintenance was a problem. The researchers were invited to perform field tests on several roads within Floyd County, both prior to and following treatment with lignosulfonate. Construction was done by county personnel under the supervision of the lignosulfonate supplier. A dirt road near Marion, Linn County, was made available by the county engineer for research. Of 6000 ft length, the 1968 traffic survey showed an ADT of 44 vehicles. Prior to treatment, the grade was built up and improved by the ditch clean-out method typical of much secondary road construction. Using lignosulfonate from a local source, stabilization of nearly 150 miles of roads was begun in Lee County in the late 1950s and early 1960s. Treatment consisted of only light surface blading and occasional application of aggregate coupled with a lignosulfonate surface spray application. Over the years, an in-depth treatment was produced. Extensive cost and maintenance records on treated roads were kept and made available to the researchers.

(IV) Soil-chemical additives as surface improvement agents for unpaved roads, by Denny, C. K., and Hoover, J. M.: The use of polyester and plastic resins as soil stabilizers is relatively new and untried. The objective of this research was to investigate the capabilities of these resins and several other chemicals and commercial dust palliatives as potential low-cost dust palliatives and surface improvement agents. The investigation was conducted entirely in the laboratory but care was taken to approximate field conditions as accurately as possible. Various soil-chemical additives were evaluated on the basis of the following tests: (1) unconfined compressive strength, (2) durability and erosibility, (3) trafficability, (4) resistance to freezing and thawing, and (5) moisture retention and density. Some of the tests were standard while others were specifically modified, but in every case the treated specimens were compared with untreated control specimens.

(V) Appendix: Mineralogical analyses of dust samples, by Handy, R. L.: This part contains results of differential thermal-thermogravimetric analysis and petrographic analysis. Thermogravimetric analysis offers a rapid, accurate method for the measurement of carbonates and organic matter in 50 mg dust samples, and gives a reliable semi-quantitative indication of the amount of clay minerals. Analysis by petrographic microscope is less accurate but requires less sample, and therefore is a valuable supplemental technique for very small samples. Dust analyses show conclusively that selective sorting is operative, calcium carbonate dominating in dust samples collected near the road, and gradually decreasing to near zero several hundred feet away from the road. Simultaneously, the contents of clay and organic matter increase with distance from the road. The efficiency of the sorting indicates that it is size-selective rather than specific gravity-selective (i.e., carbonate contents are higher close to the road because the grains are larger and settle faster). Lignin treatment will drastically reduce the carbonate percentage in road dust, by more than a factor of 10, provided the added rock amount does not exceed 1000 T/mile. The total amount of dust is less drastically reduced, and the amount roughly coincides with the amounts of noncarbonate components in dusts from untreated roads. This suggests that lignin and clay build up a protective patina at the road surface, by migration upward due to evaporation. This patina protects the limestone and is worn off by traffic; however, it should renew so long as sufficient lignin remains in the road. (Alternatively, it probably can be renewed by surface treatments.) The existence of such a coating, while greatly reducing the limestone aggregate loss from the dry road, also may contribute some slipperiness on a wet road, and probably acts to reduce bonding between the road metal and a bituminous overlay. Rock added in excess of about 1000 T/mile is not effectively protected by a 1% lignin treatment, or lignin plus lime. In addition, at the higher rock application levels, added Ca(OH)* lime tends to further reduce the protective effect on carbonates, probably by flocculating the clay and reducing migration and development of a film.

Hoover, J. M., Moeller, D. T., Pitt, J. M., Smith, S. G., and Wainaina, N. W. (1982). "Performance of randomly oriented, fiber-reinforced roadway soils: A laboratory and field investigation." Iowa Highway Research Board Project HR-211, Engineering Research Institute, Iowa State University, Ames, Iowa.

The purpose of the study was to conduct a laboratory and field investigation into the potential of improving (a) soil-aggregate surfaced and subgrade materials, including those that are frost-prone and/or highly moisture susceptible, and (b) localized base course materials, by uniting such materials through fibrous reinforcement. The envisioned objective of the project was the development of a simple construction technique(s) that could be (a) applied on a selective basis to specific areas having a history of poor performance, or (b) used for improvement of potential base materials prior to surfacing. Little background information on such purpose and objective was available. Though the envisioned process had similarities to fibrous reinforced concrete, and to fibrous reinforced resin composites, the process was devoid of a cementitious binder matrix and thus highly dependent on the cohesive and frictional interlocking processes of a soil and/or aggregate with the fibrous reinforcement; a condition not unlike the introduction of reinforcing bars into a concrete sand/aggregate mixture without benefit of portland cement. Thus the study was also directed to answering some fundamental questions: (1) would the technique work; (2) what type or types of fibers are effective; (3) are workable fibers commercially available; and (4) can such fibers be effectively incorporated with conventional construction equipment, and employed in practical field applications? The

approach to obtaining answers to these questions, was guided by the philosophy that an understanding of basic fundamentals was essential to developing a body of engineering knowledge that would serve as the basis for eventual development of design procedures with fibrous products for the applications previously noted.

Hoover, J. M., Pitt, J. M., Handfelt, L. D., and Stanley, R. L. (1981a). "Performance of soil-aggregate-fabric systems in frost-susceptible roads, Linn County, Iowa." Transportation Research Record: Journal of the Transportation Research Board, 827, 6-14.

Geotechnical construction fabric applied in soil-aggregate and granular-surfaced low-volume roadways indicate that fabric systems can, under certain circumstances, reduce thaw-induced deformations and improve field performance. Eleven test sections that involved different soil-aggregate-fabric systems were constructed on subgrades that displayed varying degrees of frost-related performance. Field evaluations were conducted over three cycles of spring thaw plus summer healing. Laboratory simulation of freeze-thaw action along with strength and deformation parameters obtained through the Iowa K-test were used on a fabric-reinforced, frost-susceptible soil to provide insight into soil fabric mechanisms and the potential for predicting field performance. Variation in the constructed soil-aggregate-fabric systems was achieved by locating fabric at different positions relative to layers of soil-aggregate or existing roadway materials, a choked macadam base course, and a thick granular backfill. Improvement was most noticeable where fabric was used as a reinforcement between a soil-aggregate surface and a frost-prone subgrade. Fabric used in conjunction with granular backfill, macadam base, and non-frost-susceptible subgrade did not appear justifiable.

Hoover, J. M., Pitt, J. M., Lusting, M. T., and Fox, D. E. (1981b). "Mission-oriented dust control and surface improvement processes for unpaved roads." Iowa DOT Project HR-194, Engineering Research Institute, Iowa State University, Ames, Iowa.

The study documented herein was implemented as a mission-oriented project designed to quantify and evaluate dust control and surface improvement processes for unpaved roads. In order to accomplish this mission, three levels of processing and treatment were established for comparison with untreated soil aggregate-surfaced roads utilizing only the existing in-place roadway materials: Category 1, surface applied dust palliation; Category 2, mixed-in-place dust palliation and surface improvement, without additional surfacing; and Category 3, mixed-in-place base stabilization with seal coat surfacing. Demonstration sections were developed in several representative geographic/geologic regions of the state including Plymouth, Pottawattamie, Story, Franklin, and Marion counties. Samples from these, as well as other possible sites, were subjected to laboratory tests including unconfined compression, freeze-thaw durability, Iowa K-Test, and trafficability testing, in both the untreated and treated conditions, as well as under varying forms of curing. The purpose of the laboratory testing was for evaluation of the subject material for potential use in one or more of the three categories of dust control and/or surface improvement processing. Field studies were initiated in each potential demonstration site for measurement of dust fall within, as well as to the exterior of the ROW. Such measurements were continued following Category 1 applications of selected palliation treatments. In-situ pre- and post-construction tests were conducted within each Category 3 demonstration section, including periodic plate-bearing, Benkelman beam, and moisture-density tests. During Category 3 construction, assistance was provided each county in construction coordination and moisture-density control. Specimens were field molded from each Category 3

mix prior to field compaction and returned to the laboratory for periodic testing of moisture-density and K-Test parameters. Dust fall testing included both quantity and particle-size distribution versus distance from roadway centerline. Through regression analyses of dust fall data, predictions were developed for quantity of dust at the ROW, as well as distance from roadway centerline at which ambient levels of dusting might be anticipated. Through such analyses, two potential control criteria for dust fall were developed. Based on comparison of pre- and post-Category 1 treatment applications, dust reduction effectiveness of several palliatives was evaluated. Such evaluations were coupled with estimated costs of each treatment as an approach to respective cost-benefits. Based on comparison of laboratory tests, pre- and post-construction in-situ tests, and visual examinations, each Category 3 stabilized base demonstration section was evaluated for structural integrity. The following generalized conclusions are thus founded on the various tests, investigations, and analyses presented within this report: (1) Unconfined compression tests of 2-in. by 2-in. cylindrical specimens can provide an initial method of trial mix suitability of various products for possible use as dust palliatives and/or surface improvement agents. Such trial mix testing should be followed by more refined testing on selected mixes. (2) Stability of various product and soil mixtures can be evaluated with freeze-thaw durability, trafficability, and the Iowa K-Test. Freeze-thaw elongation provides an indication of climatic stability as well as susceptibility to capillary moisture increases and heave potential. Trafficability tests provide a quantitative measure of waterproofing and resistance to an adverse traffic loading and environmental condition. The Iowa K-Test provides a quick measure of the undrained shear parameters: cohesion and angle of internal friction. In addition, the K-Test provides a qualitative measure of rutting potential of a mixture through the lateral stress ratio K and a measure of stress-strain relations through the vertical deformation modulus Ev. (3) Of the products evaluated through the various laboratory tests, only the combined Portland cement and fly ash appeared effective as a Category 3 stabilization process with most soil-aggregate classifications, though optimum quantities of the two products varied with each material. Variation of CSS asphalt emulsion zeta potential exhibited pronounced effects on mixture compatibility and required asphalt content, regardless of consideration of categorical usage. In a similar manner, the laboratory tests indicated categorical usage of ammonium lignosulfonate, Coherex, Polybind Acrylic DLR 81-03, and Amsco Res AB 1881 varied from negative to potentially effective depending on soil-aggregate type. (4) All demonstration sections, regardless of category level of processing, were constructed with conventional equipment. (5) Utilizing the measurement and analytical techniques described in this study, two recommendations of minimal roadway dust fall criteria were subjectively quantified. First, an ambient level should be achieved within a distance of 100 to 150 ft or less of an unpaved roadway centerline. Second, a quantity of 15 lbs/acre/day/100 vehicles, or less, should be achieved at the ROW. Such criteria should be considered as a reasonable starting point, with possible refinement with time. (6) Effective dust abatement as well as structural improvement may be obtained through Category 3 construction processing of an unpaved road using cement and fly ash or emulsified asphalt. (7) Only limited Category 1 dust palliation and cost effectiveness were obtained with Amsco Res AB 1881, Polybind Acrylic DLR 81-03, and cationic asphalt emulsion. Coherex appeared very effective as a dust palliative so long as it was not used with an absorptive aggregate. However, the cost of Coherex would limit its usage in Iowa. Calcium chloride and ammonium lignosulfonate appeared comparatively cost-effective as dust palliatives. Effectiveness of both the chloride and lignosulfonates might be enhanced if

incorporated with a soil-aggregate surface using methods and/or specifications cited in preceding sections of this report.

Hufenus, R., Rueegger, R., Banjac, R., Mayor, P., Springman, S. M., and Bronnimann, R. (2006). "Full-scale field tests on geosynthetic reinforced unpaved roads on soft subgrade." Geotextiles and Geomembranes, 24, 21-37.

A full-scale field test on a geosynthetic reinforced unpaved road was carried out, including compaction and trafficking, to investigate the bearing capacity and its performance on a soft subgrade. The test track was built with three layers of crushed, recycled fill material. The 1st layer was compacted statically, whereas the 2nd and 3rd were dynamically compacted. The geogrids were instrumented with strain gauges to measure the short- and long-term deformations and the ongoing formation of ruts was assessed from profile measurements. The various geosynthetics used for this reinforced unpaved road were found to have a relevant reinforcing effect only when used under a thin aggregate layer on a soft subgrade. Under such conditions, ruts can form in the subgrade, mobilizing strains and thus tensile forces in the geosynthetic. The achievable degree of reinforcement depends on the stiffness of the geosynthetic and is limited by finite lateral anchoring forces.

Hyvonen, L., Vuorimies, N., and Kolisoja, P. (2012a). "Road 16589 Saalahti - Mode 2 rutting site on a soft subgrade." The ROADEX “Implementing Accessibility” Project, The Swedish Transport Administration, Northern Region, Sweden.

Rutting of the road surface due to the development of permanent deformations, both in the road structure itself and in the underlying subgrade, is in most cases the dominant distress mechanism on low volume roads of the Northern Periphery area. From a road users’ point of view rutting both lowers driving comfort and reduces traffic safety. This is particularly the case when surface water is trapped in ruts, thereby increasing the risk of aquaplaning in summertime and of icing in the wheel path in winter when temperatures fall below 0°C. In addition, rutting can also be very harmful to the structural condition of the road, as it speeds up water infiltration into the road structure, increasing the effects of dynamic wheel loads etc. Rutting can develop in a road for a number of reasons. It may develop in the structural layers due to poor quality material, or as a result of poor drainage making the material more susceptible to permanent deformations. It may also develop in a weak subgrade material if the overall thickness of the structural layers is low. This is a very typical situation on the low volume roads of the Northern Periphery area, particularly during the spring thaw where the subgrade material is frost susceptible. Rutting mechanisms are discussed in greater detail in the ROADEX reports available at www.roadex.org, together with a new method of classifying rutting modes. This report describes a ROADEX demonstration exercise carried out on a low volume road section of Road 16589 Saalahti in Jämsä, Central Finland. A geogrid reinforcement was used in the demonstration to retard the development of permanent deformations of a gravel road section located on a silty subgrade. The demonstration section had been suffering from deformations primarily taking place in the subgrade material that had become very soft during the spring thaw of the seasonal frost. This had also resulted in severe widening of the road cross-section and almost total clogging of the side ditches. According to the GPR profiles the total thickness of the structural layers was much higher in the middle of the road than towards the edges of the road which was a clear indication of Mode 2 rutting. The reinforced structure consisted of two subsections in addition to which there was a reference section. One subsection was constructed

with one layer of geogrid, rather than the standard rehabilitation solution of a geotextile. The second subsection was constructed with two layers of reinforcing geogrid 150 mm apart from each other. The standard rehabilitation structure of a geotextile was used in the reference structure. After one year of service it only can be concluded that both of the test structures and the reference structure have been performing equally well, and that the road is still in very good condition. Further monitoring of the settlement tubes installed in six cross sections of the road will reveal any differences in the development rate of permanent deformations between the test structure and reference structure. According to the life cycle analysis performed, the subsection reinforced with one layer of geogrid needs to last at least one year longer and the subsection reinforced with two layers of geogrid at least three years longer to be cost effective in comparison to the reference structure, if that is assumed to have a service life of 10 years. This is slightly longer than the typical assumption of 8 years life as in this case the reference structure was also about 50 mm thicker than would have been the standard solution.

Hyvonen, L., Vuorimies, N., and Kolisoja, P. (2012b). "Road 16583 Ehikki-Juikslahti - Mode 2 rutting site on peat." The ROADEX “Implementing Accessibility” Project, The Swedish Transport Administration, Northern Region, Sweden.

Rutting of the road surface due to the development of permanent deformations, both in the road structure itself and in the underlying subgrade, is in most cases the dominant distress mechanism on low volume roads of the Northern Periphery area. From a road users’ point of view rutting both lowers driving comfort and reduces traffic safety. This is particularly the case when surface water is trapped in ruts, thereby increasing the risk of aquaplaning in summertime and of icing in the wheel path in winter when temperatures fall below 0°C. In addition, rutting can also be very harmful to the structural condition of the road, as it speeds up water infiltration into the road structure, increasing the effects of dynamic wheel loads etc. Rutting can develop in a road for a number of reasons. It may develop in the structural layers due to poor quality material, or as a result of poor drainage making the material more susceptible to permanent deformations. It may also develop in a weak subgrade material if the overall thickness of the structural layers is low. This is a very typical situation on the low volume roads of the Northern Periphery area, particularly during the spring thaw where the subgrade material is frost susceptible. Rutting mechanisms are discussed in greater detail in the ROADEX reports available at www.roadex.org, together with a new method of classifying rutting modes. This report describes a ROADEX demonstration exercise carried out on a low volume road section of Road 16583 from Ehikki to Juokslahti in Jämsä, Central Finland. The section was located on a peat subgrade and was reinforced with a geogrid. The road had been deforming and widening significantly over the section mainly due to clogged side ditches, a low outlet ditch, and settlement of the road structure into the peat subgrade. As it was very difficult in practice to improve the operation of the outlet ditch, it was decided to reduce the further development of permanent deformations on the road by the addition of a new base course layer reinforced with a geogrid. As a reference structure, half of the test section was built with the addition of a new base course layer underlain by a geotextile, which could be considered as a standard solution in this type of problem site. After the first year of service, it only can be concluded that both the test structure and the reference structure have been performing equally well, and that the road is still in very good condition. Further monitoring of the settlement tubes installed in four cross sections of the road will reveal any differences in the development rate of permanent deformations between the test structure and the reference structure. According to the life cycle analysis performed, the section reinforced with geogrid needs to last at least 1.5 years longer to be cost effective in comparison to the reference structure, assuming that the reference structure will have a typical service life of 8 years. This had also resulted in severe widening of the road cross-section and almost total clogging of the side ditches. According to the GPR profiles the total thickness of the structural layers was much higher in the middle of the road than towards the edges of the road which was a clear indication of Mode 2 rutting. The reinforced structure consisted of two subsections in addition to which there was a reference section. One subsection was constructed with one layer of geogrid, rather than the standard rehabilitation solution of a geotextile. The second subsection was constructed with two layers of reinforcing geogrid 150 mm apart from each other. The standard rehabilitation structure of a geotextile was used in the reference structure. After one year of service it only can be concluded that both of the test structures and the reference structure have been performing equally well, and that the road is still in very good condition. Further monitoring of the settlement tubes installed in six cross sections of the road will reveal any differences in the development rate of permanent deformations between the test structure and reference structure. According to the life cycle analysis performed, the subsection reinforced with one layer of geogrid needs to last at least one year longer and the subsection reinforced with two layers of geogrid at least three years longer to be cost effective in comparison to the reference structure, if that is assumed to have a service life of 10 years. This is slightly longer than the typical assumption of 8 years life as in this case the reference structure was also about 50 mm thicker than would have been the standard solution.

Jahren, C. T., White, D. J., Phan, T. H., Westercamp, C., and Becker, P. (2011). "Stabilization Procedures to Mitigate Edge Rutting for Granular Shoulders – Phase II." IHRB Project TR-591, Institute for Transportation, Iowa State University, Ames, Iowa.

A multifaceted investigation was undertaken to develop recommendations for methods to stabilize granular road shoulders with the goal of mitigating edge ruts. Included was reconnaissance of problematic shoulder locations, a laboratory study to develop a method to test for changes in granular material stability when stabilizing agents are used, and the construction of three sets of test sections under traffic at locations with problematic granular shoulders. Full results of this investigation are included in this report and its appendices. Based on the results of the investigation, the following was concluded: (1) Problematic shoulders are generally stiff enough to carry expected traffic loads for emergency pull-off and temporary parking. Material gradations are generally finer than specified for new construction and cross slopes are often steeper than called out on cross sections for new construction. However, such differences in what is expected for original construction are consistent with damage that would be expected during use and maintenance (degradation of size due to breakage and abrasion and loss of material through erosion and winter and summer maintenance). Therefore, it seems likely that edge ruts develop from a combination of vehicle offtracking and time elapsed between maintenance cycles, rather than defects regarding original geometry and material gradation or from structural weakness. Some effort to renew cross slope and material gradation may be helpful in mitigating edge ruts. In addition, a shorter maintenance cycle would most likely be required to mitigate edge ruts. (2) Calcium chloride, magnesium chloride, and Base One did not provide noticeable improvements on the US 20 shoulders. However, they were easily applied and have the potential to be applied with the Iowa DOT's own maintenance staff, using its own equipment that could be modified from winter use. These methods were attempted because it was hypothesized that an important failure mode was that fine particles near the pavement edge were being removed by wind erosion, leaving only large particles that are easily displaced by off-tracking vehicles. These products bind fine particles, mechanically with Base One and by attracting moisture with calcium chloride and magnesium chloride. Apparently, some other mechanism causes the edge ruts, despite the presence of fine particles near the pavement edge. (3) If full-depth reclamation is used to incorporate stabilizers, the Iowa DOT does not currently own and operate the necessary equipment to compact and stabilize the reclaimed material. To provide the needed compaction effort, heavier equipment would have to be purchased or rented. In particular, it would be necessary to have a pneumatic compactor that could operate bi-directionally. Typically-available, pull-behind compactors do not allow enough passes to be made quickly enough when consideration is given to the time required to safely turn the units, especially on limited access highways. (4) DUSTLOCK appears to wear well in locations where the shoulder material provides a stable base and vehicles do not off-track to the extent that they do on the US 20 test section. In areas of heavy off-tracking, preliminary indications are that stabilizing the shoulders reduces the number of maintenance cycles to half of what they would be without the stabilizer. (5) The laboratory test method for investigating stabilizer performance appeared to be a reasonable effort that provided some information about stabilized material behavior in confined situations. However, the method would have to be combined with a test similar to an asphalt rut test to detect instability for unconfined circumstances.

Jobgen, M. C., Callahan, M., Harris, G., and Tymkowicz, S. (1994). "Low cost techniques of base stabilization." Project HR-312, Iowa Department of Transportation, Ames, Iowa.

The IHRB HR-312 research project (Jobgen et al. 1994) evaluated performance of four different stabilization methods for on unsurfaced roads. These stabilization methods included using: a) high float emulsion (HFE-300) to treat top 3 in. of base stone, b) a bio-chemical formula called as BIO CAT 300-1 to treat the base stone for different thicknesses (6 in., 8in., and 10 in.), c) Consolid System method in the top 10 in. of subgrade soil, wherein when the soil is dry a combination of two inverted emulsions are used and when the soil is wet a combination of an inverted emulsion and a lime hydrated base powder are used to treat the base stone, and d) 5 in. of macadam base and 2 in. of choke stone along with fabric under one of the sections. All test sections were sealed using a double seal coat and performance evaluation was conducted on these sections using Iowa Road Rater, Roughometer, and visual inspection annually from 1989 to 1992. Some key findings from the field testing were as follows: (a) Test sections stabilized with BIO CAT300-1 and Consolid system showed the highest average k-value (207 pci to 225+ pci) four years after construction. HFE-300 stabilized section showed an average k-value of 181 pci, macadam subbase section showed an average k-value of 172 pci, and macadam subbase with fabric section showed an average k-value of 116 pci, four years after construction. (b) Although the BIO CAT 300-1 and Consolid System stabilized sections showed high k-values, they showed poor performance with alligator cracking and rutting under traffic, and continued deterioration every year. It is speculated in the report that these failures could have been due to freeze-thaw cycles in the stabilized layers. (c) HFE-300 treated test sections showed some deterioration with alligator cracking. Macadam subbase test sections (with and without fabric) experienced minor rutting and showed the best overall performance than all other sections. The use of fabric did not show noticeable improvement. (d) Use of macadam base and HFE-300 treatment showed cost effectiveness than other treatment options evaluated in this study.

Keller, G. R., and Sherar, J. (2003). "Low-Volume Roads Engineering - Best Management Practices Field Guide." Forest Service, United States Department of Agriculture, Washington, D.C.

This Low-Volume Roads Engineering Best Management Practices Field Guide is intended to provide an overview of the key planning, location, design, construction, and maintenance aspects of roads that can cause adverse environmental impacts and to list key ways to prevent those impacts. Best Management Practices are general techniques or design practices that, when applied and adapted to fit site specific conditions, will prevent or reduce pollution and maintain water quality. BMPs for roads have been developed by many agencies since roads often have a major adverse impact on water quality, and most of those impacts are preventable with good engineering and management practices. Roads that are not well planned or located, not properly designed or constructed, not well maintained, or not made with durable materials often have negative effects on water quality and the environment. This Guide presents many of those desirable practices. Fortunately, most of these "Best Management Practices" are also sound engineering practices and ones that are cost-effective by preventing failures and reducing maintenance needs and repair costs. Also keep in mind that "best" is relative and so appropriate practices depend to some degree upon the location or country, degree of need for improvements, and upon local laws and regulations. Best practices are also constantly evolving with time. This guide tries to address most basic roads issues in as simple a manner as possible. Complex issues should be addressed by experienced engineers and specialists. Included are key "DO's" (RECOMMENDED PRACTICES) and "DON'Ts" (PRACTICES TO AVOID) in low-volume roads activities, along with some relevant basic design information. These fundamental practices apply to roads worldwide and for a wide range of road uses and standards. Often recommended practices have to be adapted to fit local conditions and available materials. Additional information on how to do the work is found in other Selected References, such as the "Minimum Impact Low-Volume Roads Manual". Most practices apply to a wide range of road standards, from native surfaced, single-lane roads to double-lane paved roads. Desirable general practices include good road planning and location, performing environmental analysis, recognizing the need for positive surface drainage, ensuring adequately sized drainage crossing structures, using stable cut and fill slopes, using erosion control measures, developing good materials sources, and reclaiming sites once work has been completed. Certain design practices, such as use of rolling dips, outsloped roads, or low-water stream crossings, are very cost-effective and practical but typically apply to low-volume, low-speed roads because of safety concerns, vertical alignment issues, or unacceptable traffic delays. Other issues, such as the use of log stringer bridges, are very desirable for stream crossings in developing regions to avoid driving through the water, yet their use is now discouraged by some agencies, such as the U.S. Forest Service, because of their short design life and potentially unpredictable performance. Thus the information presented herein must be considered in terms of local conditions, available materials, road standards, project or resource priorities, and then applied in a manner that is practical and safe. Local rules, agency policies or regulations, or laws may conflict with some of this information or may include more specific information than that included herein. Thus, good judgment should be used in the application of the information presented in this guide, and local regulations and laws should be followed or modified as needed.

Koch, S., Ksaibati, K., and Huntington, G. (2011). "Performance of Recycled Asphalt Pavement in Gravel Roads." Transportation Research Record: Journal of the Transportation Research Board, 2204, 221-229.

Because more recycled asphalt pavement (RAP) has become available to use in roadways, the Wyoming Technology Transfer–Local Technical Assistance Program Center and two Wyoming counties saw a need to investigate the use of RAP in gravel roads. The Wyoming Department of Transportation along with the Mountain Plains Consortium funded this study. The investigation explored the use of RAP as a means of dust suppression while considering road serviceability. Test sections were constructed in the two counties and were monitored for dust loss by means of the Colorado State University dustometer. Surface distress evaluations of the test sections were performed following a technique developed by the U.S. Army Corps of Engineers in Unsurfaced Road Maintenance Management (Special Report 92-26). The data collected were statistically summarized and then analyzed. The performance of RAP sections was compared with that of gravel control sections. This comparison allowed fundamental conclusions and recommendations to be made for RAP and its ability to abate dust. It was found that RAP-incorporated gravel roads can reduce dust loss without adversely affecting the road's serviceability. Other counties and agencies can expand on this research to add to the toolbox for dust control on gravel roads.

Li, L., Benson, C. H., Edil, T. B., and Hatipoglu, B. (2008). "Sustainable Construction Case History: Fly Ash Stabilization of Recycled Asphalt Pavement Material." Geotechnical and Geological Engineering, 26, 177-187.

A case history is described where Class C fly ash was used to stabilize recycled pavement material (RPM) during construction of a flexible pavement in Waseca, MN, USA. The project consisted of pulverizing the existing hot-mix asphalt (HMA), base, and subgrade to a depth of 300 mm to form RPM, blending the RPM with fly ash (10% by dry weight) and water, compacting the RPM, and placement of a new HMA surface. California bearing ratio (CBR), resilient modulus (Mr), and unconfined compression (qu) tests were conducted on the RPM alone and the fly ash stabilized RPM (SRPM) prepared in the field and laboratory to evaluate how addition of fly ash improved the strength and stiffness. After 7 days of curing, SRPM prepared in the laboratory had CBR ranging between 70 and 94, Mr between 78 and 119 MPa, and qu between 284 and 454 kPa, whereas the RPM alone had CBR between 3 and 17 and Mr between 46 and 50 MPa. Lower CBR, Mr, and qu were obtained for SRPM mixed in the field relative to the SRPM mixed in the laboratory (64% lower for CBR, 25% lower for Mr, and 50% lower for qu). In situ falling weight deflectometer testing conducted 1 year after construction showed no degradation in the modulus of the SRPM, even though the SRPM underwent a freeze–thaw cycle. Analysis of leachate collected in the lysimeter showed that concentrations of all trace elements were below USEPA maximum contaminant levels.

Maurer, G., Bemanian, S., and Polish, P. (2007). "Alternative Strategies for Rehabilitation of Low-Volume Roads in Neveda." Transportation Research Record: Journal of the Transportation Research Board, 1989, 309-320.

An overview of the attempt by the Nevada Department of Transportation (NDOT) to find alternative rehabilitation strategies to rehabilitate its low-volume road network effectively is provided. Because of Nevada's continuing growth, NDOT is faced with the challenge of how to balance its available funding between pavement preservation and capacity improvement projects.

NDOT is responsible for 13,000 lane miles of roadway, of which 3,385 lane miles (26%) qualify as low-volume roads. The low-volume roads have a two-directional average daily traffic of 400 or less. Five roadway projects with a combined total of 111 centerline miles were rehabilitated with 29 combinations of structural and surface strategies. The rehabilitation strategies investigated included full-depth reclamation with lime, cement, asphalts, and foamed asphalt. Various cold-mix, cold-in-place recycling with millings and different rejuvenating agents, and surface treatment test sections were constructed. The constructability issues that were reported during construction are discussed. In addition, pavement condition is examined and laboratory testing is reviewed. Results suggest that NDOT can use alternative rehabilitation strategies in place of its conventional method of 2-in. plant-mix bituminous surface overlay and chip seal to rejuvenate its low-volume roadway network. A cost saving of approximately $100,000 per centerline mile is anticipated.

Mekkawy, M. M., White, D. J., Suleiman, M. T., and Jahren, C. T. (2011). "Mechanically reinforced granular shoulders on soft subgrade: Laboratory and full scale studies." Geotextiles and Geomembranes, 29, 149-160.

A recently completed field study in Iowa showed that many granular shoulders overlie clayey subgrade layer with California Bearing Ratio (CBR) value of 10 or less. When subjected to repeated traffic loads, some of these sections develop considerable rutting. Due to costly recurring maintenance and safety concerns, the authors evaluated the use of biaxial geogrids in stabilizing a severely rutted 310 m tests section supported on soft subgrade soils. Monitoring the test section for about one year, demonstrated the application of geogrid as a relatively simple method for improving the shoulder performance. The field test was supplemented with a laboratory testing program, where cyclic loading was used to study the performance of nine granular shoulder models. Each laboratory model simulated a granular shoulder supported on soft subgrade with geogrid reinforcement at the interface between both layers. Based on the research findings, a design chart correlating rut depth and number of load cycles to subgrade CBR was developed. The chart was verified by field and laboratory measurements and used to optimize the granular shoulder design parameters and better predict the performance of granular shoulders.

Monlux, S. (2003). "Stabilizing Unpaved Roads with Calcium Chloride." Transportation Research Record: Journal of the Transportation Research Board, 1819, 52-56.

The U.S. Department of Agriculture Forest Service has stabilized unpaved road surfacing materials with relatively high concentrations of calcium chloride salt. The percentage of calcium chloride is higher than that traditionally used for dust abatement or aggregate base stabilization. Up to 2% pure salt by weight of aggregate was mixed into the top 2 in. (50 mm) of both aggregate and native road surfaces. The results were monitored for 2 to 4 years. The stabilized road surfaces resisted raveling and washboarding for several seasons and significantly reduced road blading and aggregate loss. As a result, calcium chloride stabilization may be a cost-effective treatment for roads with daily traffic volumes less than 200. Other benefits include reduced surface erosion and sedimentation; improved safety from reduced dust, raveling, and washboarding; and less frost penetration. Encouraged by these results, the Forest Service is conducting additional evaluations to determine the cost-effectiveness of surface stabilization with both magnesium chloride and calcium chloride in different environments and with different aggregate materials.

Monlux, S., and Mitchell, M. (2007). "Chloride Stabilization of Unpaved Road Aggregate Surfacing." Transportation Research Record: Journal of the Transportation Research Board, 1989(2), 50-58.

There are few alternatives for improving long-term performance of aggregate surfacing materials in dry climates other than annual dust abatement treatments. In-place stabilization of properly graded aggregate with chloride additives is cost-effective and provides performance and intangible benefits. Similar results are achieved by mixing additives with aggregate during crushing. This 2-year study identifies conditions in which chloride-stabilized roads have a projected life of 10 years or more if properly maintained. The greatest benefits are realized in projects with high aggregate surfacing replacement costs and average daily traffic volumes that exceed 100. Stabilization provides a higher standard of road surface performance by improving ride quality and reducing dust, corrugations (washboarding), and raveling (loose aggregate). Other intangible benefits include reduced sedimentation in streams, reduced aggregate resource depletion, reduced health hazards from dust, and increased road-user safety. This project developed guidelines for chloride stabilization of various aggregate surfacing materials in semiarid to arid environments. Performance and cost-effectiveness of chloride stabilization were measured on 12 projects and monitored for two seasons in four western states; monitoring included construction and maintenance costs, road surface deterioration, traffic, weather conditions, environmental effects, and materials testing. Treated surfaces needed blading after 25,500 vehicles, whereas untreated surfaces needed blading after only 3,200 vehicles. Environmental effects on trees, streams, and roadside soils were insignificant. Many tools were developed to assist in the proper implementation of chloride stabilization of road surface aggregates.

Morgan, R. J., Schaefer, V. R., and Sharma, R. S. (2005). "Determination and Evaluation of Alternative Methods for Managing and Controlling Highway-Related Dust Phase II—Demonstration Project." IHRB Project TR-506, Department of Civil, Construction and Environmental Engineering, Iowa State University, Ames, Iowa.

The State of Iowa currently has approximately 69,000 miles of unpaved secondary roads. Due to the low traffic count on these unpaved roads, paving with asphalt or Portland cement concrete is not economical. Therefore to reduce dust production, the use of dust suppressants has been utilized for decades. This study was conducted to evaluate the effectiveness of several widely used dust suppressants through quantitative field testing on two of Iowa's most widely used secondary road surface treatments: crushed limestone rock and alluvial sand/gravel. These commercially available dust suppressants included: lignin sulfonate, calcium chloride, and soybean oil soapstock. These suppressants were applied to 1000 ft test sections on four unpaved roads in Story County, Iowa. Duplicate field conditions, the suppressants were applied as a surface spray once in early June and again in late August or early September. The four unpaved roads included two with crushed limestone rock and two with alluvial sand/gravel surface treatment well as high and low traffic counts. The effectiveness of the dust suppressants was evaluated by comparing the dust produced on treated and untreated test sections. Dust collection was scheduled for 1, 2, 4, 6, and 8 weeks after each application, for a total test period of 16 weeks. Results of a cost analysis between annual dust suppressant application and biennial aggregate replacement indicated that the cost of the dust suppressant, its transportation, and application were relatively high when compared to that of aggregate types. Therefore, the biennial aggregate replacement is considered more economical than annual dust suppressant

application, although the application of annual dust suppressant reduced the cost of road maintenance by 75 %. Results of the collection indicated that the lignin sulfonate suppressant outperformed calcium chloride and soybean oil soapstock on all four unpaved roads, the effect of the suppressants on the alluvial sand/gravel surface treatment was less than that on the crushed limestone rock, the residual effects of all the products seem reasonably well after blading, and the combination of alluvial sand/gravel surface treatment an high traffic count caused dust reduction to decrease dramatically.

Munro, R., Evans, R., and Saarenketo, T. (2007). "ROADEX II Project: Focusing on Low-Volume Roads in the European Northern Periphery." Transportation Research Record: Journal of the Transportation Research Board, 1989(2), 292-299.

The ROADEX Project is a living case study on the benefits of partnering across road districts to make the best use of available budgets. The ROADEX Project partners had an early shared vision of cooperation that has since materialized in great benefits to their respective areas through collaboration in research and development and enhancement of their in-house capabilities by direct access to experience within the other partners' organizations. This sharing of information and experience has enabled them to have cost-effective research programs on shorter time scales than would otherwise have been the case and has avoided "reinventing the wheel" in research and development in each national district. The ROADEX II Project addresses the specific problems that arise in dealing with low-volume road management across the northern periphery of Europe so that reliable and regular year-round road networks can be provided to remote communities there. The outputs delivered in the ROADEX II Project offer a range of sustainable fit-for-purpose solutions to local road problems that together compose a tool kit of solutions for local managers to enable them to give better public service to their areas year after year.

Newman, J. K., and White, D. J. (2008). "Rapid Assessment of Cement and Fiber-Stabilized Soil Using Roller-Integrated Compaction Monitoring." Transportation Research Record: Journal of the Transportation Research Board, 2059, 95-102.

Test sections of high-early strength (Type III) portland cement and polypropylene monofilament fibers were constructed at the Bradshaw Field Training Area in the Northern Territory (NT), Australia as part of a Joint Rapid Airfield Construction (JRAC) project. Aprons, taxiways, and a helipad were stabilized using these materials in combination with screened native soil. The purpose of the test sections was to (a) evaluate the resulting properties for different stabilization dosage rates; (b) develop construction methods, criteria (including limits), and quality control guidelines; and (c) provide a hands-on training opportunity for the joint United States and Australia military construction team. Testing and monitoring consisted of roller-integrated compaction monitoring (global position systems monitoring pass coverages and compaction machine values) and in situ testing, which included dynamic cone penetration tests, Clegg impact tests, and light-weight deflectometer tests. After the test sections, construction of the helipad helped refine the construction methods and quality control testing for the selected stabilization dosage rates and machine speed. Lessons learned on the helipad were applied to the subsequent aircraft parking aprons and taxiways. Recommendations were developed for rapid stabilization construction procedures and quality control testing using Clegg impact values and light-weight deflectometer for cement-fiber stabilized soils, and the application of roller-integrated compaction technology was demonstrated to document compaction effort and uniformity.

Powell, W., Keller, G. R., and Brunette, B. (1999). "Applications for geosynthetics on forest service low-volume roads." Transportation Research Record: Journal of the Transportation Research Board, 1999, 113-120.

Today's geosynthetic products have many useful, creative, and cost-effective applications for rural, low-volume roads. In the management of almost a half-million km (quarter-million mi) of low-volume roads, the U.S. Department of Agriculture, Forest Service (USFS), has developed and adopted many uses for geosynthetics. An overview is presented of many of those uses and their advantages. The USFS gained much of its experience and practice with geosynthetics while constructing a wide variety of Mechanically Stabilized Earth (MSE) retaining walls, including geotextile, timber, modular-block, and tire-faced structures, and reinforced soil slopes. More recently, the USFS has used geosynthetics for MSE bridge abutments and Deep Patch road-shoulder reinforcement. Other typical geosynthetic applications include filtration, drainage, subgrade reinforcement, and erosion control.

Raymond, G. P., and Bathurst, R. J. (2000). "Facilitating cold climate pavement drainage using geosynthetics." Testing and Performance of Geosynthetics in Subusurface Drainage - ASTM STP 1390, L. D. Suits, J. B. Goddard, and J. S. Baldwin, eds., ASTM, West Conshohocken, PA.

Good highway drainage has been recognized for many centuries. The theoretical concepts are simple and the technology applicable to highways built today (1999) is widely available in the technical literature. It is widely understood that efficient drainage is essential to good highway performance independent of aggregate compacted density or aggregate stability. While the theoretical concepts are simple they are often not effective in cold climates. Indeed, for cold climates, these simple concepts are shown by field excavations described herein to be lacking in a number of aspects. Based on field excavations and performance of some selected Ontario highway locations, involving both clay and sand subgrades, recommendations are presented for the design detailing, selection and installation of geosynthetic edge drains. Installation at the investigated sites was by various techniques that included: ploughed-in-place, trench excavation, and mechanical trencher and boot. All excavated edge drains were installed as retrofits either at the time of the original pavement construction or several years later. The retrofits used the existing excavated/displaced shoulder granular material as backfill. Frost action, despite what was considered good drainage practice at the time of installation, and is shown to have had a major effect on field performance.

Rollings, M. P., and Rollings, R. S. (1996). Geotechnical Materials in Construction, McGraw-Hill, New York, NY.

Chapter 6 of this book provides information on Stabilization: Seldom does nature provide the ideal soil or aggregate for construction. To overcome deficiencies in soil or aggregate properties such as poor grading, excess plasticity, or inadequate strength, we may blend two or more soils together, or we may add stabilizing admixtures such as lime, portland cement, or bituminous materials to the soil or aggregates. These techniques are effective if we can readily mix the materials. Other techniques for improving soil conditions at depth will be covered in Chap. 7. We often think of stabilization as a method of providing structural strength, but it can have a number of other construction and behavioral effects that are equally beneficial. These

might include improved soil workability, an all-weather construction platform, or reduced swelling of expansive materials. Stabilization may improve the properties of an on-site or local material to allow its use rather than incurring the cost of importing a better material from a distant source. In the following sections we will examine the effects of blending and stabilizing with lime, portland cement, bituminous materials, pozzolanic and slag materials, and specialty admixtures.

Saarenketo, T., and Aho, S. (2005). "Managing Spring Thaw Weakening on Low Volume Roads - Problem Description, Load Restriction Policies, Monitoring and Rehabilitation." The ROADEXII Project, The Swedish Road Administration, Northern Region, Sweden.

This is a final report from the Phase II subproject 2_3 survey of the Roadex II project, a technical transnational cooperation project between the Highland Council, the Western Isles Council, and Forest Enterprise from Scotland; the Northern Region (formerly Troms district) of the Norwegian Public Roads Administration and the Norwegian Road Haulage Association; the Northern Region of the Swedish National Road Administration; and from Finland the Regions of Central Finland and Lapland of the Finnish Road Administration, as well as Metsähallitus Region of Eastern Lapland, the Forestry Centre of Lapland (Lapin Metsäkeskus), Stora Enso Metsä, and Metsäliitto, Procurement Area of Northern Finland. The Roadex project is partly financed by the ERDF IIIB Northern Periphery Programme. The lead partner in the project is the Highland Council from Scotland and project consultant is Roadscanners Oy from Finland. Roadex II project Chairman is Ron Munro from the Highland Council and project manager is Timo Saarenketo from Roadscanners. The report summarizes the work done on Task 2_3 “Spring Thaw Weakening” of the Roadex II project. The report will describe the theory behind spring thaw weakening and different load restriction policies used in the cold climate areas. It will also report the results of the field tests done in Scotland, Sweden and Norway and present some new structural solutions which have been found to work well at spring thaw weakening sites. Finally, new technologies for both road owners and/or road users that could be used in more effective spring thaw weakening management will be revealed.

Shoop, S., Affleck, R., Janoo, V. C., Haehnel, R., and Barrett, B. (2005). "Constitutive Model for a Thawing, Frost-Susceptible Sand." ERDC/CRREL TR-05-3, Cold Regions Research and Engineering Laboratory, U.S. Army Engineer Research and Development Center, Hanover, New Hampshire.

A material model for soft, wet soil was generated to simulate the deformation behavior of thawing soil under vehicle loading on paved and unpaved roads. Freeze–thaw action produces a loose, wet soil that undergoes large deformation when subjected to vehicle loads. The soil modeled is a frost-susceptible fine sand, which was used in full-scale tests of paved and unpaved road sections in CRREL’s Frost Effects Research Facility (FERF). The soil was subjected to a full suite of saturated and unsaturated triaxial testing, using density, moisture, and loading conditions duplicating those experienced during the freeze–thaw testing in the FERF. Material parameters were generated for a capped Drucker–Prager plasticity model. These were calibrated in triaxial test simulations using the commercial finite element code ABAQUS. The material model was then implemented in several three-dimensional finite element simulations for validation and robustness. The model for Lebanon Sand was compared to the same model for other granular materials.

Shoop, S., Haehnel, R., Janoo, V. C., Harjes, D., and Liston, R. (2006). "Seasonal deterioration of unsurfaced roads." Journal of Geotechnical and Geoenvironmental Engineering, 132(7), 852-860.

Seasonal deformation of unsurfaced roads was observed over several years and was studied using pavement deterioration models and finite-element analysis. The Mathematical Model of Pavement Performance is a model designed for pavement deterioration prediction and was successfully used for seasonal deterioration modeling because of its flexibility in defining the pavement structure, properties, and seasonal impact. However, these types of models are designed for highways and are somewhat limited in soils characterization and manipulation of the forces at the road–tire interface. Therefore, a three-dimensional dynamic finite-element model of a wheel rolling over soil was applied to simulate local vehicle traffic on a secondary unpaved road. These simulations were used to study the effects of vehicle speed, load, suspension system, wheel torque, and wheel slip on rutting and washboard formation. Modeling results are compared to field measurements and observations.

Shoop, S., Kester, M., Stark, J., Ryerson, C., and Affleck, R. (2003). "Rapid stabilization of thawing soils: field experience and application." Journal of Terramechanics, 39, 181-194.

Thawing soils can severely restrict vehicle travel on unpaved surfaces. However, a variety of materials and construction techniques can be used to stabilize thawing soils to reduce immobilization problems. The US Engineer Research and Development Center’s Army Cold Regions Research and Engineering Laboratory (CRREL) and the Wisconsin National Guard evaluated several stabilization techniques in a field demonstration project during spring thaw at Fort McCoy, Wisconsin, in 1995. Additional tests on chemical stabilizing techniques were conducted at CRREL’s Frost Effects Research Facility. The results of these test programs were reduced to a decision matrix for stabilizing thawing ground, and used during the deployment of US troops in Bosnia during January and February of 1996. The soil frost and moisture conditions expected during this time frame were predicted using MIDFROCAL (MIDwest FROst CALculator). This paper is an overview of the stabilization techniques evaluated and their recommended application based on the expected soil frost conditions and traffic requirements. Although the experiments were performed with military vehicles in mind, the techniques are suitable for many civilian applications such as forestry, construction, mining, and oil exploration.

Sigurdsson, O. (1991). "Geosynthetic stabilization of unpaved roads on soft ground: a field evaluation." MS, The University of British Columbia, British Columbia, Canada.

A full scale field trial was carried out to investigate the performance of different geosynthetics in unpaved road construction over soft ground. The test site comprises of five 16 m long by 4.5 m wide test sections, build on a subgrade of undrained shear strength approximately 40 kPa. One is unreinforced and serves as a control section in the study, three sections include a geotextile, and one includes a geogrid. Each test section incorporated a variable thickness of sandy gravel base course material, between 25 and 50 cm thick. They were trafficked in sequence by a vehicle of standard axle load. An important governing parameter for interpretation of behavior is the influence of base course thickness on the relationship between number of passes and rut depth, base course thickness, base course deformations, geosynthetic strain, and deformed profile of the geosynthetic, with increasing number of vehicle passes. Vehicle trafficking was continued to a rut depth of about 20 cm, which constitutes a serviceability failure. Results from the full scale field trial show a better performance in the reinforced sections than

the unreinforced section. The performance of the unreinforced section shows good agreement with other well-documented field data at large rut depths, between 10 and 15 cm, but not at small ruts. Although the four geosynthetics exhibited a broad range of stiffness and material properties, the general performance of the four reinforced sections was similar on the thicker base course layers. This is attributed to a reinforced mechanism governed by stiffness and separation, and all materials appear adequately stiff for the site conditions and vehicle loading. On the thinner subgrades, a tensioned-membrane effect is mobilized and a significant difference is observed between the geosynthetics.

Vennapusa, P., White, D. J., and Miller, D. K. (2013). "Western Iowa Missouri River Flooding—Geo-Infrastructure Damage Assessment, Repair, and Mitigation Strategies." IHRB Project TR-638, Center for Earthworks Engineering Research, Iowa State University, Ames, Iowa.

The 2011 Missouri River flooding caused significant damage to many geo-infrastructure systems including levees, bridge abutments/foundations, paved and unpaved roadways, culverts, and embankment slopes in western Iowa. The flooding resulted in closures of several interchanges along Interstate 29 and of more than 100 miles of secondary roads in western Iowa, causing severe inconvenience to residents and losses to local businesses. The main goals of this research project were to assist county and city engineers by deploying and using advanced technologies to rapidly assess the damage to geo-infrastructure and develop effective repair and mitigation strategies and solutions for use during future flood events in Iowa. The research team visited selected sites in western Iowa to conduct field reconnaissance, in situ testing on bridge abutment backfills that were affected by floods, flooded and non-flooded secondary roadways, and culverts. In situ testing was conducted shortly after the flood waters receded, and several months after flooding to evaluate recovery and performance. Tests included falling weight deflectometer, dynamic cone enetrometer, three-dimensional (3D) laser scanning, ground penetrating radar, and hand auger soil sampling. Field results indicated significant differences in roadway support characteristics between flooded and non-flooded areas. Support characteristics in some flooded areas recovered over time, while others did not. Voids were detected in culvert and bridge abutment backfill materials shortly after flooding and several months after flooding. A catalog of field assessment techniques and 20 potential repair/mitigation solutions are provided in this report. A flow chart relating the damages observed, assessment techniques, and potential repair/mitigation solutions is provided. These options are discussed for paved/unpaved roads, culverts, and bridge abutments, and are applicable for both primary and secondary roadways.

White, D. J., Mekkawy, M. M., Jahren, C. T., Smith, D., and Suleiman, M. T. (2007). "Effective Shoulder Design and Maintenance." IHRB Project TR-531, Center for Transportation Research and Education, Iowa State University, Ames, Iowa.

Granular shoulders are an important element of the transportation system and are constantly subjected to performance problems due to wind- and water-induced erosion, rutting, edge drop-off, and slope irregularities. Such problems can directly affect drivers' safety and often require regular maintenance. The present research study was undertaken to investigate the factors contributing to these performance problems and to propose new ideas to design and maintain granular shoulders while keeping ownership costs low. This report includes observations made during a field reconnaissance study, findings from an effort to stabilize the granular and subgrade layer at six shoulder test sections, and the results of a laboratory box study

where a shoulder section overlying a soft foundation layer was simulated. Based on the research described in this report, the following changes are proposed to the construction and maintenance methods for granular shoulders: • A minimum CBR value for the granular and subgrade layer should be selected to alleviate edge drop-off and rutting formation. • For those constructing new shoulder sections, the design charts provided in this report can be used as a rapid guide based on an allowable rut depth. The charts can also be used to predict the behavior of existing shoulders. • In the case of existing shoulder sections overlying soft foundations, the use of geogrid or fly ash stabilization proved to be an effective technique for mitigating shoulder rutting.

Field Study (Paved Roads)

Addison, M. B., and Polma, F. A. (2007). "Extending Durability of Lime Modified Clay Subgrades With Cement Stabilization." GSP 172 Soil Improvement, V. R. Schaefer, G. M. Filz, P. M. Gallagher, A. L. Sehn, and K. J. Wissmann, eds., ASCE, Denver, Colorado.

Many municipalities and private owners have faced increased pavement maintenance and replacement costs when lime modified clay subgrades prematurely fail. Preliminary laboratory test results determined that the typical lime treatment (7% by dry weight) used by the City of Garland, TX was approximately one-half the amount of lime necessary to permanently stabilize a high P.I. (39) clay. Further laboratory and a field testing program was then undertaken to determine if an economical alternative to 14% lime could be used to extend the durability of street subgrades. Four test sections were constructed using various combinations of lime to pre-treat the clays before stabilizing with cement. The testing program revealed that using combinations of lime and cement increased the typical subgrade durability based upon 4.8 to 5.7 times greater strengths after one year of exposure to in-place conditions. In addition, 28 day moist cured then saturated samples had 3.7 times greater compressive strength and 3.5 times better strength following 12 cycles of wetting and drying after 4 months of moist curing.

Aiban, S. A., Wahhab, H. I. A., Al-Amoudi, O. S. B., and Ahmed, H. R. (1998). "Performance of a stabilized marl base: a case study." Construction and Building Materials, 12, 329-340.

The formation of depressions and settlement in roads shortly after being constructed is one of the major challenges facing the road authorities in the Arabian Gulf States. Such problems have been closely related to the nature of pavement materials and loading conditions as well as to the proximity of groundwater tables to the surface. A major road in eastern Saudi Arabia was reported for frequent deterioration even when the construction was properly carried out. A preliminary investigation was conducted to quantify the properties of the base course material i.e. marl soil and the cause of failure. The laboratory investigation indicated that the marl used in the construction, similar to other marls, has acute water sensitivity and loss of strength whenever the soil is inundated. A precautionary and immediate solution was proposed to stabilize the soil with cement. Consequently, a comprehensive laboratory program was carried out to assess the performance of cement-stabilized marl mixtures under different exposure conditions. Based on the laboratory results and the traffic data for the road under investigation, four sections were constructed, two of them being without any additive while in the other two the base course being treated with 4% cement. Continuous monitoring and evaluation of the four sections for 4 years indicated that the cement-treated road sections have exhibited superior performance over the untreated ones. Unlike the untreated sections, which have experienced various forms of

deterioration within a few months after construction, the stabilized sections are still in an excellent condition.

Al-Qadi, I. L., and Appea, A. K. (2003). "Eight-Year Field Performance of Secondary Road Incorporating Geosynthetics at Subgrade-Base Interface." Transportation Research Record: Journal of the Transportation Research Board, 1849, 212-220.

In June 1994 an instrumented 150-m-long secondary road pavement section was built in Bedford County, Virginia. This pavement section was composed of nine individual segments each 15 m long. The nine sections include three groups with aggregate base layer thicknesses of 100, 150, and 200 mm. Three sections from each group were stabilized with geotextiles and three were stabilized with geogrids at the base-sub grade interface. The remaining three sections were kept as control sections. As part of the structural analysis, deflection data parameters such as the base damage index and surface curvature index calculated from falling weight deflectometer (FWD) data were analyzed after being corrected for temperature variations from the time of construction until October 2001. Performance criteria such as rutting measurements were also collected over the whole period. A nonlinear exponential model was used to describe the development of rutting versus cumulative equivalent single-axle loads for the 100-mm base course. A linear elastic program incorporating constitutive material properties was used to calculate vertical compressive stresses, which were used with FWD deflections to predict rutting rates with a mechanistic equation. The rutting rate results confirmed the separation function of geosynthetics that prevented the migration of fines from the subgrade to the base course layer and the penetration of the aggregate base layer into the subgrade. Rutting results, deflection data, and service life analysis showed that geosynthetically stabilized sections significantly improved the performance of the 100-mm base course sections.

Benson, C. H., Edil, T. B., Tanyu, B. F., and Kim, W.-H. (2005). "Equivalency of Crushed Rock with Industrial By-Products and Geosynthetic-Reinforced Aggregates Used for Working Platforms during Pavement Construction." WHRP Final Report No. 0092-00-12, Department of Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, WI.

A study was conducted to define an equivalency criterion for five materials used for working platforms during pavement construction on a poor subgrade: conventional crushed rock (referred to as “breaker run”) and four alternatives (i.e. Grade 2 granular backfill (referred to as “Grade 2”), foundry slag, bottom ash, and foundry sand). Total deflection data for the equivalency assessment were obtained from a large-scale model experiment (LSME) simulating a prototype-scale pavement structure and in the field using a rolling wheel deflectometer (RWD). Design charts were developed for selecting the equivalent thickness of alternative working platform materials so that the alternative provides equal deflection as a layer of breaker run. Another phase of the study was conducted to determine the equivalency of geosynthetic reinforced aggregate working platforms in providing support during pavement construction over soft subgrade. Four reinforcing geosynthetics (a geogrid, a woven geotextile, a non-woven geotextile, and drainage geocomposite) incorporated into two granular materials: Grade 2 and breaker run were used in this study. Design charts were developed for selecting the equivalent thickness of an alternative geosynthetic-reinforced working platform material so that the alternative provides equal deflection as a layer of breaker run.

Bergeson, K. L., and Barnes, A. G. (1998). "Iowa thickness design guide for low volume roads using reclaimed Class C fly ash bases." Iowa State University, Ames, Iowa.

This paper is intended to provide flexible pavement thickness design parameters and a design method for low volume roads and streets utilizing Iowa reclaimed hydrated Class C fly ashes as artificial aggregates for a base material. AASHTO design guidelines are presented for using these materials untreated, or if higher strengths are needed, stabilized with raw fly ash or hydrated lime. Hydrated Class C fly ashes in Iowa are produced at sluice pond disposal sites at generating stations burning western sub-bituminous coals. They may be formed by dozing raw ash into the sluice pond where it hydrates to form a cementitious mass or they may be constructed as an engineered fill (above the sluice pond level) by placing the raw ash in lifts, followed by watering, compaction and subsequent hydration. The hydrated ash is typically mined by using conventional recycling-reclaiming equipment to pulverize the material where it is stockpiled on-site for use as an artificial aggregate. Research has been conducted on these materials, on an on-going basis, under the Iowa Fly Ash Affiliate Research Program since 1991. Test roads have been constructed using reclaimed fly ash as an aggregate base in Marshalltown (1994) and near Ottumwa (1995). They have been, and are, performing well. Based on extensive laboratory testing, this paper presents layer coefficients for reclaimed hydrated Class C fly ash bases for use in AASHTO thickness design for low volume roads and streets.

Christopher, B. R., Hayden, S. A., and Zhao, A. (2000). "Roadway base and subgrade geocomposite drainage layers." Testing and Performance of Geosynthetics in Subsurface Drainage, ASTM STP1390, L. D. Suits, J. B. Goddard, and J. S. Baldwin, eds., ASTM, West Conshohocken, PA.

The Maine Department of Transportation (DOT) in conjunction with the University of Maine and the U.S. Army Cold Regions Research Laboratory evaluated the use of a special geocomposite drainage net as a drainage layer and capillary barrier (to mitigate frost heave) on a section of road plagued with weak, frost-susceptible subgrade soils and poor pavement performance. The special geocomposite drainage net that is being used has a higher flow capacity than conventional geonets and, based on tests performed by the University of Illinois, does not deform significantly under heavy traffic loading. For the 425-m-long test section, the geonet drainage geocomposite was placed horizontally across the entire roadway but varied in vertical location to form three separate subsections for evaluating drainage of 1) the base coarse aggregate, 2) the asphaltic concrete pavement, and 3) the subgrade to allow for a capillary break in order to reduce frost action. An integral drainage collection system was installed to collect the water flowing in the geonet. This paper includes a project description, material and construction specifications, installation procedures, instrumentation, and test results based upon two seasons of monitoring. Laboratory characterization and performance testing initially used to evaluate the geocomposite are compared with the monitored results.

Collings, D., Lindsay, R., and Shunmugam, R. "LTPP Exercise on a Foamed Bitumen Treated Base - Evaluation of Almost 10 Years of Heavy Trafficking on MR504 in Kwazulu-Natal." Proc., 8th Conference on Asphalt Pavements for Southern Africa (CAPSA'04), Document Transformation Technologies.

Situated halfway between the cities of Pietermaritzburg and Durban, Provincial Main Road (MR) 504 provides primary access to a large asphalt plant, a commercial quarry and a pre-cast concrete products factory. A 700m section of this road, located on a steep gradient (+10%),

and was upgraded to blacktop standards during 1995 by constructing a single layer of foamed bitumen treated material on top of a prepared subbase layer. The single slurry seal that was applied soon after construction proved adequate for three years before requiring a competent surfacing. This road provides an ideal opportunity for assessing the performance of what was originally termed an "experimental" pavement. The relevant traffic that this pavement has carried is estimated from dispatch records at each of the plants. In addition to as-built data, information is available from investigations that were carried out in 1997 by the CSIR Transportek Division, commissioned by the Provincial Department of Transport to evaluate this and other pavements with foamed bitumen treated bases. This information is reviewed and supplemented by additional surveys and tests conducted in the first quarter of 2004. This paper portrays the change that has taken place in the pavement between the time it was constructed, two years after trafficking, and again six years later. Deflection data is used as a primary measure of changing conditions. Additional tests include those carried out on cores extracted from the foamed bitumen treated base, test pit excavations and a DCP survey. Prediction models that were compiled in 2002 from HVS trials on foamed bitumen treated materials are also reviewed. As the first LTPP exercise on a foamed bitumen treated material, this paper endeavours to portray the difference between the condition of a such material in a pavement subjected to continuous HVS loading over a short time period compared to heavy trafficking over an extended period of nine years.

Edil, T. B., Benson, C. H., Bin-Shafique, M. S., Tanyu, B. F., Kim, W.-H., and TSenol, A. (2002). "Field Evaluation of Construction Alternatives for Roadways over Soft Subgrade." Transportation Research Record: Journal of the Transportation Research Board, 1786, 36-48.

Alternative methods for providing a stable platform over soft subgrades were evaluated using a 1.4-km section along a Wisconsin State highway that incorporated 12 test sections to evaluate 9 different stabilization alternatives. A variety of industrial by-products and geosynthetics were evaluated for stabilization. The industrial by-products included foundry slag, foundry sand, bottom ash, and fly ash as subbase layer materials. The geosynthetics included geocells, a nonwoven geotextile, a woven geotextile, a drainage geocomposite, and a geogrid. The same pavement structure was used for all test sections except for the subbase layer, which varied depending on the properties of the alternative material being used. All test sections were designed to have approximately the same structural number as the conventional pavement structure used for the highway, which included a subbase of granular excavated rock. Observations made during and after construction indicated that all sections provided adequate support for the construction equipment and no distress was evident in any part of the highway. Each of the alternative stabilization methods, except a subbase prepared with foundry sand, appear to provide equivalent or greater stiffness than that provided by control sections constructed with excavated rock. However, the foundry sand subbase is providing adequate support. Analysis of leachate collected from the base of the test sections shows that the by-products discharge contaminants of concern at very low concentrations.

Embacher, R. A. (2006). "Duration of Spring-Thaw Recovery for Aggregate-Surfaced Roads." MN/RC-2006-12, Minnesota Department of Transportation, St. Paul, Minnesota.

Low-volume roads constructed in regions susceptible to freezing and thawing periods are often at risk of load-related damage during the spring-thaw period. The reduced support capacity during the thawing period is a result of excess melt water that becomes trapped above the underlying frozen layers. Many agencies place spring load restrictions (SLR) during the thaw period to reduce unnecessary damage to the roadways. The period of SLR set forth by the Minnesota Department of Transportation is effective for all flexible pavements; however, experience suggests that many aggregate-surfaced roads require additional time relative to flexible pavements to recover strength sufficient to carry unrestricted loads. An investigation was performed to improve local agencies' ability to evaluate the duration of SLR on aggregate-surfaced roadways. This was accomplished through seasonal measurements of in situ shear strengths, measured using the dynamic cone penetrometer (DCP), on various Minnesota county routes. In situ strength tests were conducted on selected county gravel roads over the course of three years. Strength levels recorded during the spring-thaw weakened period were compared to fully recovered periods that typically occur in late spring/summer. The results indicate that aggregate-surfaced roads generally require 1 to 3 additional weeks, over that of flexible pavements, to reach recovered bearing capacity. Additionally, a strong correlation was found between duration required to attain given strength recovery values and climatic and grading inputs.

Foye, K. C. (2011). "Use of reclaimed asphalt pavement in conjunction with ground improvement: A case history." Advances in Civil Engineering, Hindawi Publishing Corporation, 2011(Article ID808561).

The use of Reclaimed Asphalt Pavement (RAP) in lieu of virgin crushed stone aggregate is becoming a widely accepted practice for a number of construction applications, particularly pavement base courses. A number of laboratory RAP studies have considered the mechanical properties of RAP bases in order to support pavement designs incorporating RAP. These studies have revealed a number of interesting relationships between RAP moisture content, compaction, and stiffness. This paper discusses the experiences of a design-build contractor integrating a geosynthetic ground improvement program with a RAP base during the reconstruction of a 1.95 ha asphalt parking lot. Field observations of base course construction with RAP explore some of the implications of laboratory findings. A number of interesting observations on the technical, construction, and economic issues resulting from the project challenges and the use of RAP are presented.

Heath, A., Theyse, H., and Lea, J. (1999). "Use of ash in low-volume road construction in South Africa." Transportation Research Record: Journal of the Transportation Research Board, 1652, 196-202.

Sasol Chemical Industries produces large quantities of coarse clinker and fly ash as a by-product of the coal gasification process at their Sasolburg plant in South Af1ica. If this ash could be used as an aggregate in roads, the demand on natural reserves for aggregates would be reduced and an effective method of disposing of these materials would result. The ash is processed at a blending plant in Sasolburg and is marketed under the name Premamix. Trial sections were constructed using labor-based techniques with unstabilized and bitumen emulsion-treated Premamix as a base course material. As the Premamix is a lightweight material and is delivered at a specified moisture content (the optimum moisture content for compaction), it is ideal for labor-based construction of low-volume roads as only spreading and compaction of the layers are required. The trial sections were subjected to accelerated pavement testing with the heavy-vehicle simulator. Although high deflections were measured in the pavement structure, the Premamix performed well under trafficking, even after the base was soaked with water.

Helstrom, C. L., Humphrey, D. N., and Labbe, J. M. (2007). "Performance and Effectiveness of a Thin Pavement Section Using Geogrids and Drainage Geocomposites in a Cold Region." NETCR60, Department of Civil and Environmental Engineering, University of Maine, Orono, Maine.

Test sections were constructed in two portions of Maine Route 9 to investigate the use of geosynthetics for reinforcement and drainage for subbase courses that were 300 mm (12 in.) and 600 mm (24 in.) thick with 150 mm (6-in.) of flexible pavement. Four types of test sections were constructed: geogrid reinforcement, drainage geocomposite, drainage geocomposite with geogrid reinforcement, and control. Test sections using reinforcement geogrid have strain gages attached to the geogrid to measure induced forces. Some of the reinforcement sections have geogrid on subgrade whereas some have geogrid in the center of the subbase to evaluate the effects of geogrid location. Drainage geocomposite and control sections have vibrating wire piezometers to monitor porewater pressure in the subgrade and subbase course. Thermocouples were used to measure the depth of frost penetration. The results of falling weight deflectometer tests were used to backcalculate the effective structural number for each section. Reinforcement geogrid and drainage geocomposite increased the effective structural number by between 5% and 17% for sections with 300 mm (12 in.) subbase. However, they had no apparent effect for sections with 600 mm (24 in.) of subbase. The increase in backcalculated effective structural number that was produced by geogrid and/or drainage geocomposite in the 300-mm (12-in.) subbase sections could also be obtained by adding between 25 and 75 mm (1 and 3 in.) of subbase aggregate to an unreinforced section.

Hopkins, T. C., Beckham, T. L., and Hunsucker, D. Q. (1995). "Modification of highway soil subgrades." Report KTC 94-11, Kentucky Transportation Center, University of Kentucky, Lexington, KY.

Major study objectives were to develop highway pavement subgrade stabilization guidelines, examine long-term benefits of chemical stabilizers, such as cement, hydrated lime, and two byproducts from industrial processes, and to establish a subgrade stabilization program in Kentucky. In developing a program, a number of design and construction issues had to be resolved. Factors affecting subgrade behavior are examined. Changes in moisture content and CBR strengths of untreated and chemically treated subgrades at three experimental highway routes were monitored over a 7-year period. CBR strengths of the untreated subgrades decreased dramatically while moisture contents increased. CBR strengths of subgrade sections treated with hydrated lime, cement and multicone kiln dust generally exceeded 12 and increased over the study period. At four other highway routs ranging in ages from 10 to 30 years, CBR strengths of soil-cement subgrades exceed 90. Knowing when subgrade stabilization is needed is critical to the development of an economical design and to insure the efficient construction of pavements. Bearing capacity analyses using a newly developed, stability model based on limit equilibrium and assuming a tire constant stress of 552 kPa show that stabilization should be considered when the CBR strength is less than 6.5. For other tire contact stresses, relationships corresponding to factors of safety of 1 and 1.5 are presented. Stability analysis of the first lifts of the paving materials showed that CBR strengths of untreated subgrade should be > 9. Guidelines for using geogrids as subgrade reinforcement are presented. Factors of safety of geogrid reinforced granular bases are approximately 10 to 25 percent larger than granular bases without reinforcement. As shown by strength tests and stability analysis, when the percent finer than the 0.002mm particle size of a soil increases to a value greater than about 15%, the factor of safety

decreases significantly. Guidelines are also presented for this selection of the design strengths of untreated and treated subgrades with hydrated lime and cement. Based on a number of stabilization projects, recommended design undrained shear strengths of hydrated lime- and cement-treated subgrades are about 300 and 690 kPa, respectively. A laboratory testing procedure for determining the optimum percentage of chemical admixture is described. Correlations of dynamic cone penetrometer and Clegg impact hammer and in situ CBR strengths and unconfined compressive strengths are presented.

Hopkins, T. C., Beckham, T. L., Sun, L., Ni, B., and Butcher, B. (2002). "Long-Term Benefits of Stabilizing Soil Subgrades." KTC-02-19/SPR196-99-1F, Kentucky Transportation Center, University of Kentucky, Lexington, Kentucky.

Chemical admixtures have been used extensively since the mid-eighties in Kentucky to improve bearing strengths of soil subgrades. Most pavements in Kentucky are constructed on clayey soils. Although short-term observations at a small number of sites showed that chemical stabilization worked very well, a need existed to perform a more comprehensive review and to assess the long-term benefits of this subgrade stabilization method. The main intent of this study was an attempt to address questions concerning bearing strengths, longevity, durability, structural credit, economics, and performance of pavements resting on soil subgrades mixed with chemical admixtures. In-depth field and laboratory studies were performed at fourteen roadway sites containing twenty different treated subgrade sections. Ages of the sites range from about 8 to 15 years. About 455 borings were made at the various sites. Air, instead of water, was used as the drilling media. In-situ CBR tests were performed on the treated subgrades and the untreated subgrades lying directly below the treated layers. Index tests and resilient modulus tests were performed on samples collected from the treated and untreated subgrades. Falling weight deflectometer (FWD) tests were performed. At the 85th percentile test value, the in situ CBR values of subgrades mixed with hydrated lime, Portland cement, a combination of hydrated lime and Portland cement, and a byproduct (MKD) obtained in the production of hydrated lime were 12 to 30 times greater than in CBR values of the untreated subgrades. In-situ CBR values of the treated layer ranged from 24 to 59 while the in-situ CBR of the untreated layer at the 85th percentile test value was only 2. Based on rating criteria of the Kentucky Transportation Cabinet, the conditions of the pavements at twelve sites could be rated “good” at the time of the study– pavement ages were 8 to 15 years– and “good” at the end of the twenty-year design period, based on projected data. At two sites, thin asphalt overlays had been constructed after 15 years. However, accumulated values of ESAL at those sites had exceeded or were near the values of ESAL assumed in the pavement designs. At the 20th percentile test value, rutting depths of the pavements resting on the treated subgrades were less than about 0.27 inches. Structural layer coefficients, a3, for use in pavement design of the different chemically stabilized subgrades were developed. The proposed values were verified at sites where reduced pavement thickness was used and “in service” structural coefficients could be observed. Back-calculated values of FWD modulus of the treated layers were about two times the values of modulus of the untreated subgrade. Resilient modulus of the treated subgrades was larger than the resilient modulus of the untreated subgrades. Moisture contents at the top of the untreated subgrade layers showed that a “soft” layer of material exists at the very top of the untreated subgrade. This soft zone did not exist at the top of the treated layer. This discovery has significant engineering implications. Future research will focus attention on an in-depth examination of this weak layer of soil.

Chemical admixture stabilization is a good, durable and economical technique for improving subgrade strengths.

Kendall, M., Baker, B., Evans, P., and Ramanujan, J. "Foamed Bitumen Stabilization - The Queensland Experience." Proc., 20th Australian Road Research Board (ARRB) Conference, Sydney, Australia.

This paper addresses: (a) the basics of foamed bitumen stabilization, (b) situations where foamed bitumen stabilization could be considered, (c) the design method used by the Queensland Department of Main Roads, (d) lessons learnt from the $2.5M, 17.6 km New England Highway Project, (e) what to look for when carrying out foamed bitumen stabilsation, and (f) the future of foamed bitumen stabilisation within the Queensland Department of Main Roads.

Less, R. A., and Paulson, C. K. (1977). "Experimental macadam stone base - Des Moines County." Project HR-175, Iowa Department of Transportation, Ames, Iowa.

The IHRB HR-175 research project evaluated the feasibility and economics of using macadam subbase material (with different thicknesses) with choke stone under PCC and asphalt pavements. The macadam subbase material used on this project had a typical gradation with 4 in. maximum particle size and 12 to 26% passing the 1 in. sieve. The choke stone had a typical gradation with 1 in. maximum particle size and 6 to 12% passing the No. 200 sieve. The study indicated that the macadam subbase performed well under both PCC and asphalt pavements, but the cost was relatively more. During construction, the finished macadam subbase showed a uniform structure with negligible amount of degradation during compaction. Production rates on placement of the macadam subbase material varied from about 2900 to 5000 tons per day. Lateral subdrain trenches backfilled with porous backfill was used on this project for drainage. This system performed well and minimized effects of frost boils, spring thaw, and other subsurface drainage issues.

Litzka, J., and Haslehner, W. "Cold In-Place Recycling on Low-Volume Roads in Austria." Proc., Sixth International Conference on Low-Volume Roads, Minneapolis, Minnesota.

Modern methods for road maintenance should involve used construction materials, take account of environmental compatibility, and eliminate road damage economically and durably. Regarding these basic requirements, attention should be paid to cold in-place recycling of damaged asphalt layers using cement stabilization. Within the last few years, cold in-place recycling has become an appropriate alternative for the rehabilitation of low-volume roads in Austria. In the course of documentation carried out at the Institute for Traffic and Transportation Engineering of the Vienna University of Bodenkultur, the individual steps of construction were analyzed. The advantage of the described procedure is that none of the old pavement need be hauled to a special repository. An innovative method for cold in-place recycling on low-volume roads using cement stabilization is described. The first step of this method contains a detailed analysis of the section to be restored, including bearing capacity measurements and the determination of the grading curves of existing unbound layers. Grading curves are also determined for the existing asphalt layer after trial milling in order to consider refinement by milling. This analysis forms the basis for adding material before milling in order to achieve a well-graded aggregate. On the construction site, the necessary additional aggregate is spread over the existing pavement. In the next step, the cement binder is distributed on the road surface. A

soil stabilizer breaks up the existing road structure and mixes it thoroughly with the aggregates and

Lynam, D., and Jones, K. (1979). "Pavement surfaced on macadam base - Adair County." Project HR-209, Iowa Department of Transportation, Ames, Iowa.

The IHRB HR-209 research project evaluated the feasibility and economics of using macadam subbase material (without choke stone) under PCC and asphalt pavements. The macadam subbase material used on this project had a typical gradation with 3 in. maximum particle size and < 1% passing the #8 sieve. Field testing was conducted using Road Rater testing and visual crack/distress surveys. Some key findings from this study were as follows: (a) Road Rater testing indicated that the structural rating of a PCC pavement is improved if macadam subbase is used under the pavement. However, the improvement structural rating from using 5 in. of macadam subbase is equivalent to about additional ½ or ¾ in. PCC. The macadam subbase served primarily as a drainage layer and therefore could be reduced to 3.5 to 4 in. thickness instead of 5 in. Asphalt treating the macadam stone could be of additional benefit for stability of the base. (b) 2 to 3 in. thick PCC pavements over 5 in. macadam subbase showed poor performance and low structural rating. It is indicated that a minimum 5.5 in. PCC pavement is required over macadam to obtain 20 year design life. (c) Macadam served as a good drainage layer and prevented D-cracking on PCC pavements (within the 5 years of evaluation), which was a common problem in the area with using Class 1 aggregate (which contained fines). (d) Significant allowance should be made for material overruns when placing either PCC or asphalt pavement on macadam without chokestone (215 cubic yards per mile for PCC). (E) The quarry must be in close proximity for the project (within 10 to 20 miles) for macadam stone base to be economically practical.

Maxwell, S., Kim, W.-H., Edil, T. B., and Benson, C. H. (2004). "Geosynthetics in Stabilizing Soft Subgrade with Breaker Run." Report No. 0092-45-15, Department of Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, WI.

This report introduced the research begun in 1999 at the University of Wisconsin-Madison to further understand aspects of geosynthetic-reinforced subbases in a pavement system. To learn more about how the performance of highway pavement is improved with geosynthetics, a field demonstration was conducted using a 21-m section along a Wisconsin highway (USH 45) near Antigo, Wisconsin, that incorporated three test sub-sections. Three different geosynthetics including a woven geotextile and two different types of geogrids were evaluated for stabilization. The same pavement structure was used for all test sections except for the geosynthetics. Observations made during and after construction indicate that all sections provided adequate support for the construction equipment and that no distress is evident in any part of the highway. Much has been learned about instrumentation of geosynthetics with foil-type strain gages. The installation procedures and weatherization techniques used during this demonstration project appeared to be a success. Additionally, better strain gage results are possible for a geotextile when a longer (25 mm) strain gage is used. The falling weight deflectometer did not provide sufficient resolution to differentiate between different types of geosynthetic test sections especially in a field environment where there's heterogeneity of natural soils. However, a greater seasonal variability of the subgrade was noted. A control section without reinforcement was not constructed at this time that would have allowed for comparison and assessment of the geosynthetic addition.

Parsons, R. L., and Kneebone, E. (2005). "Field performance of fly ash stabilised subgrades." Ground Improvement, 9(1), 33-38.

Class C fly ash has been used to improve the properties of subgrade soils for several decades. This report contains a summary of the results of a study to quantify the level of improvement provided by Class C fly ash and the degree to which those improvements are effectively permanent. A series of dynamic cone penetrometer values were obtained for 12 streets with fly ash treated subgrades, and for five streets with untreated subgrades. Streets ranged in age from zero to nine years. For subgrades with fly ash the penetration resistance was recorded for the fly ash treated layer and the untreated soil beneath. Higher strengths were recorded for all fly ash treated subgrade layers than for the untreated soil beneath. No deterioration with age was observed for the subgrades evaluated. Laboratory and field testing of soils treated with fly ash also showed that fly ash contributed to soil strength and stiffness while plasticity and swell potential were reduced, although swelling was not eliminated.

Salour, F., and Erlingsson, S. (2012). "Pavement Structural Behavior during Spring Thaw - Interpretation of FWD measurements by monitoring environmental data from county road 126 at Torpsbruk." 2009/0572-29, Swedish National Road and Transport Research Institute (VTI), Linkoping, Sweden.

The present research report has been carried out based on the environmental data and Falling Weight Deflectometer (FWD) measurements from the county road Lv 126 in Southern Sweden during the year 2010. The Lv 126 county road has a relatively thin flexible pavement structure with unbound aggregate base and subbase layers. The major intention of this study was to investigate the behaviour of the pavement structure during spring thaw. Temperature and moisture content of the pavement structure profile were continuously monitored throughout the year 2010. Layer moduli backcalculation as well as deflection basin analyses were performed using the FWD measurements data. A comprehensive study on the effect of environmental factor variations and pavement structural capacity were carried out during the spring thaw and recovery period. The result showed a considerable decrease in the bearing capacity of the pavement structure during the spring thaw period when the highest annual moisture content was also registered. Both deflection basin indices and backcalculated layer modulus indicated that the pavement was weakest during the subgrade thawing phase. Backcalculation on the FWD measurements showed a 63% loss in stiffness of the subgrade soil and 48% in the granular base and subbase course during the spring thaw compared to the summer values. In addition, the compatibility of the analysis with a predictive stiffness moduli- moisture content model for unbound materials was studied. The measured field data from the test road pavement in Torpsbruk showed promising agreement with the resilient modulus predictive model, both for the granular layer and subgrade material. Similar models could be developed or calibrated for other soils and granular materials if sufficient data become available in the future.

Sirivitmaitrie, C., Puppala, A. J., Saride, S., and Hoyos, L. (2011). "Combined lime–cement stabilization for longer life of low-volume roads." Transportation Research Record: Journal of the Transportation Research Board, 2204, 140-147.

Low-volume roads are an important part of the world’s transportation infrastructure and a direct cause of the socioeconomic development of small city and rural communities. Construction, maintenance, and rehabilitation of these roads are major tasks and require a major part of the public works budget. Better design and construction methods can prolong pavement

service life and result in lower maintenance and rehabilitation costs. This paper presents a research study done for the city of Arlington in north Texas to stabilize road subsoils with a combined lime and cement stabilizer, which in turn is expected to enhance service life of the roads. Both laboratory tests on stabilized soil mixtures and field performance data are analyzed and presented.

White, D. J., Ceylan, H., Jahren, C. T., Phan, T. H., Kim, S. H., Gopalakrishnan, K., and Suleiman, M. T. (2008). "Performance Evaluation of Concrete Pavement Granular Subbase—Pavement Surface Condition Evaluation." IHRB Project TR-554, Center for Transportation Research and Education, Iowa State University, Ames, Iowa.

This research project covered a wide range of activities that allowed researchers to understand the relationship between stability, pavement distress, and recycled portland cement concrete (RPCC) subbase aggregate materials. Detailed laboratory and field tests, including pavement distress surveys, were conducted at 26 sites in Iowa were conducted. Findings show that specific gravities of RPCC are lower than those of crushed limestone. RPCC aggregate material varies from poorly or well-graded sand to gravel. A modified Micro-Deval test procedure showed that abrasion losses of virgin aggregate materials were within the maximum Micro-Deval abrasion loss of 30% recommended by ASTM D6028-06. Micro-Deval abrasion loss of RPCC aggregate materials, however were much higher than those of virgin materials and exceeded 30% loss. Modulus of elasticity of RPCC subbase materials is high but variable. RPCC subbase layers normally have low permeability. The pavement surfaces for both virgin and RPCC subbase across Iowa were evaluated to fulfill the objectives of this study related to field evaluation. Visual distress surveys were conducted to gather the detailed current pavement condition information including the type, extent, and severity of the pavement distresses. The historical pavement condition information for the surveyed field sections was extracted from the Iowa DOT's Pavement Management Information System (PMIS). The current surface condition of existing field pavements with RPCC subbase was compared with the virgin aggregate subbase sections using two different approaches. The changes in pavement condition indices (PCI and IRI) with time for both types of pavements (subbases) were compared.

White, D. J., Harrington, D., and Thomas, Z. (2005a). "Fly Ash Soil Stabilization for Non-Uniform Subgrade Soils, Volume I: Engineering Properties and Construction Guidelines." IHRB Project TR-461, FHWA Project 4, Center for Transportation Research and Education, Iowa State University, Ames, Iowa.

Soil treated with self-cementing fly ash is increasingly being used in Iowa to stabilize fine-grained pavement subgrades, but without a complete understanding of the short- and long-term behavior. To develop a broader understanding of fly ash engineering properties, mixtures of five different soil types, ranging from ML to CH, and several different fly ash sources (including hydrated and conditioned fly ashes) were evaluated. Results show that soil compaction characteristics, compressive strength, wet/dry durability, freeze-thaw durability, hydration characteristics, rate of strength gain, and plasticity characteristics are all affected by the addition of fly ash. Specifically, Iowa self-cementing fly ashes are effective at stabilizing fine-grained Iowa soils for earthwork and paving operations; fly ash increases compacted dry density and reduces the optimum moisture content; strength gain in soil-fly ash mixtures depends on cure time and temperature, compaction energy, and compaction delay; sulfur contents can form expansive minerals in soil–fly ash mixtures, which severely reduces the long-term strength and

durability; fly ash increases the California bearing ratio of fine-grained soil–fly ash effectively dries wet soils and provides an initial rapid strength gain; fly ash decreases swell potential of expansive soils; soil-fly ash mixtures cured below freezing temperatures and then soaked in water are highly susceptible to slaking and strength loss; soil stabilized with fly ash exhibits increased freeze-thaw durability; soil strength can be increased with the addition of hydrated fly ash and conditioned fly ash, but at higher rates and not as effectively as self-cementing fly ash. Based on the results of this study, three proposed specifications were developed for the use of self-cementing fly ash, hydrated fly ash, and conditioned fly ash. The specifications describe laboratory evaluation, field placement, moisture conditioning, compaction, quality control testing procedures, and basis of payment.

Environmental Impacts

Ashmawy, A., McDonald, R., Carreon, D., and Atalay, F. (2006). "Stabilization of Marginal Soils Using Recycled Materials." BD-544-4, Department of Civil and Environmental Engineering, University of South Florida, Tallahassee, Florida.

Loose sand, soft clays, and organic deposits are often unsuitable for use in construction due to their less-than-desirable engineering properties. Traditional methods of stabilizing these soils through in-situ ground improvement or replacement techniques are costly. Recycled materials such as scrap tires, plastics, ash, slag, and construction debris provide a viable alternative both for their relatively lower cost and desirable engineering properties. Furthermore, use of recycled materials prevents their disposal into landfills, which are approaching capacity in Florida and across the nation. This report provides a comprehensive assessment of various recycled materials that can be used to stabilize marginal soils in Florida. Particular attention is given to material availability and environmental properties in addition to engineering properties. A methodology is proposed to guide FDOT personnel in evaluating, testing, and approving any new material for use as a highway construction material.

Austroads (1998). "Guide to stabilisation in roadworks." Austroads, Sydney, A4, New Zealand.

This Guide provides systematic guidance to practitioners for the selection, design and construction of stabilised pavement layers for use in the construction of new road pavements and the maintenance, rehabilitation and recycling of existing road pavements. It replaces the 1986 NAASRA Guide to Stabilisation in Roadworks. Since the NAASRA Guide was published, there have been substantial improvements in many aspects of stabilisation technology including: (1) improved pavement design procedures; (2) improved materials characterisation procedures; (3) higher capacity plant and equipment; (4) wider range of stabilisation agents with greater effectiveness; and (5) increased environmental awareness of the benefits of stabilisation. Guidance is given to assist the practitioner to select the appropriate type of stabilisation for a particular application as well as materials and pavement design guidance for the following broad types of stabilisation techniques: cementitious stabilisation, lime stabilisation, bituminous stabilisation, granular stabilisation, and other forms of stabilisation. Construction and quality management issues are also addressed. While there have been significant advances in stabilisation technology in the past decade, there are still a number of areas in need of greater understanding including: materials mix design and characterisation, erosion mechanisms, long term strength gains, and stabilisation under traffic. While the information given in the Guide is considered to represent best practice at the time of publication, with the current rate of change of stabilisation technology, it will continue to improve in the future.

Bland, A. E., Brown, T. H., and Sheesley, D. C. (1991). "Fly ash use for unpaved road stabilization - Phase I." Interim Technical Report WRI-92-R017, The University of Wyoming, Laramie, Wyoming.

Western Research Institute (WRI) has conducted both laboratory and field demonstrations of a relatively new nonstandard unpaved road stabilization technique burning Class C fly ash from coal-fired power generation plants using Wyoming subbituminous coals. The experimental construction technique uses lean fly ash/soil/water formulations for stabilizing unpaved road materials to reduce maintenance costs and to provide new expanded markets for coal fly ash. The experimental testing program was designed to evaluate different soil/fly ash conditions as well as different construction techniques. Laboratory testing was conducted using ash from the PacifiCorp Dave Johnston Power Plant (DJPP) near Glenrock, Wyoming and five different soil types from a road adjacent to the plant. The laboratory testing examined the geotechnical performance of the various amounts of fly ash treatment of the soils. Moisture-density relationships and moisture-strength relationships were determined. The Dave Johnston fly ash is a slow-reacting fly ash, and early strength development was low (less than 100 psi) for all mixtures tested up to 25% fly ash. A twofold increase in strength was noted between the low fly ash dosage rates (5%) and the high fly ash dosage (25%). Based on the results of the laboratory testing, it is recommended to use 20% fly ash and optimum moisture for compaction of 11 to 13% water. Two 1,000-ft experimental test sections demonstrating the fly ash stabilized unpaved road process were constructed in July 1991, near the DJPP. The unpaved road had a continued history of washboarding and required regular high levels of maintenance. Based on the laboratory testing and design, the experimental test road was constructed using Dave Johnston fly ash as a binder to stabilize the upper 9 inches of the road surface. The intent was to treat the road sections by scarifying\ adding fly ash, and thoroughly mixing these materials with water and compacting the mixture to a highly densified and stable road surface. It was intended that the road be immediately available to traffic and continue to improve in strength and durability with time. WRI decided to use a fly ash application of 20% to construct the test section for several reasons: (1) The fly ash source was adjacent to the road construction site, and no transportation costs would be incurred. (2) A high application percentage would provide a range of high and low ash concentrations to study. (3) The laboratory studies suggested that a 20% application of fly ash from the DJPP was required for maximum strength development in the test section. Two demonstration test sections were constructed. Fly ash from Unit 3 of the DJPP was used for the treatment. Also, water from the Dave Johnston recycle pond was used. The materials consisted of 240 tons of fly ash and 10,000 gallons of water. Based on calculations of the depth of treatment and the bulk density of the road material, a fly ash treatment of 20% and a water addition of 11 % were achieved. The laboratory design testing suggested that optimum moistures in the range of 11 to 13% were required for maximum compaction. Visual monitoring of the road showed that some areas required remedial attention. This was a result of inadequate mixing of the fly ash and soil, and insufficient water addition during construction. A soft spot in the road with a high fly ash content, was patched to reduce dusting and improve trafficability. The test sections were dusting because either insufficient water was added during construction or the fly ash mixtures dried out before sufficient curing could occur. The treated sections were covered with bottom ash to act as a moisture barrier and covering the surface. The barrier was successful, but the bottom ash developed severe washboarding. As a result, the bottom ash was removed after the fly ash/soil achieved sufficient strength and · durability. Additional water applications helped develop a hard, upper 2- to 3-inch surface in the fly ash treated section of the road. Performance monitoring and evaluation of the construction techniques show that mixing was inadequate, whereas compaction appears to be satisfactory. Fly ash distribution via blade mixing did not produce a homogeneous mixture, although improvement may have been possible if additional passes had been performed. Evidence for both lateral variations in the test section from 15 to 50% fly ash and a vertical layering in the treated section have been documented. Inadequate water distribution due to improper mixing was also noted as evidenced by the fact that areas were found that appeared to have received little or no water. Compaction of the fly ash treated soil mixtures was in the range of 95% of the laboratory results and the estimated maximum dry density. The performance of the fly ash treated section is presently quite good, showing continued strength development and reduced potential for dusting. The mechanically treated section is developing cracks, which are expected to create problems by Spring 1992. The control section is already showing washboarding as it has in the past. The fly ash stabilization technology appears to be an environmentally acceptable technology that does not pose a threat to groundwater. The surface water and storm water runoff have not been assessed because rainfall in the area has been too low. However, WRI does not anticipate problems associated with surface water or storm water runoff quality. In addition, the level of radioactivity for the fly ash is too low to be a health concern. However, the application of the fly ash during the construction phase needs to be improved to prevent excessive fugitive dust emissions. Options for modifying the construction procedure are being addressed and will be incorporated into future test sections. The results of the phase I testing and demonstration activities show that the process of fly ash stabilization of unpaved roads is promising. Although the strength development with the Dave Johnston fly ash is very slow, engineering performance of the road demonstration test sections is quite good. The fly ash treated test section has shown no evidence of washboarding, and the dust from the road has been reduced to levels comparable to the control section of the unpaved road.

Carreon, D. G. (2006). "Stabilization of Marginal Soils Using Recycled Materials." Department of Civil and Environmental Engineering, University of South Florida, Florida.

Marginal soils, including loose sands, soft clays, and organics are not adequate materials for construction projects. These marginal soils do not possess valuable physical properties for construction applications. The current methods for remediation of these weak soils such as stone columns, vibro-compaction, etc. are typically expensive. Waste materials such as scrap tires, ash, and wastewater sludge, offer a cheaper method for stabilizing marginal soils. As an added benefit, utilizing waste materials in soil stabilization applications keeps these materials from being dumped into landfills, thereby saving already depleting landfill space. Included in this report is an extensive investigation into the current state of research on waste and recycled materials in construction applications. Also included is an investigation on actual implementation of this research in construction projects. Upon completion of this investigation, an effort was made to determine waste materials specific to the state of Florida (waste roofing shingles, municipal solid waste ash, waste tires, and paper mill sludge) that could be used in stabilizing marginal soils through soil mixing techniques. Changes in the engineering properties of soils as a result of adding these waste materials were studied and recommendations on implementing these effects into construction applications are offered.

Christoffersson, P., and Johansson, S. (2011). "Rehabilitation of the Forest Road Timmerleden." A ROADEX demonstration report, The Swedish Transport Administration, Northern Region, Sweden.

The European Union ROADEX Project 1998 – 2012 was a trans-national roads cooperation that aimed at developing ways for interactive and innovative management of low volume roads across the European Northern Periphery. Its main goals were to facilitate co-operation and research into the common problems of constructing and maintaining low volume roads in harsh climates. This report gives a summary of a local demonstration of ROADEX methods for assessing forest roads for heavy timber traffic and based on the results making a rehabilitation design proposal. Using the ROADEX-method the road was first surveyed using the modern non-destructive road survey techniques of video, ground penetrating radar and falling weight deflectometer. Three samples were also taken to check the grading and to verify the GPR-results. Following this an integrated analysis was carried out using Road Doctor software to produce a strength assessment of the road. The results were then used to do an analytical design of the strengthening measures needed to carry the load from the timber trucks. The ROADEX method was compared to regular road condition assessments and rehabilitation proposals from the project partners: The Swedish Forest Agency and the forest companies Sveaskog and SCA Forest. The partners used their normal procedures for field surveys, analyses and design. The comparison included: (1) Design, (2) Volumes of road materials used, (3) Environmental influence, (4) costs for design, materials, construction, and environmental impacts. The results demonstrate that making a more careful road condition investigation and an analytical road rehabilitation design based on the road condition analyses, can reduce the overall rehabilitation costs.

Christoffersson, P., and Johansson, S. (2012). "Rehabilitation of the Timmerleden Forest Road - Condition Survey, Design Proposals, Construction and Quality Control." A ROADEX demonstration report, The Swedish Transport Administration, Northern Region, Sweden.

The European Union ROADEX Project 1998 – 2012 was a trans-national roads cooperation that aimed at developing ways for interactive and innovative management of low volume roads across the European Northern Periphery. Its main goals were to facilitate co-operation and research into the common problems of constructing and maintaining low volume roads in harsh climates. This report gives a summary of a local demonstration of ROADEX methods for assessing forest roads for heavy timber traffic and based on the results making a rehabilitation design proposal. The report also gives a short description of the construction of the rehabilitation and the quality control. Using the ROADEX-method the road was first surveyed using the modern non-destructive road survey techniques of video, ground penetrating radar and falling weight deflectometer. Three samples were also taken to check the grading and to verify the GPR-results. Following this an integrated analysis was carried out using Road Doctor software to produce a strength assessment of the road. The results were then used to do an analytical design of the strengthening measures needed to carry the load from the timber trucks. The ROADEX method was compared to regular road condition assessments and rehabilitation proposals from the project partners: The Swedish Forest Agency and the forest companies Sveaskog and SCA Forest. The partners used their normal procedures for field surveys, analyses and design. The comparison included: (1) Design, (2) Volumes of road materials used, (3) Environmental influence, (4) costs for design, materials, construction, and environmental impacts. To make the ROADEX forest road rehabilitation package complete a quality control

was carried out to check if the measures were done right in place, if the layer thicknesses were constructed in accordance with the design and if the bearing capacity target was reached. New GPR- and FWD surveys were carried out about a month after the rehabilitation work was finished. It was found from the GPR survey that measures were very well in place but in some places the base course was a little thinner than the design thickness. A new calculation in accordance with the Odemark method based on the new survey results showed that 98 % of the road length met the bearing capacity target of 90 MPa. The results demonstrate that making a more careful road condition investigation and an analytical road rehabilitation design based on the road condition analyses, can reduce the overall rehabilitation costs and the environmental impacts significantly. The demonstration project has shown that the use of the ROADEX method in this case reduced the costs between 15 and 50%.

Kestler, M. A. (2009). "Stabilization selection guide for aggregate and native-surfaced low-volume roads." National Technology and Development Program, Forest Service, U.S. Department of Agriculture, Washington, D.C.

The purpose of this guide is to facilitate the selection of modification/stabilization agents and techniques for aggregate surfaced and native/unsurfaced LVRs. The objective is to provide low-cost alternatives that reduce aggregate wear and loss, reduce road-surface maintenance (i.e., blading out ruts), and reduce the time period between major rehabilitation (i.e., between adding new aggregate or the total reconditioning of the road pavement). This guide provides information on available stabilizing agents, appropriate conditions for use, selection procedures, quantity determination, and contact information for manufacturers/suppliers. Emphasis is on the modification/stabilization of existing in-place road surface materials, but many of the methods can be used in the construction of new roads. Construction procedures for application are also presented. The intended audience includes road managers, engineers, and technicians involved in road maintenance, construction, and reconstruction. Those involved in trail maintenance and construction also may find the guide beneficial, as stabilizers used on trails, particularly accessible trails, help provide a smooth, durable surface.

Li, L., Benson, C. H., Edil, T. B., and Hatipoglu, B. (2008). "Sustainable Construction Case History: Fly Ash Stabilization of Recycled Asphalt Pavement Material." Geotechnical and Geological Engineering, 26, 177-187.

A case history is described where Class C fly ash was used to stabilize recycled pavement material (RPM) during construction of a flexible pavement in Waseca, MN, USA. The project consisted of pulverizing the existing hot-mix asphalt (HMA), base, and subgrade to a depth of 300 mm to form RPM, blending the RPM with fly ash (10% by dry weight) and water, compacting the RPM, and placement of a new HMA surface. California bearing ratio (CBR), resilient modulus (Mr), and unconfined compression (qu) tests were conducted on the RPM alone and the fly ash stabilized RPM (SRPM) prepared in the field and laboratory to evaluate how addition of fly ash improved the strength and stiffness. After 7 days of curing, SRPM prepared in the laboratory had CBR ranging between 70 and 94, Mr between 78 and 119 MPa, and qu between 284 and 454 kPa, whereas the RPM alone had CBR between 3 and 17 and Mr between 46 and 50 MPa. Lower CBR, Mr, and qu were obtained for SRPM mixed in the field relative to the SRPM mixed in the laboratory (64% lower for CBR, 25% lower for Mr, and 50% lower for qu). In situ falling weight deflectometer testing conducted 1 year after construction showed no degradation in the modulus of the SRPM, even though the SRPM underwent a freeze–thaw cycle. Analysis of leachate collected in the lysimeter showed that concentrations of all trace elements were below USEPA maximum contaminant levels.

Parsons, R. L., and Kneebone, E. (2005). "Field performance of fly ash stabilised subgrades." Ground Improvement, 9(1), 33-38.

Class C fly ash has been used to improve the properties of subgrade soils for several decades. This report contains a summary of the results of a study to quantify the level of improvement provided by Class C fly ash and the degree to which those improvements are effectively permanent. A series of dynamic cone penetrometer values were obtained for 12 streets with fly ash treated subgrades, and for five streets with untreated subgrades. Streets ranged in age from zero to nine years. For subgrades with fly ash the penetration resistance was recorded for the fly ash treated layer and the untreated soil beneath. Higher strengths were recorded for all fly ash treated subgrade layers than for the untreated soil beneath. No deterioration with age was observed for the subgrades evaluated. Laboratory and field testing of soils treated with fly ash also showed that fly ash contributed to soil strength and stiffness while plasticity and swell potential were reduced, although swelling was not eliminated.

Initial Costs

Bassel, J. R., Edwards, A., Leibbrand, L., Keller, G. R., and Dauer, W. (1999). "Three road-crushing demonstration projects." Transportation Research Record: Journal of the Transportation Research Board, 1652.

At the Sixth International Conference on Low-Volume Roads Yves Provencher, Forest Engineering Research Institute of Canada, presented a paper on the F.A.H.R. rock crusher mounted to a front-end loader. At the same time the Coronado National Forest in Arizona was renting a F.A.H.R. rock crusher for an in-place road-crushing project. In 1997 San Dimas Technology and Development Center, in partnership with the Coronado National Forest, sponsored two demonstration projects to further test the crusher at unique locations to gain additional information from actual field trials. These projects were located on the Rio Grande National Forest in Colorado and the Plumas National Forest in California. The three projects are described here, with results and conclusions gained from the demonstration projects. The concentration is on the characteristics of the processed material. Samples taken from windrows during the crushing operation were tested to determine hardness and gradations before and after crushing. Cost varied from $8 to $26 per m3 including roadbed preparation, crushing, and blading. Rocks and boulders to 405-mm maximum size were crushed. The processed material has a maximum size of 50 to 75 mm. The product produced by the crusher offers a viable alternative for aggregate on a road surface, particularly as a road surface cushion material, where the quality and expense of standard crushed aggregate, such as base course material, are not needed on low-volume roads.

Bergeson, K. L., Waddingham, J. W., Brocka, S. G., and Lapke, R. K. (1995). "Bentonite treatment for economical dust reduction on limestone surface secondary roads." Iowa DOT Project HR-351, Engineering Research Institute, Iowa State University, Ames, Iowa.

This research project was directed at laboratory and field evaluation of sodium montmorillonite clay (Bentonite) as a dust palliative for limestone surfaced secondary roads. It was postulated that the electrically charged surfaces (negative) of the clay particles could interact with the charged surfaces (positive) of the limestone and act as a bonding agent to agglomerate fine (- #200) particulates, and also to bond the fine particulates to larger (+ #200) limestone panicles. One mile test roads were constructed in Tama, Appanoose, and Hancock counties in Iowa using Bentonite treatment levels (by weight of aggregate) ranging from 3.0 to 12.0 percent. Construction was accomplished by adding dry Bentonite to the surfacing material and then dry road mixing. The soda ash water solution (dispersing agent) was spray applied and the treated surfacing material wet mixed by motor graders to a consistency of 2 to 3 inch slump concrete. Two motor graders working in tandem provided rapid mixing. Following wet mixing the material was surface spread and compacted by local traffic. Quantitative and qualitative periodic evaluations and testing of the test roads was conducted with respect to dust generation, crust development, roughness, and braking characteristics. As the Bentonite treatment level increased dust generation decreased. From a cost benefit standpoint, an optimum level of treatment is about 8 percent (by weight of aggregate). For roads with light traffic, one application at this treatment level resulted in a 60-70 percent average dust reduction in the first season, 40-50 percent in the second season, and 20-30 percent in the third season. Crust development was rated at two times better than untreated control sections. No discernible trend was evident with respect to roughness. There was no evident difference in any of the test sections with respect to braking distance and braking handling characteristics, under wet surface conditions compared to the control sections. Chloride treatments are more effective in dust reduction in the short term (3-4 months). Bentonite treatment is capable dust reduction over the lone: term (2-3 seasons). Normal maintenance blading operations can be used on Bentonite treated areas. Soda ash dispersed Bentonite treatment is conservatively estimated to be more than twice as cost effective per percent dust reduction than conventional chloride treatments, with respect to time. However, the disadvantage is that there is not the initial dramatic reduction in dust generation as with the chloride treatment. Although dust is reduced significantly after treatment there is still dust being generated. Video evidence indicates that the dust cloud in the Bentonite treated sections does not rise as high, or spread as wide as the cloud in the untreated section. It also settles faster than the cloud in the untreated section. This is considered important for driving safety of following traffic, and for nuisance dust invasion of residences and residential areas. The Bentonite appears to be functioning as a bonding agent to bind small limestone particulates to larger particles and is acting to agglomerate fine particles of limestone as evidenced by laboratory sieve analysis data, and by SEM micrographs. This bonding capability appears recoverable from environmental effects of winter, and from alternating wet and dry periods. The Bentonite is able to interact with new applications of limestone maintenance material and maintains a dust reduction capability.

Bushman, W. H., Freeman, T. E., and Hoppe, E. J. (2005). "Stabilization techniques for unpaved roads." Transportation Research Record: Journal of the Transportation Research Board, 1936, 26-33.

An amendment to Virginia House Bill 1400, Item 490, No. 1h, calls for the Virginia Transportation Research Council to “continue its evaluation of soil stabilizers as an alternative to paving low-volume secondary roads.” In response, promising soil stabilization products were evaluated with the relatively new technique of deeply mixing chemical additives into unpaved roadbeds. This work is based on the construction of a 1.75-m-long trial installation on Old Wheatland Road in Loudoun County, where seven commercially available stabilization products were applied to the unpaved road. A rigorous evaluation of treatment performance will provide the basis for recommendations to the Virginia Department of Transportation’s operating

divisions regarding improvements to the maintenance practices for gravel roads. Results thus far indicate that the introduction of soil stabilizers through deep mixing is a promising technique. The life-cycle cost analysis indicates that constructing a standard bituminous surface-treated roadway and maintaining it as such is much more cost-effective than using any of the products in this trial. Further, the analysis indicates that using the bituminous surface treatment alternative is also much more cost-effective than maintaining an unpaved road.

Christoffersson, P., and Johansson, S. (2011). "Rehabilitation of the Forest Road Timmerleden." A ROADEX demonstration report, The Swedish Transport Administration, Northern Region, Sweden.

The European Union ROADEX Project 1998 – 2012 was a trans-national roads cooperation that aimed at developing ways for interactive and innovative management of low volume roads across the European Northern Periphery. Its main goals were to facilitate co-operation and research into the common problems of constructing and maintaining low volume roads in harsh climates. This report gives a summary of a local demonstration of ROADEX methods for assessing forest roads for heavy timber traffic and based on the results making a rehabilitation design proposal. Using the ROADEX-method the road was first surveyed using the modern non-destructive road survey techniques of video, ground penetrating radar and falling weight deflectometer. Three samples were also taken to check the grading and to verify the GPR-results. Following this an integrated analysis was carried out using Road Doctor software to produce a strength assessment of the road. The results were then used to do an analytical design of the strengthening measures needed to carry the load from the timber trucks. The ROADEX method was compared to regular road condition assessments and rehabilitation proposals from the project partners: The Swedish Forest Agency and the forest companies Sveaskog and SCA Forest. The partners used their normal procedures for field surveys, analyses and design. The comparison included: (1) Design, (2) Volumes of road materials used, (3) Environmental influence, (4) costs for design, materials, construction, and environmental impacts. The results demonstrate that making a more careful road condition investigation and an analytical road rehabilitation design based on the road condition analyses, can reduce the overall rehabilitation costs.

Christoffersson, P., and Johansson, S. (2012). "Rehabilitation of the Timmerleden Forest Road - Condition Survey, Design Proposals, Construction and Quality Control." A ROADEX demonstration report, The Swedish Transport Administration, Northern Region, Sweden.

The European Union ROADEX Project 1998 – 2012 was a trans-national roads cooperation that aimed at developing ways for interactive and innovative management of low volume roads across the European Northern Periphery. Its main goals were to facilitate co-operation and research into the common problems of constructing and maintaining low volume roads in harsh climates. This report gives a summary of a local demonstration of ROADEX methods for assessing forest roads for heavy timber traffic and based on the results making a rehabilitation design proposal. The report also gives a short description of the construction of the rehabilitation and the quality control. Using the ROADEX-method the road was first surveyed using the modern non-destructive road survey techniques of video, ground penetrating radar and falling weight deflectometer. Three samples were also taken to check the grading and to verify the GPR-results. Following this an integrated analysis was carried out using Road Doctor software to produce a strength assessment of the road. The results were then used to do an

analytical design of the strengthening measures needed to carry the load from the timber trucks. The ROADEX method was compared to regular road condition assessments and rehabilitation proposals from the project partners: The Swedish Forest Agency and the forest companies Sveaskog and SCA Forest. The partners used their normal procedures for field surveys, analyses and design. The comparison included: (1) Design, (2) Volumes of road materials used, (3) Environmental influence, (4) costs for design, materials, construction, and environmental impacts. To make the ROADEX forest road rehabilitation package complete a quality control was carried out to check if the measures were done right in place, if the layer thicknesses were constructed in accordance with the design and if the bearing capacity target was reached. New GPR- and FWD surveys were carried out about a month after the rehabilitation work was finished. It was found from the GPR survey that measures were very well in place but in some places the base course was a little thinner than the design thickness. A new calculation in accordance with the Odemark method based on the new survey results showed that 98 % of the road length met the bearing capacity target of 90 MPa. The results demonstrate that making a more careful road condition investigation and an analytical road rehabilitation design based on the road condition analyses, can reduce the overall rehabilitation costs and the environmental impacts significantly. The demonstration project has shown that the use of the ROADEX method in this case reduced the costs between 15 and 50%.

Henry, K. S., Olson, J. P., Farrington, S. P., and Lens, J. (2005). "Improved performance of unpaved roads during spring thaw." ERDC/CRREL TR-05-01, Engineer Research and Development Center Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Unpaved roads in Vermont are subject to deterioration from seasonal freezing and thawing, and many towns have roads that suffer chronic serviceability problems during the so-called “spring thaw,” or mud season. Several techniques thought to mitigate deterioration of unpaved roads during spring thaw were constructed on test sections of unpaved roads in two towns. Each potential remedy was aimed at providing some combination of limiting the availability of moisture in the winter, improving drainage during spring, and strengthening the upper portion of the road. Each technique used local and/or commercially available materials, and all were easy to construct, i.e., a town road crew could build them. For two spring thaw seasons, we compared strength estimates based on dynamic cone penetrometer tests and the percentage of the road surface rutted for treated and control sections. Methods that permanently improved the strength of the top 12 inches of the road or decreased the water content of the upper 12 inches of the road resulted in significant performance improvement during spring thaw. Cement and cellular confinement systems worked well by improving the strength of the upper layers of the soil. Two new techniques— geowrap, comprising clean sand sandwiched by geotextile separators placed 12–18 inches deep, and the patented Geosynthetic Capillary Barrier Drain—provided benefit by keeping the upper layers of the soil relatively dry. Geogrid and geotextile separators placed 12 inch deep and trench drains parallel to the road provided no observable benefit.

Hicks, R. G. (2002). "Alaska soil stabilization design guide." FHWA-AK-RD-01-6B, State of Alaska Department of Transportation and Public Facilities, Fairbanks, Alaska.

This guide presents information on the types of soil stabilization techniques that have or can be used in the state of Alaska. It covers techniques including asphalt, cement, lime, mechanical, chemical, and other methods. For each method there is a discussion on materials and design considerations, construction issues, and expected performance and costs. The appendices include a glossary of terms, a reading list on prior stabilization used in Alaska, a discussion on the soils in Alaska, and a slide presentation summarizing the highlights of the guide.

Hoover, J. M. (1973). "Surface improvements and dust palliation of unpaved secondary roads and streets." Iowa Highway Research Board Project HR-151, Engineering Research Institute, Iowa State University, Ames, Iowa.

The report contains five parts:

(I) Project Summary by Hoover, J. M. - As of December 31, 1970 there were 57,270 miles of Local Secondary roads and 32,958 miles of Farm to Market roads in the Iowa secondary road system. The Local Secondary system carried a traffic load of 2,714,180 daily vehicle miles, accounting for 32% of all traffic in secondary system. For all Local Secondary roads having some form of surfacing, 98% were surfaced with gravel or crushed stone. During the 1970 construction year, 335 miles of surfaced roads were constructed in the Local Secondary system with 78% being surfaced with gravel or crushed stone. The total maintenance expenditure for all secondary roads in Iowa during 1970 amounted to $40,086,091. Of this, 42%, or $17,020,332, was spent for aggregate replacement on existing gravel or crushed stone roads with an additional 31% ($12,604,456) being spent on maintenance other than resurfacing. This amounts to 73% of the total maintenance budget and are the largest two maintenance expenditure items out of a list of 10 ranging from bridges to drainage assessments. The next largest item was 7%, for maintenance of existing flexible bases. Present costs of high-type flexible or rigid pavements range from $40,000 per mile up. Because of high cost, budget limitations, and low mileage of high traffic volume on Local Secondary roads, most Iowa counties are severely restricted as to the number of miles of roads that may be paved each year. Present design and construction standards provide adequate means for improvement of grade and cross section of secondary roads followed by: (a) immediate road metal surfacing, or (b) eventual high-type surfacing. There are, at present, no formal provisions for an intermediate type surfacing between these two extremes. Therefore, nearly all Iowa counties are in a situation in which they have only a few miles of high-type pavements with the bulk being surfaced with gravel or crushed stone. From the maintenance expenditures for 1970, it can be seen that the primary method of maintaining aggregate surfaced secondary roads remains, as it has in the past, as aggregate replacement. Roads continue to rut, washboard, ravel, pothole, and become the source for billowing clouds of dust. Loose aggregate makes driving hazardous, and results in cases of vehicle damage including cracked windshields, chipped paint, and dents, as well as increased fatalities. During the spring thaw and subsequent rains, many roads become extremely soft, slippery, and heavily rutted. As aggregate supplies decrease, inferior quality soft limestones and gravels are being used, resulting in faster degradation contributing to the dusting problem. Dust creates a safety hazard to both passing and oncoming traffic. It is also a definite household nuisance in rural areas, especially in heavily populated regions surrounding larger towns and cities where traffic on unpaved roads may range as high as 500 vehicles per day. The severity of these problems continues to increase as: (a) traffic volume increases, (b) more people move to rural areas surrounding larger towns and cities, and (c) the current concern over air pollution increases. The Iowa Air Pollution Control Commission has drafted guidelines with respect to "fugitive" dust, which ultimately will affect all unpaved state, county, and city roads and streets. Besides the above problems, most counties are faced with (a) rising costs of high-type pavement, (b) rising costs of maintenance, and (c) rising costs of replacement aggregates. The foregoing considerations dictated the need for finding a means to provide for low-cost surface improvement and dust control, using existing in-place materials, for immediate (and intermediate) use as a treated surface course on unpaved secondary roads - the objective of this research project. Three concurrent phases of study were included in the project: (1) laboratory screenings studies of various additives thought to have potential for long-lasting dust palliation, soil additive strength, durability, and additive retention potential; (2) test road construction using those additives that indicated promise for performance-serviceability usage; and (3) observations and tests of constructed sections for evaluation of the additive's contribution to performance and serviceability as well as the relationship to initial costs.

(II) Asphaltic products and elastometers as dust palliatives and surface improvement agents for unpaved secondary roads, by Bergeson, K. H. and Hoover, J. M.: Bituminous materials have long been used, with varying degrees of success, as soil stabilizers and waterproofing agents. With advancing technological developments many new asphaltic products, whose properties have been altered and supposedly enhanced by the addition of chemicals and selected emulsifying agents, are being marketed. Elastomers, which contain rubber in a modified form, have also been introduced. The beneficial effects of these products, as soil stabilizers and dust palliatives, can only be determined by laboratory evaluation and field trials. This investigation was conducted essentially as a three phase project consisting of (a) laboratory screenings of various asphaltic products and elastomers to evaluate their effectiveness as soil stabilizers and dust palliatives, (b) construction of a test road, based on the results of the laboratory screening phase, using those additives that appeared to be the most effective and economical, and (c) observation and tests of the various sections of the test road for evaluation of the additives' performance and serviceability with respect to dust palliation and surface improvement. The primary purpose of this study is to present the results of each of the above phases. The test road was constructed in September 1971 and had been in service only one year and three months at the time of termination of research. Therefore, phase 3 analyses are somewhat limited due to the period of time covered.

(III) Ammonium lignosulfonates as dust palliatives and surface improvement agents for unpaved secondary roads, by Fox, D. E., and Hoover, J. M.: At the time the research project was initiated in mid-1970, county engineer offices in Iowa were requested to propose locations for test roads within their respective counties. It was explained that all men, material, and equipment would be furnished by the individual counties. Laboratory screenings of additives and field testing of experimental roads would be carried out by the researchers, who would also be present to observe construction and provide technical assistance when and where needed. Four counties responded with interest in lignosulfonate stabilization. Lignosulfonates are available in almost unlimited quantities from paper mills. Ten years ago, lignosulfonates cost 6 cents per gallon at the mill and the price has not increased, although production has. Due to different pulping processes, the cation associated with lignosulfonate varies. Sodium, calcium, and ammonium lignosulfonates have all been used in soil stabilization and prices are similar. The study reported here utilized commercially-available lignosulfonate with ammonium as the associated cation. The following paragraphs explain the participation offered for lignosulfonate research by the corresponding county. The county engineer's office of Clinton County, Iowa made available a section of road 2620 ft long to which crushed limestone had been added at a rate of 2000 tons per mile. This length was naturally divided into three approximately equal sections, a flat upland location, a curve on a hill of about 6% grade, and a level bottomland section on a backwater area of the Mississippi River. The road was located between, and connected with, paved roads terminating at the Clinton and Camanche city limits. Two nearby industries contributed to a 1967 ADT (average daily traffic) of 500 vehicles per day, and maintenance was a problem. The researchers were invited to perform field tests on several roads within Floyd County, both prior to and following treatment with lignosulfonate. Construction was done by county personnel under the supervision of the lignosulfonate supplier. A dirt road near Marion, Linn County, was made available by the county engineer for research. Of 6000 ft length, the 1968 traffic survey showed an ADT of 44 vehicles. Prior to treatment, the grade was built up and improved by the ditch clean-out method typical of much secondary road construction. Using lignosulfonate from a local source, stabilization of nearly 150 miles of roads was begun in Lee County in the late 1950s and early 1960s. Treatment consisted of only light surface blading and occasional application of aggregate coupled with a lignosulfonate surface spray application. Over the years, an in-depth treatment was produced. Extensive cost and maintenance records on treated roads were kept and made available to the researchers.

(IV) Soil-chemical additives as surface improvement agents for unpaved roads, by Denny, C. K., and Hoover, J. M.: The use of polyester and plastic resins as soil stabilizers is relatively new and untried. The objective of this research was to investigate the capabilities of these resins and several other chemicals and commercial dust palliatives as potential low-cost dust palliatives and surface improvement agents. The investigation was conducted entirely in the laboratory but care was taken to approximate field conditions as accurately as possible. Various soil-chemical additives were evaluated on the basis of the following tests: (1) unconfined compressive strength, (2) durability and erosibility, (3) trafficability, (4) resistance to freezing and thawing, and (5) moisture retention and density. Some of the tests were standard while others were specifically modified, but in every case the treated specimens were compared with untreated control specimens.

(V) Appendix: Mineralogical analyses of dust samples, by Handy, R. L.: This part contains results of differential thermal-thermogravimetric analysis and petrographic analysis. Thermogravimetric analysis offers a rapid, accurate method for the measurement of carbonates and organic matter in 50 mg dust samples, and gives a reliable semi-quantitative indication of the amount of clay minerals. Analysis by petrographic microscope is less accurate but requires less sample, and therefore is a valuable supplemental technique for very small samples. Dust analyses show conclusively that selective sorting is operative, calcium carbonate dominating in dust samples collected near the road, and gradually decreasing to near zero several hundred feet away from the road. Simultaneously, the contents of clay and organic matter increase with distance from the road. The efficiency of the sorting indicates that it is size-selective rather than specific gravity-selective (i.e., carbonate contents are higher close to the road because the grains are larger and settle faster). Lignin treatment will drastically reduce the carbonate percentage in road dust, by more than a factor of 10, provided the added rock amount does not exceed 1000 T/mile. The total amount of dust is less drastically reduced, and the amount roughly coincides with the amounts of noncarbonate components in dusts from untreated roads. This suggests that lignin and clay build up a protective patina at the road surface, by migration upward due to evaporation. This patina protects the limestone and is worn off by traffic; however, it should renew so long as sufficient lignin remains in the road. (Alternatively, it probably can be renewed by surface treatments.) The existence of such a coating, while greatly reducing the limestone aggregate loss from the dry road, also may contribute some slipperiness on a wet road, and probably acts to reduce bonding between the road metal and a bituminous overlay. Rock added in excess of about

1000 T/mile is not effectively protected by a 1% lignin treatment, or lignin plus lime. In addition, at the higher rock application levels, added Ca(OH)* lime tends to further reduce the protective effect on carbonates, probably by flocculating the clay and reducing migration and development of a film.

Hoover, J. M., Pitt, J. M., Handfelt, L. D., and Stanley, R. L. (1981a). "Performance of soil-aggregate-fabric systems in frost-susceptible roads, Linn County, Iowa." Transportation Research Record: Journal of the Transportation Research Board, 827, 6-14.

Geotechnical construction fabric applied in soil-aggregate and granular-surfaced low-volume roadways indicate that fabric systems can, under certain circumstances, reduce thaw-induced deformations and improve field performance. Eleven test sections that involved different soil-aggregate-fabric systems were constructed on subgrades that displayed varying degrees of frost-related performance. Field evaluations were conducted over three cycles of spring thaw plus summer healing. Laboratory simulation of freeze-thaw action along with strength and deformation parameters obtained through the Iowa K-test were used on a fabric-reinforced, frost-susceptible soil to provide insight into soil fabric mechanisms and the potential for predicting field performance. Variation in the constructed soil-aggregate-fabric systems was achieved by locating fabric at different positions relative to layers of soil-aggregate or existing roadway materials, a choked macadam base course, and a thick granular backfill. Improvement was most noticeable where fabric was used as a reinforcement between a soil-aggregate surface and a frost-prone subgrade. Fabric used in conjunction with granular backfill, macadam base, and non-frost-susceptible subgrade did not appear justifiable.

Hoover, J. M., Pitt, J. M., Lusting, M. T., and Fox, D. E. (1981b). "Mission-oriented dust control and surface improvement processes for unpaved roads." Iowa DOT Project HR-194, Engineering Research Institute, Iowa State University, Ames, Iowa.

The study documented herein was implemented as a mission-oriented project designed to quantify and evaluate dust control and surface improvement processes for unpaved roads. In order to accomplish this mission, three levels of processing and treatment were established for comparison with untreated soil aggregate-surfaced roads utilizing only the existing in-place roadway materials: Category 1, surface applied dust palliation; Category 2, mixed-in-place dust palliation and surface improvement, without additional surfacing; and Category 3, mixed-in-place base stabilization with seal coat surfacing. Demonstration sections were developed in several representative geographic/geologic regions of the state including Plymouth, Pottawattamie, Story, Franklin, and Marion counties. Samples from these, as well as other possible sites, were subjected to laboratory tests including unconfined compression, freeze-thaw durability, Iowa K-Test, and trafficability testing, in both the untreated and treated conditions, as well as under varying forms of curing. The purpose of the laboratory testing was for evaluation of the subject material for potential use in one or more of the three categories of dust control and/or surface improvement processing. Field studies were initiated in each potential demonstration site for measurement of dust fall within, as well as to the exterior of the ROW. Such measurements were continued following Category 1 applications of selected palliation treatments. In-situ pre- and post-construction tests were conducted within each Category 3 demonstration section, including periodic plate-bearing, Benkelman beam, and moisture-density tests. During Category 3 construction, assistance was provided each county in construction coordination and moisture-density control. Specimens were field molded from each Category 3 mix prior to field compaction and returned to the laboratory for periodic testing of moisture-density and K-Test parameters. Dust fall testing included both quantity and particle-size distribution versus distance from roadway centerline. Through regression analyses of dust fall data, predictions were developed for quantity of dust at the ROW, as well as distance from roadway centerline at which ambient levels of dusting might be anticipated. Through such analyses, two potential control criteria for dust fall were developed. Based on comparison of pre- and post-Category 1 treatment applications, dust reduction effectiveness of several palliatives was evaluated. Such evaluations were coupled with estimated costs of each treatment as an approach to respective cost-benefits. Based on comparison of laboratory tests, pre- and post-construction in-situ tests, and visual examinations, each Category 3 stabilized base demonstration section was evaluated for structural integrity. The following generalized conclusions are thus founded on the various tests, investigations, and analyses presented within this report: (1) Unconfined compression tests of 2-in. by 2-in. cylindrical specimens can provide an initial method of trial mix suitability of various products for possible use as dust palliatives and/or surface improvement agents. Such trial mix testing should be followed by more refined testing on selected mixes. (2) Stability of various product and soil mixtures can be evaluated with freeze-thaw durability, trafficability, and the Iowa K-Test. Freeze-thaw elongation provides an indication of climatic stability as well as susceptibility to capillary moisture increases and heave potential. Trafficability tests provide a quantitative measure of waterproofing and resistance to an adverse traffic loading and environmental condition. The Iowa K-Test provides a quick measure of the undrained shear parameters: cohesion and angle of internal friction. In addition, the K-Test provides a qualitative measure of rutting potential of a mixture through the lateral stress ratio K and a measure of stress-strain relations through the vertical deformation modulus Ev. (3) Of the products evaluated through the various laboratory tests, only the combined Portland cement and fly ash appeared effective as a Category 3 stabilization process with most soil-aggregate classifications, though optimum quantities of the two products varied with each material. Variation of CSS asphalt emulsion zeta potential exhibited pronounced effects on mixture compatibility and required asphalt content, regardless of consideration of categorical usage. In a similar manner, the laboratory tests indicated categorical usage of ammonium lignosulfonate, Coherex, Polybind Acrylic DLR 81-03, and Amsco Res AB 1881 varied from negative to potentially effective depending on soil-aggregate type. (4) All demonstration sections, regardless of category level of processing, were constructed with conventional equipment. (5) Utilizing the measurement and analytical techniques described in this study, two recommendations of minimal roadway dust fall criteria were subjectively quantified. First, an ambient level should be achieved within a distance of 100 to 150 ft or less of an unpaved roadway centerline. Second, a quantity of 15 lbs/acre/day/100 vehicles, or less, should be achieved at the ROW. Such criteria should be considered as a reasonable starting point, with possible refinement with time. (6) Effective dust abatement as well as structural improvement may be obtained through Category 3 construction processing of an unpaved road using cement and fly ash or emulsified asphalt. (7) Only limited Category 1 dust palliation and cost effectiveness were obtained with Amsco Res AB 1881, Polybind Acrylic DLR 81-03, and cationic asphalt emulsion. Coherex appeared very effective as a dust palliative so long as it was not used with an absorptive aggregate. However, the cost of Coherex would limit its usage in Iowa. Calcium chloride and ammonium lignosulfonate appeared comparatively cost-effective as dust palliatives. Effectiveness of both the chloride and lignosulfonates might be enhanced if incorporated with a soil-aggregate surface using methods and/or specifications cited in preceding sections of this report.

Jobgen, M. C., Callahan, M., Harris, G., and Tymkowicz, S. (1994). "Low cost techniques of base stabilization." Project HR-312, Iowa Department of Transportation, Ames, Iowa.

The IHRB HR-312 research project (Jobgen et al. 1994) evaluated performance of four different stabilization methods for on unsurfaced roads. These stabilization methods included using: a) high float emulsion (HFE-300) to treat top 3 in. of base stone, b) a bio-chemical formula called as BIO CAT 300-1 to treat the base stone for different thicknesses (6 in., 8in., and 10 in.), c) Consolid System method in the top 10 in. of subgrade soil, wherein when the soil is dry a combination of two inverted emulsions are used and when the soil is wet a combination of an inverted emulsion and a lime hydrated base powder are used to treat the base stone, and d) 5 in. of macadam base and 2 in. of choke stone along with fabric under one of the sections. All test sections were sealed using a double seal coat and performance evaluation was conducted on these sections using Iowa Road Rater, Roughometer, and visual inspection annually from 1989 to 1992. Some key findings from the field testing were as follows: (a) Test sections stabilized with BIO CAT300-1 and Consolid system showed the highest average k-value (207 pci to 225+ pci) four years after construction. HFE-300 stabilized section showed an average k-value of 181 pci, macadam subbase section showed an average k-value of 172 pci, and macadam subbase with fabric section showed an average k-value of 116 pci, four years after construction. (b) Although the BIO CAT 300-1 and Consolid System stabilized sections showed high k-values, they showed poor performance with alligator cracking and rutting under traffic, and continued deterioration every year. It is speculated in the report that these failures could have been due to freeze-thaw cycles in the stabilized layers. (c) HFE-300 treated test sections showed some deterioration with alligator cracking. Macadam subbase test sections (with and without fabric) experienced minor rutting and showed the best overall performance than all other sections. The use of fabric did not show noticeable improvement. (d) Use of macadam base and HFE-300 treatment showed cost effectiveness than other treatment options evaluated in this study.

Kendall, M., Baker, B., Evans, P., and Ramanujan, J. "Foamed Bitumen Stabilization - The Queensland Experience." Proc., 20th Australian Road Research Board (ARRB) Conference, Sydney, Australia.

This paper addresses: (a) the basics of foamed bitumen stabilization, (b) situations where foamed bitumen stabilization could be considered, (c) the design method used by the Queensland Department of Main Roads, (d) lessons learnt from the $2.5M, 17.6 km New England Highway Project, (e) what to look for when carrying out foamed bitumen stabilsation, and (f) the future of foamed bitumen stabilisation within the Queensland Department of Main Roads.

Kestler, M. A. (2009). "Stabilization selection guide for aggregate and native-surfaced low-volume roads." National Technology and Development Program, Forest Service, U.S. Department of Agriculture, Washington, D.C.

The purpose of this guide is to facilitate the selection of modification/stabilization agents and techniques for aggregate surfaced and native/unsurfaced LVRs. The objective is to provide low-cost alternatives that reduce aggregate wear and loss, reduce road-surface maintenance (i.e., blading out ruts), and reduce the time period between major rehabilitation (i.e., between adding new aggregate and the total reconditioning of the road pavement). This guide provides

information on available stabilizing agents, appropriate conditions for use, selection procedures, quantity determination, and contact information for manufacturers/suppliers. Emphasis is on the modification/stabilization of existing in-place road surface materials, but many of the methods can be used in the construction of new roads. Construction procedures for application are also presented. The intended audience includes road managers, engineers, and technicians involved in road maintenance, construction, and reconstruction. Those involved in trail maintenance and construction also may find the guide beneficial, as stabilizers used on trails, particularly accessible trails, help provide a smooth, durable surface.

Less, R. A., and Paulson, C. K. (1977). "Experimental macadam stone base - Des Moines County." Project HR-175, Iowa Department of Transportation, Ames, Iowa.

The IHRB HR-175 research project evaluated the feasibility and economics of using macadam subbase material (with different thicknesses) with choke stone under PCC and asphalt pavements. The macadam subbase material used on this project had a typical gradation with 4 in. maximum particle size and 12 to 26% passing the 1 in. sieve. The choke stone had a typical gradation with 1 in. maximum particle size and 6 to 12% passing the No. 200 sieve. The study indicated that the macadam subbase performed well under both PCC and asphalt pavements, but the cost was relatively more. During construction, the finished macadam subbase showed a uniform structure with negligible amount of degradation during compaction. Production rates on placement of the macadam subbase material varied from about 2900 to 5000 tons per day. Lateral subdrain trenches backfilled with porous backfill was used on this project for drainage. This system performed well and minimized effects of frost boils, spring thaw, and other subsurface drainage issues.

Litzka, J., and Haslehner, W. "Cold In-Place Recycling on Low-Volume Roads in Austria." Proc., Sixth International Conference on Low-Volume Roads, Minneapolis, Minnesota.

Modern methods for road maintenance should involve used construction materials, take account of environmental compatibility, and eliminate road damage economically and durably. Regarding these basic requirements, attention should be paid to cold in-place recycling of damaged asphalt layers using cement stabilization. Within the last few years, cold in-place recycling has become an appropriate alternative for the rehabilitation of low-volume roads in Austria. In the course of documentation carried out at the Institute for Traffic and Transportation Engineering of the Vienna University of Bodenkultur, the individual steps of construction were analyzed. The advantage of the described procedure is that none of the old pavement need be hauled to a special repository. An innovative method for cold in-place recycling on low-volume roads using cement stabilization is described. The first step of this method contains a detailed analysis of the section to be restored, including bearing capacity measurements and the determination of the grading curves of existing unbound layers. Grading curves are also determined for the existing asphalt layer after trial milling in order to consider refinement by milling. This analysis forms the basis for adding material before milling in order to achieve a well-graded aggregate. On the construction site, the necessary additional aggregate is spread over the existing pavement. In the next step, the cement binder is distributed on the road surface. A soil stabilizer breaks up the existing road structure and mixes it thoroughly with the aggregates and

Monlux, S. (2003). "Stabilizing Unpaved Roads with Calcium Chloride." Transportation Research Record: Journal of the Transportation Research Board, 1819, 52-56.

The U.S. Department of Agriculture Forest Service has stabilized unpaved road surfacing materials with relatively high concentrations of calcium chloride salt. The percentage of calcium chloride is higher than that traditionally used for dust abatement or aggregate base stabilization. Up to 2% pure salt by weight of aggregate was mixed into the top 2 in. (50 mm) of both aggregate and native road surfaces. The results were monitored for 2 to 4 years. The stabilized road surfaces resisted raveling and washboarding for several seasons and significantly reduced road blading and aggregate loss. As a result, calcium chloride stabilization may be a cost-effective treatment for roads with daily traffic volumes less than 200. Other benefits include reduced surface erosion and sedimentation; improved safety from reduced dust, raveling, and washboarding; and less frost penetration. Encouraged by these results, the Forest Service is conducting additional evaluations to determine the cost-effectiveness of surface stabilization with both magnesium chloride and calcium chloride in different environments and with different aggregate materials.

Monlux, S., and Mitchell, M. (2007). "Chloride Stabilization of Unpaved Road Aggregate Surfacing." Transportation Research Record: Journal of the Transportation Research Board, 1989(2), 50-58.

There are few alternatives for improving long-term performance of aggregate surfacing materials in dry climates other than annual dust abatement treatments. In-place stabilization of properly graded aggregate with chloride additives is cost-effective and provides performance and intangible benefits. Similar results are achieved by mixing additives with aggregate during crushing. This 2-year study identifies conditions in which chloride-stabilized roads have a projected life of 10 years or more if properly maintained. The greatest benefits are realized in projects with high aggregate surfacing replacement costs and average daily traffic volumes that exceed 100. Stabilization provides a higher standard of road surface performance by improving ride quality and reducing dust, corrugations (washboarding), and raveling (loose aggregate). Other intangible benefits include reduced sedimentation in streams, reduced aggregate resource depletion, reduced health hazards from dust, and increased road-user safety. This project developed guidelines for chloride stabilization of various aggregate surfacing materials in semiarid to arid environments. Performance and cost-effectiveness of chloride stabilization were measured on 12 projects and monitored for two seasons in four western states; monitoring included construction and maintenance costs, road surface deterioration, traffic, weather conditions, environmental effects, and materials testing. Treated surfaces needed blading after 25,500 vehicles, whereas untreated surfaces needed blading after only 3,200 vehicles. Environmental effects on trees, streams, and roadside soils were insignificant. Many tools were developed to assist in the proper implementation of chloride stabilization of road surface aggregates.

Morgan, R. J., Schaefer, V. R., and Sharma, R. S. (2005). "Determination and Evaluation of Alternative Methods for Managing and Controlling Highway-Related Dust Phase II—Demonstration Project." IHRB Project TR-506, Department of Civil, Construction and Environmental Engineering, Iowa State University, Ames, Iowa.

The State of Iowa currently has approximately 69,000 miles of unpaved secondary roads. Due to the low traffic count on these unpaved roads, paving with asphalt or Portland cement

concrete is not economical. Therefore to reduce dust production, the use of dust suppressants has been utilized for decades. This study was conducted to evaluate the effectiveness of several widely used dust suppressants through quantitative field testing on two of Iowa's most widely used secondary road surface treatments: crushed limestone rock and alluvial sand/gravel. These commercially available dust suppressants included: lignin sulfonate, calcium chloride, and soybean oil soapstock. These suppressants were applied to 1000 ft test sections on four unpaved roads in Story County, Iowa. Duplicate field conditions, the suppressants were applied as a surface spray once in early June and again in late August or early September. The four unpaved roads included two with crushed limestone rock and two with alluvial sand/gravel surface treatment well as high and low traffic counts. The effectiveness of the dust suppressants was evaluated by comparing the dust produced on treated and untreated test sections. Dust collection was scheduled for 1, 2, 4, 6, and 8 weeks after each application, for a total test period of 16 weeks. Results of a cost analysis between annual dust suppressant application and biennial aggregate replacement indicated that the cost of the dust suppressant, its transportation, and application were relatively high when compared to that of aggregate types. Therefore, the biennial aggregate replacement is considered more economical than annual dust suppressant application, although the application of annual dust suppressant reduced the cost of road maintenance by 75 %. Results of the collection indicated that the lignin sulfonate suppressant outperformed calcium chloride and soybean oil soapstock on all four unpaved roads, the effect of the suppressants on the alluvial sand/gravel surface treatment was less than that on the crushed limestone rock, the residual effects of all the products seem reasonably well after blading, and the combination of alluvial sand/gravel surface treatment an high traffic count caused dust reduction to decrease dramatically.

Powell, W., Keller, G. R., and Brunette, B. (1999). "Applications for geosynthetics on forest service low-volume roads." Transportation Research Record: Journal of the Transportation Research Board, 1999, 113-120.

Today's geosynthetic products have many useful, creative, and cost-effective applications for rural, low-volume roads. In the management of almost a half-million km (quarter-million mi) of low-volume roads, the U.S. Department of Agriculture, Forest Service (USFS), has developed and adopted many uses for geosynthetics. An overview is presented of many of those uses and their advantages. The USFS gained much of its experience and practice with geosynthetics while constructing a wide variety of Mechanically Stabilized Earth (MSE) retaining walls, including geotextile, timber, modular-block, and tire-faced structures, and reinforced soil slopes. More recently, the USFS has used geosynthetics for MSE bridge abutments and Deep Patch road-shoulder reinforcement. Other typical geosynthetic applications include filtration, drainage, subgrade reinforcement, and erosion control.

Shoop, S., Kester, M., Stark, J., Ryerson, C., and Affleck, R. (2003). "Rapid stabilization of thawing soils: field experience and application." Journal of Terramechanics, 39, 181-194.

Thawing soils can severely restrict vehicle travel on unpaved surfaces. However, a variety of materials and construction techniques can be used to stabilize thawing soils to reduce immobilization problems. The US Engineer Research and Development Center's Army Cold Regions Research and Engineering Laboratory (CRREL) and the Wisconsin National Guard evaluated several stabilization techniques in a field demonstration project during spring thaw at Fort McCoy, Wisconsin, in 1995. Additional tests on chemical stabilizing techniques were

conducted at CRREL's Frost Effects Research Facility. The results of these test programs were reduced to a decision matrix for stabilizing thawing ground, and used during the deployment of US troops in Bosnia during January and February of 1996. The soil frost and moisture conditions expected during this time frame were predicted using MIDFROCAL (MIDwest FROst CALculator). This paper is an overview of the stabilization techniques evaluated and their recommended application based on the expected soil frost conditions and traffic requirements. Although the experiments were performed with military vehicles in mind, the techniques are suitable for many civilian applications such as forestry, construction, mining, and oil exploration.

Life Cycle Costs

Aho, S., and Saarenketo, T. (2006). "Design and repair of roads suffering spring thaw weakening." The Swedish Road Administration, Northern Region, Sweden.

The ROADEX Project is a technical cooperation between roads organizations across northern Europe that aims to share roads related information and research between the partners. The Project was started in 1998 as a 3 year pilot co-operation between the roads districts of Finnish Lapland, Troms County of Norway, the Northern Region of Sweden and The Highland Council of Scotland and this was later followed up with a second project, ROADEX II, from 2002 to 2005. The partners in the ROADEX II Project comprised public road administrations, forestry organizations, forest companies and haulage organizations from regions in the Northern Periphery. These were The Highland Council, Forest Enterprise & The Western Isles Council from Scotland. The Region Nord of The Norwegian Public Roads Administration and The Norwegian Road Haulage Association, The Northern Region of The Swedish Road Administration and The Lappi and Keski-Suomi Regions of The Finnish National Roads Administration. (These latter Finnish Regions also received aid from their local forest industry organizations of Metsähallitus, Lapin Metsäkeskus, Metsäliitto & Stora-Enso.). The goal of the project was to develop ways for interactive and innovative road condition management of low traffic volume roads integrating the needs of local industry, society and roads organizations. 8 formal reports were published together with a project DVD and full copies of all reports are available for download at the ROADEX web site at www.roadex.org. This Executive Summary report is one of 8 summaries that have been prepared under the direction of the ROADEX III project (2006-2007), a new Project where the named project Partners above were joined by the additional Northern Periphery Partners of the Municipality of Sisimiut, Greenland, The Iceland Public Roads Administration and the Finnish Road Administration Region of Savo-Karjala.

Berg, R. R., Christoper, B. R., and Perkins, S. (2000). "Geosynthetic Reinforcement of the Aggregate Base/Subbase Courses of Pavement Structures." Geosynthetic Materials Association, Roseville, MN.

Geosynthetic reinforcement of the base, or subbase, course of pavement structures is addressed. The value added with reinforcement, design criteria/protocols, and practices for design and for material specifications are presented. Base, or subbase, reinforcement is defined within as the use of geosynthetic reinforcement in flexible pavements to support vehicular traffic over the life of a pavement structure. Primary base reinforcement benefits are to improve the service life and/or obtain equivalent performance with a reduced structural section. Substantial life-cycle cost savings are possible with base reinforcement. Cost saving benefits should be quantified using life-cycle analyses, and on an agency specific basis due to the many input

variables. Recommended design procedure and material specifications are presented. It is recommended that specification with an approved products list be utilized, as the mechanisms of reinforcement are not fully understood and the geosynthetic performance should be considered product, and test conditions, specific. Equivalent materials must demonstrate equivalent performance in test structures and/or possess equivalent material properties, as defined by the specifier. The use of geosynthetic reinforcement to aid in construction over low strength subgrades, termed subgrade restraint within, is also addressed. Geosynthetic reinforcement is used to increase the support equipment during construction of a roadway. Subgrade restraint design procedures are based upon either (i) generic material properties, wherein a generic specification can be prepared based upon those design property requirements; or (ii) product-specific, empirically derived design methods, wherein an approved products list specification approach may be used. Geogrid, geotextile, and geogrid-geotextile composite materials are addressed within. This paper provides government agencies with current, logical recommended practice for the systematic use of geosynthetic reinforcement of pavement base courses. Refined guidance should be developed as the use of base reinforcement increases and additional long-term performance data becomes available.

Bushman, W. H., Freeman, T. E., and Hoppe, E. J. (2005). "Stabilization techniques for unpaved roads." Transportation Research Record: Journal of the Transportation Research Board, 1936, 26-33.

An amendment to Virginia House Bill 1400, Item 490, No. 1h, calls for the Virginia Transportation Research Council to “continue its evaluation of soil stabilizers as an alternative to paving low-volume secondary roads.” In response, promising soil stabilization products were evaluated with the relatively new technique of deeply mixing chemical additives into unpaved roadbeds. This work is based on the construction of a 1.75-m-long trial installation on Old Wheatland Road in Loudoun County, where seven commercially available stabilization products were applied to the unpaved road. A rigorous evaluation of treatment performance will provide the basis for recommendations to the Virginia Department of Transportation’s operating divisions regarding improvements to the maintenance practices for gravel roads. Results thus far indicate that the introduction of soil stabilizers through deep mixing is a promising technique. The life-cycle cost analysis indicates that constructing a standard bituminous surface-treated roadway and maintaining it as such is much more cost-effective than using any of the products in this trial. Further, the analysis indicates that using the bituminous surface treatment alternative is also much more cost-effective than maintaining an unpaved road.

Henry, K. S., Olson, J. P., Farrington, S. P., and Lens, J. (2005). "Improved performance of unpaved roads during spring thaw." ERDC/CRREL TR-05-01, Engineer Research and Development Center Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Unpaved roads in Vermont are subject to deterioration from seasonal freezing and thawing, and many towns have roads that suffer chronic serviceability problems during the so-called “spring thaw,” or mud season. Several techniques thought to mitigate deterioration of unpaved roads during spring thaw were constructed on test sections of unpaved roads in two towns. Each potential remedy was aimed at providing some combination of limiting the availability of moisture in the winter, improving drainage during spring, and strengthening the upper portion of the road. Each technique used local and/or commercially available materials,

and all were easy to construct, i.e., a town road crew could build them. For two spring thaw seasons, we compared strength estimates based on dynamic cone penetrometer tests and the percentage of the road surface rutted for treated and control sections. Methods that permanently improved the strength of the top 12 inches of the road or decreased the water content of the upper 12 inches of the road resulted in significant performance improvement during spring thaw. Cement and cellular confinement systems worked well by improving the strength of the upper layers of the soil. Two new techniques— geowrap, comprising clean sand sandwiched by geotextile separators placed 12–18 inches deep, and the patented Geosynthetic Capillary Barrier Drain—provided benefit by keeping the upper layers of the soil relatively dry. Geogrid and geotextile separators placed 12 inch deep and trench drains parallel to the road provided no observable benefit.

Hicks, R. G. (2002). "Alaska soil stabilization design guide." FHWA-AK-RD-01-6B, State of Alaska Department of Transportation and Public Facilities, Fairbanks, Alaska.

This guide presents information on the types of soil stabilization techniques that have or can be used in the state of Alaska. It covers techniques including asphalt, cement, lime, mechanical, chemical, and other methods. For each method there is a discussion on materials and design considerations, construction issues, and expected performance and costs. The appendices include a glossary of terms, a reading list on prior stabilization used in Alaska, a discussion on the soils in Alaska, and a slide presentation summarizing the highlights of the guide.

Hyvonen, L., Vuorimies, N., and Kolisoja, P. (2012a). "Road 16589 Saalahti - Mode 2 rutting site on a soft subgrade." The ROADEX “Implementing Accessibility” Project, The Swedish Transport Administration, Northern Region, Sweden.

Rutting of the road surface due to the development of permanent deformations, both in the road structure itself and in the underlying subgrade, is in most cases the dominant distress mechanism on low volume roads of the Northern Periphery area. From a road users’ point of view rutting both lowers driving comfort and reduces traffic safety. This is particularly the case when surface water is trapped in ruts, thereby increasing the risk of aquaplaning in summertime and of icing in the wheel path in winter when temperatures fall below 0°C. In addition, rutting can also be very harmful to the structural condition of the road, as it speeds up water infiltration into the road structure, increasing the effects of dynamic wheel loads etc. Rutting can develop in a road for a number of reasons. It may develop in the structural layers due to poor quality material, or as a result of poor drainage making the material more susceptible to permanent deformations. It may also develop in a weak subgrade material if the overall thickness of the structural layers is low. This is a very typical situation on the low volume roads of the Northern Periphery area, particularly during the spring thaw where the subgrade material is frost susceptible. Rutting mechanisms are discussed in greater detail in the ROADEX reports available at www.roadex.org, together with a new method of classifying rutting modes. This report describes a ROADEX demonstration exercise carried out on a low volume road section of Road 16589 Saalahti in Jämsä, Central Finland. A geogrid reinforcement was used in the demonstration to retard the development of permanent deformations of a gravel road section located on a silty subgrade. The demonstration section had been suffering from deformations primarily taking place in the subgrade material that had become very soft during the spring thaw of the seasonal frost. This had also resulted in severe widening of the road cross-section and almost total clogging of the side ditches. According to the GPR profiles the total thickness of the structural layers was much higher in the middle of the road than towards the edges of the road which was a clear indication of Mode 2 rutting. The reinforced structure consisted of two subsections in addition to which there was a reference section. One subsection was constructed with one layer of geogrid, rather than the standard rehabilitation solution of a geotextile. The second subsection was constructed with two layers of reinforcing geogrid 150 mm apart from each other. The standard rehabilitation structure of a geotextile was used in the reference structure. After one year of service it only can be concluded that both of the test structures and the reference structure have been performing equally well, and that the road is still in very good condition. Further monitoring of the settlement tubes installed in six cross sections of the road will reveal any differences in the development rate of permanent deformations between the test structure and reference structure. According to the life cycle analysis performed, the subsection reinforced with one layer of geogrid needs to last at least one year longer and the subsection reinforced with two layers of geogrid at least three years longer to be cost effective in comparison to the reference structure, if that is assumed to have a service life of 10 years. This is slightly longer than the typical assumption of 8 years life as in this case the reference structure was also about 50 mm thicker than would have been the standard solution.

Hyvonen, L., Vuorimies, N., and Kolisoja, P. (2012b). "Road 16583 Ehikki-Juikslahti - Mode 2 rutting site on peat." The ROADEX “Implementing Accessibility” Project, The Swedish Transport Administration, Northern Region, Sweden.

Rutting of the road surface due to the development of permanent deformations, both in the road structure itself and in the underlying subgrade, is in most cases the dominant distress mechanism on low volume roads of the Northern Periphery area. From a road users’ point of view rutting both lowers driving comfort and reduces traffic safety. This is particularly the case when surface water is trapped in ruts, thereby increasing the risk of aquaplaning in summertime and of icing in the wheel path in winter when temperatures fall below 0°C. In addition, rutting can also be very harmful to the structural condition of the road, as it speeds up water infiltration into the road structure, increasing the effects of dynamic wheel loads etc. Rutting can develop in a road for a number of reasons. It may develop in the structural layers due to poor quality material, or as a result of poor drainage making the material more susceptible to permanent deformations. It may also develop in a weak subgrade material if the overall thickness of the structural layers is low. This is a very typical situation on the low volume roads of the Northern Periphery area, particularly during the spring thaw where the subgrade material is frost susceptible. Rutting mechanisms are discussed in greater detail in the ROADEX reports available at www.roadex.org, together with a new method of classifying rutting modes. This report describes a ROADEX demonstration exercise carried out on a low volume road section of Road 16583 from Ehikki to Juokslahti in Jämsä, Central Finland. The section was located on a peat subgrade and was reinforced with a geogrid. The road had been deforming and widening significantly over the section mainly due to clogged side ditches, a low outlet ditch, and settlement of the road structure into the peat subgrade. As it was very difficult in practice to improve the operation of the outlet ditch, it was decided to reduce the further development of permanent deformations on the road by the addition of a new base course layer reinforced with a geogrid. As a reference structure, half of the test section was built with the addition of a new base course layer underlain by a geotextile, which could be considered as a standard solution in this type of problem site. After the first year of service, it only can be concluded that both the test structure and the reference structure have been performing equally well, and that the road is still

in very good condition. Further monitoring of the settlement tubes installed in four cross sections of the road will reveal any differences in the development rate of permanent deformations between the test structure and the reference structure. According to the life cycle analysis performed, the section reinforced with geogrid needs to last at least 1.5 years longer to be cost effective in comparison to the reference structure, assuming that the reference structure will have a typical service life of 8 years. This had also resulted in severe widening of the road cross-section and almost total clogging of the side ditches. According to the GPR profiles the total thickness of the structural layers was much higher in the middle of the road than towards the edges of the road which was a clear indication of Mode 2 rutting. The reinforced structure consisted of two subsections in addition to which there was a reference section. One subsection was constructed with one layer of geogrid, rather than the standard rehabilitation solution of a geotextile. The second subsection was constructed with two layers of reinforcing geogrid 150 mm apart from each other. The standard rehabilitation structure of a geotextile was used in the reference structure. After one year of service it only can be concluded that both of the test structures and the reference structure have been performing equally well, and that the road is still in very good condition. Further monitoring of the settlement tubes installed in six cross sections of the road will reveal any differences in the development rate of permanent deformations between the test structure and reference structure. According to the life cycle analysis performed, the subsection reinforced with one layer of geogrid needs to last at least one year longer and the subsection reinforced with two layers of geogrid at least three years longer to be cost effective in comparison to the reference structure, if that is assumed to have a service life of 10 years. This is slightly longer than the typical assumption of 8 years life as in this case the reference structure was also about 50 mm thicker than would have been the standard solution.

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intangible benefits. Similar results are achieved by mixing additives with aggregate during crushing. This 2-year study identifies conditions in which chloride-stabilized roads have a projected life of 10 years or more if properly maintained. The greatest benefits are realized in projects with high aggregate surfacing replacement costs and average daily traffic volumes that exceed 100. Stabilization provides a higher standard of road surface performance by improving ride quality and reducing dust, corrugations (washboarding), and raveling (loose aggregate). Other intangible benefits include reduced sedimentation in streams, reduced aggregate resource depletion, reduced health hazards from dust, and increased road-user safety. This project developed guidelines for chloride stabilization of various aggregate surfacing materials in semiarid to arid environments. Performance and cost-effectiveness of chloride stabilization were measured on 12 projects and monitored for two seasons in four western states; monitoring included construction and maintenance costs, road surface deterioration, traffic, weather conditions, environmental effects, and materials testing. Treated surfaces needed blading after 25,500 vehicles, whereas untreated surfaces needed blading after only 3,200 vehicles. Environmental effects on trees, streams, and roadside soils were insignificant. Many tools were developed to assist in the proper implementation of chloride stabilization of road surface aggregates.

Pratico, F., Saride, S., and Puppala, A. J. (2011). "Comprehensive Life-Cycle Cost Analysis for Selection of Stabilization Alternatives for Better Performance of Low-Volume Roads." Transportation Research Record: Journal of the Transportation Research Board, 2204, 120-129.

Low-volume roads (LVRs), such as rural, farm-to-market, and less-used local and city roads, are an important part of the world's transportation infrastructure. LVRs have been credited as a direct cause of the socioeconomic development of rural communities. It has been estimated that 60% of the road network in the United States is made up of low-volume roads. The construction, maintenance, and rehabilitation of these roads are major tasks that result in about 54% of the total annual expenditure of transportation agencies in the United States. Better design and construction methods will lead to lower maintenance and rehabilitation costs of LVRs. Stabilization of weak subgrade soils to support LVRs is a widely accepted method of improving their performance. However, the selection of a stabilization alternative on the basis of cost–benefit analysis is a crucial task for a transportation agency and one that has not been addressed in a systematic manner. In this paper, a new conceptual engineering economics tool–based life-cycle cost analysis (LCCA) is developed to optimize and to select the best stabilizer and the stabilization technique for a given subgrade soil and given traffic conditions. In this analysis, agency, user, and externality costs are addressed. Two case studies are analyzed for European and U.S. road conditions to validate the LCCA model. Results demonstrate that, under specific boundary conditions, soil stabilization can play an important role, merging the environmental and mechanical effectiveness of low-volume roads.

Maintenance Issues

Alzubaidi, H. (1999). "Operation and Maintenance of Gravel Roads - A Literature Study." Swedish National Road and Transport Research Institute, Linkoping, Sweden, 231.

Gravel roads form a large percentage of the road network in Sweden. The public road network under the jurisdiction of the Swedish National Road Administration has a total length of some 98,000 kilometers. About 22,000 km of this network consist of gravel roads. In addition,

there are about 74,000 kilometers of private road and 210,000 kilometers of forest roads. This report describes the present position in the operation and maintenance of gravel roads. It presents a comprehensive literature survey of current and recent national and international research. It deals only with summer maintenance and focuses primarily on roads surfaced with aggregate. The following aspects are covered in the report: 1. Definitions and terms regarding the operation and maintenance of gravel roads. 2. General description of the Swedish road network. 3. Major factors causing deterioration of gravel roads. 4. Technical requirements for Swedish gravel roads. 5. Factors influencing the operation and maintenance of gravel roads. 6. Operation and maintenance methods. 7. Condition assessment of gravel roads. 8. Planning and evaluation of operation and maintenance measures.

Bergeson, K. L., Kane, M. J., and Callen, D. O. (1990). "Crushed stone granular surfacing materials." Sponsored by the Iowa Limestone Produces Association and National Stone Association Research Program, Report by Engineering Research Institute, Iowa State University, Ames, Iowa.

The results of this research project indicate that crushed stone surfacing material graded on the fine side of IDOT Class A surfacing specifications provides lower roughness and better rideability; better braking and handling characteristics; and less dust generation than the coarser gradations. This is believed to be because there is sufficient fines (-#40 to - #200) available to act as a binder for the coarser material, which in turn promotes the formation of tight surface crust. This crust acts to provide a smooth riding surface, reduces dust generation, and improves vehicle braking and handling characteristics.

Bloser, S. M. (2007). "Commonly Used Aggregate Materials and Placement Methods: Comparative Analysis for a Wearing Course on Low-Volume Roads in Pennsylvania." Transportation Research Record: Journal of the Transportation Research Board, 1989, 178-185.

Aggregate-surfaced roads are a viable component of the transportation network; they provide significant increases in road stability over earthen surfaced roads while avoiding the high placement and maintenance costs of pavements. The use of higher-quality, more stable aggregates will significantly reduce both the cost of maintaining gravel roads and the environmental concerns related to road runoff. This paper aims to provide a better understanding of wearing course aggregates by describing a comparative analysis experiment done as part of Pennsylvania's Dirt and Gravel Road Maintenance Program. Three aggregates commonly used in Pennsylvania were placed side by side under two different placement methods for each type of aggregate as part of a 3-year study to compare their long-term durability and cost-effectiveness. The two methods tested were the "dump and spread" method known as tailgating and the application of aggregate by a motor paver. Cross-sectional surveys were done on each aggregate section for 3 years following placement to determine elevation changes in the road surfaces. No significant difference in performance was found between aggregate sections placed with a paver and the same aggregate placed by tailgating. Driving surface aggregate was the only aggregate of the three tested that did not show a statistically significant change in road elevation during the 3-year course of study. Results illustrate the importance of selecting a properly graded aggregate containing minimal clay and soil material for use as surface aggregate on low-volume roads.

Embacher, R. A. (2006). "Duration of Spring-Thaw Recovery for Aggregate-Surfaced Roads." MN/RC-2006-12, Minnesota Department of Transportation, St. Paul, Minnesota.

Low-volume roads constructed in regions susceptible to freezing and thawing periods are often at risk of load-related damage during the spring-thaw period. The reduced support capacity during the thawing period is a result of excess melt water that becomes trapped above the underlying frozen layers. Many agencies place spring load restrictions (SLR) during the thaw period to reduce unnecessary damage to the roadways. The period of SLR set forth by the Minnesota Department of Transportation is effective for all flexible pavements; however, experience suggests that many aggregate-surfaced roads require additional time relative to flexible pavements to recover strength sufficient to carry unrestricted loads. An investigation was performed to improve local agencies' ability to evaluate the duration of SLR on aggregate-surfaced roadways. This was accomplished through seasonal measurements of in situ shear strengths, measured using the dynamic cone penetrometer (DCP), on various Minnesota county routes. In situ strength tests were conducted on selected county gravel roads over the course of three years. Strength levels recorded during the spring-thaw weakened period were compared to fully recovered periods that typically occur in late spring/summer. The results indicate that aggregate-surfaced roads generally require 1 to 3 additional weeks, over that of flexible pavements, to reach recovered bearing capacity. Additionally, a strong correlation was found between duration required to attain given strength recovery values and climatic and grading inputs.

Henry, K. S., Olson, J. P., Farrington, S. P., and Lens, J. (2005). "Improved performance of unpaved roads during spring thaw." ERDC/CRREL TR-05-01, Engineer Research and Development Center Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Unpaved roads in Vermont are subject to deterioration from seasonal freezing and thawing, and many towns have roads that suffer chronic serviceability problems during the so-called "spring thaw," or mud season. Several techniques thought to mitigate deterioration of unpaved roads during spring thaw were constructed on test sections of unpaved roads in two towns. Each potential remedy was aimed at providing some combination of limiting the availability of moisture in the winter, improving drainage during spring, and strengthening the upper portion of the road. Each technique used local and/or commercially available materials, and all were easy to construct, i.e., a town road crew could build them. For two spring thaw seasons, we compared strength estimates based on dynamic cone penetrometer tests and the percentage of the road surface rutted for treated and control sections. Methods that permanently improved the strength of the top 12 inches of the road or decreased the water content of the upper 12 inches of the road resulted in significant performance improvement during spring thaw. Cement and cellular confinement systems worked well by improving the strength of the upper layers of the soil. Two new techniques— geowrap, comprising clean sand sandwiched by geotextile separators placed 12–18 inches deep, and the patented Geosynthetic Capillary Barrier Drain—provided benefit by keeping the upper layers of the soil relatively dry. Geogrid and geotextile separators placed 12 inch deep and trench drains parallel to the road provided no observable benefit.

Huntington, G., and Ksaibati, K. (2011). "Implementation guide for the management of unsealed gravel roads." Transportation Research Record: Journal of the Transportation Research Board, 2205, 189-197.

To address the current lack of a gravel roads management system (GRMS) appropriate for the rural agencies of the Intermountain West and the Great Plains, the Wyoming Technology Transfer Center (T2/LTAP) consulted with a volunteer group of experts and practitioners in the fields of unsealed earth and gravel roads and roadway management to put together a set of recommendations and guidelines for managing unsealed roads. This paper describes and summarizes the gravel roads management methodology developed by T2/LTAP under the guidance of this group. Steps in implementing a GRMS are described, beginning with an assessment stage in which an agency evaluates its current unsealed roads information management and the resources available to improve it. Next, three elements of a GRMS are described: data management, inventory, and data collection. Eight maintenance tasks for unsealed roads are described: blading, reshaping, regraveling, dust control, stabilization, isolated repairs, major work, and drainage maintenance. Primary outputs of a GRMS are described, including cyclic maintenance scheduling, triggered maintenance scheduling, and network-level outputs, including network-level monitoring, financial tables, and road tables and maps. Safety and drainage assessments are described briefly. Recommendations are made for putting these procedures into practice.

Keller, G. R., and Sherar, J. (2003). "Low-Volume Roads Engineering - Best Management Practices Field Guide." Forest Service, United States Department of Agriculture, Washington, D.C.

This Low-Volume Roads Engineering Best Management Practices Field Guide is intended to provide an overview of the key planning, location, design, construction, and maintenance aspects of roads that can cause adverse environmental impacts and to list key ways to prevent those impacts. Best Management Practices are general techniques or design practices that, when applied and adapted to fit site specific conditions, will prevent or reduce pollution and maintain water quality. BMPs for roads have been developed by many agencies since roads often have a major adverse impact on water quality, and most of those impacts are preventable with good engineering and management practices. Roads that are not well planned or located, not properly designed or constructed, not well maintained, or not made with durable materials often have negative effects on water quality and the environment. This Guide presents many of those desirable practices. Fortunately, most of these "Best Management Practices" are also sound engineering practices and ones that are cost-effective by preventing failures and reducing maintenance needs and repair costs. Also keep in mind that "best" is relative and so appropriate practices depend to some degree upon the location or country, degree of need for improvements, and upon local laws and regulations. Best practices are also constantly evolving with time. This guide tries to address most basic roads issues in as simple a manner as possible. Complex issues should be addressed by experienced engineers and specialists. Included are key "DO's" (RECOMMENDED PRACTICES) and "DON'Ts" (PRACTICES TO AVOID) in low-volume roads activities, along with some relevant basic design information. These fundamental practices apply to roads worldwide and for a wide range of road uses and standards. Often recommended practices have to be adapted to fit local conditions and available materials. Additional information on how to do the work is found in other Selected References, such as the "Minimum Impact Low-Volume Roads Manual". Most practices apply to a wide range of road standards, from native surfaced, single-lane roads to double-lane paved roads. Desirable general practices include good road planning and location, performing environmental analysis, recognizing the need for positive surface drainage, ensuring adequately sized drainage crossing structures, using stable cut and fill slopes, using erosion control measures, developing good materials sources, and reclaiming sites once work has been completed. Certain design practices, such as use of rolling dips, outsloped roads, or low-water stream crossings, are very cost-effective and practical but typically apply to low-volume, low-speed roads because of safety concerns, vertical alignment issues, or unacceptable traffic delays. Other issues, such as the use of log stringer bridges, are very desirable for stream crossings in developing regions to avoid driving through the water, yet their use is now discouraged by some agencies, such as the U.S. Forest Service, because of their short design life and potentially unpredictable performance. Thus the information presented herein must be considered in terms of local conditions, available materials, road standards, project or resource priorities, and then applied in a manner that is practical and safe. Local rules, agency policies or regulations, or laws may conflict with some of this information or may include more specific information than that included herein. Thus, good judgment should be used in the application of the information presented in this guide, and local regulations and laws should be followed or modified as needed.

Marti, M. M., Mielke, A. J., and Hubbard, C. D. (2003). "Effective Methods to Repair Frost Damaged Roadways." Research Implementation Series Number 27, Minnesota Local Road Research Board, Minnesota Department of Transportation, St. Paul, Minnesota.

This report describes common causes for frost-related damage (non-uniform subgrades, shallow ground water table, low lying areas), means to evaluating prospective repair alternatives, methods to improve subgrade uniformity, and strategies to reduce/limit subgrade moisture.

McHattie, R. L. (2010). "Evaluating & Upgrading Gravel Roads For Paving." Alaska Department of Transportation.

Scenario: The Matanuska-Susitna Borough wants to consider paving an existing gravel road. As a Borough engineer you are assigned to develop and/or manage such a project. The road must handle only light, local traffic, and you would therefore like to pave it at the lowest possible cost. As an engineer you need a comfortable degree of confidence that you can properly design the new pavement, and that it can be justified, economically and otherwise. Is it possible to simply go ahead and apply new hot mix asphalt concrete or an asphalt surface treatment (AST) pavement to that old gravel road surface? For a number of good reasons that would not be prudent. As the engineer assigned to the project, your involvement begins with a couple of basic questions: (a) Is the Borough committed to a road management program, including new maintenance and load restriction policies that will sustain the service life of the new pavement? (b) Have you considered the public’s opinions, user costs, and safety issues? You must answer these questions before this engineering guide will be of use. Then, in order to provide Borough management with realistic estimates of economic feasibility, and design requirements, you must answer these questions: (a) Do predicted traffic levels confirm that asphalt concrete pavement is appropriate? (b) What kind of asphalt pavement is best? (c) Are you prepared, in terms of engineering time and resources, to evaluate and upgrade the existing gravel road, as necessary, to obtain a predictable service life? (d) Is the candidate gravel road in nearly good enough condition to receive pavement? (e) Does the existing road need to be significantly upgraded prior to paving? (f) If upgrading is needed, what type and how much is necessary? These latter questions

are directly related to evaluating the existing gravel road and designing for a new asphalt pavement surface — the subject of this guide.

Monlux, S. (2003). "Stabilizing Unpaved Roads with Calcium Chloride." Transportation Research Record: Journal of the Transportation Research Board, 1819, 52-56.

The U.S. Department of Agriculture Forest Service has stabilized unpaved road surfacing materials with relatively high concentrations of calcium chloride salt. The percentage of calcium chloride is higher than that traditionally used for dust abatement or aggregate base stabilization. Up to 2% pure salt by weight of aggregate was mixed into the top 2 in. (50 mm) of both aggregate and native road surfaces. The results were monitored for 2 to 4 years. The stabilized road surfaces resisted raveling and washboarding for several seasons and significantly reduced road blading and aggregate loss. As a result, calcium chloride stabilization may be a cost-effective treatment for roads with daily traffic volumes less than 200. Other benefits include reduced surface erosion and sedimentation; improved safety from reduced dust, raveling, and washboarding; and less frost penetration. Encouraged by these results, the Forest Service is conducting additional evaluations to determine the cost-effectiveness of surface stabilization with both magnesium chloride and calcium chloride in different environments and with different aggregate materials.

Monlux, S., and Mitchell, M. (2007). "Chloride Stabilization of Unpaved Road Aggregate Surfacing." Transportation Research Record: Journal of the Transportation Research Board, 1989(2), 50-58.

There are few alternatives for improving long-term performance of aggregate surfacing materials in dry climates other than annual dust abatement treatments. In-place stabilization of properly graded aggregate with chloride additives is cost-effective and provides performance and intangible benefits. Similar results are achieved by mixing additives with aggregate during crushing. This 2-year study identifies conditions in which chloride-stabilized roads have a projected life of 10 years or more if properly maintained. The greatest benefits are realized in projects with high aggregate surfacing replacement costs and average daily traffic volumes that exceed 100. Stabilization provides a higher standard of road surface performance by improving ride quality and reducing dust, corrugations (washboarding), and raveling (loose aggregate). Other intangible benefits include reduced sedimentation in streams, reduced aggregate resource depletion, reduced health hazards from dust, and increased road-user safety. This project developed guidelines for chloride stabilization of various aggregate surfacing materials in semiarid to arid environments. Performance and cost-effectiveness of chloride stabilization were measured on 12 projects and monitored for two seasons in four western states; monitoring included construction and maintenance costs, road surface deterioration, traffic, weather conditions, environmental effects, and materials testing. Treated surfaces needed blading after 25,500 vehicles, whereas untreated surfaces needed blading after only 3,200 vehicles. Environmental effects on trees, streams, and roadside soils were insignificant. Many tools were developed to assist in the proper implementation of chloride stabilization of road surface aggregates.

Numerical Analysis/Pavement Thickness Design

Aho, S., and Saarenketo, T. (2006). "Design and repair of roads suffering spring thaw weakening." The Swedish Road Administration, Northern Region, Sweden.

The ROADEX Project is a technical cooperation between roads organizations across northern Europe that aims to share roads related information and research between the partners. The Project was started in 1998 as a 3 year pilot co-operation between the roads districts of Finnish Lapland, Troms County of Norway, the Northern Region of Sweden and The Highland Council of Scotland and this was later followed up with a second project, ROADEX II, from 2002 to 2005. The partners in the ROADEX II Project comprised public road administrations, forestry organizations, forest companies and haulage organizations from regions in the Northern Periphery. These were The Highland Council, Forest Enterprise & The Western Isles Council from Scotland. The Region Nord of The Norwegian Public Roads Administration and The Norwegian Road Haulage Association, The Northern Region of The Swedish Road Administration and The Lappi and Keski-Suomi Regions of The Finnish National Roads Administration. (These latter Finnish Regions also received aid from their local forest industry organizations of Metsähallitus, Lapin Metsäkeskus, Metsäliitto & Stora-Enso.). The goal of the project was to develop ways for interactive and innovative road condition management of low traffic volume roads integrating the needs of local industry, society and roads organizations. 8 formal reports were published together with a project DVD and full copies of all reports are available for download at the ROADEX web site at www.roadex.org. This Executive Summary report is one of 8 summaries that have been prepared under the direction of the ROADEX III project (2006-2007), a new Project where the named project Partners above were joined by the additional Northern Periphery Partners of the Municipality of Sisimiut, Greenland, The Iceland Public Roads Administration and the Finnish Road Administration Region of Savo-Karjala.

Arnold, G. (1999). "Design of Rehabilitation Treatments for New Zealand's Thin-Surfaced Unbound Granular Pavements." Transportation Research Record: Journal of the Transportation Research Board, 1652, 42-50.

Most thin-surfaced unbound granular pavements are rehabilitated by overlaying with an unbound granular material and surfaced with a chip seal (thin-surfacing). The unbound granular overlay thickness is the difference between the total granular thickness required for future traffic and the granular thickness required for past traffic as determined from the design chart. However, where there are signs of shoving or other indications of a weak and degraded aggregate base layer then a smoothing treatment will not be adequate. For this situation the appropriate rehabilitation is either in situ stabilization (to improve the strength of the aggregate base material) or to cover with a minimum thickness of unbound granular material (determined from the thickness design chart by assuming the existing pavement acts as a subbase). This method of unbound granular overlay design has resulted in significant cost savings over the past 20 years in rehabilitation treatments for New Zealand roads, as the existing pavement has been fully utilized. In 1995 New Zealand adopted the Austroads (the Association of State, Territory and Federal Road and Traffic Authorities in Australia) procedures for pavement design. The Austroads procedures encourage the use of mechanistic procedures for pavement design. By using the same assumptions as the design chart method for determination of granular overlay depths, a mechanistic design procedure for rehabilitation treatments was developed. This method produces comparable results and has the advantage of being able to design a range of rehabilitation treatments.

Berg, R. R., Christoper, B. R., and Perkins, S. (2000). "Geosynthetic Reinforcement of the Aggregate Base/Subbase Courses of Pavement Structures." Geosynthetic Materials Association, Roseville, MN.

Geosynthetic reinforcement of the base, or subbase, course of pavement structures is addressed. The value added with reinforcement, design criteria/protocols, and practices for design and for material specifications are presented. Base, or subbase, reinforcement is defined within as the use of geosynthetic reinforcement in flexible pavements to support vehicular traffic over the life of a pavement structure. Primary base reinforcement benefits are to improve the service life and/or obtain equivalent performance with a reduced structural section. Substantial life-cycle cost savings are possible with base reinforcement. Cost saving benefits should be quantified using life-cycle analyses, and on an agency specific basis due to the many input variables. Recommended design procedure and material specifications are presented. It is recommended that specification with an approved products list be utilized, as the mechanisms of reinforcement are not fully understood and the geosynthetic performance should be considered product, and test conditions, specific. Equivalent materials must demonstrate equivalent performance in test structures and/or possess equivalent material properties, as defined by the specifier. The use of geosynthetic reinforcement to aid in construction over low strength subgrades, termed subgrade restraint within, is also addressed. Geosynthetic reinforcement is used to increase the support equipment during construction of a roadway. Subgrade restraint design procedures are based upon either (i) generic material properties, wherein a generic specification can be prepared based upon those design property requirements; or (ii) product-specific, empirically derived design methods, wherein an approved products list specification approach may be used. Geogrid, geotextile, and geogrid-geotextile composite materials are addressed within. This paper provides government agencies with current, logical recommended practice for the systematic use of geosynthetic reinforcement of pavement base courses. Refined guidance should be developed as the use of base reinforcement increases and additional long-term performance data becomes available.

Bergeson, K. L., and Barnes, A. G. (1998). "Iowa thickness design guide for low volume roads using reclaimed Class C fly ash bases." Iowa State University, Ames, Iowa.

This paper is intended to provide flexible pavement thickness design parameters and a design method for low volume roads and streets utilizing Iowa reclaimed hydrated Class C fly ashes as artificial aggregates for a base material. AASHTO design guidelines are presented for using these materials untreated, or if higher strengths are needed, stabilized with raw fly ash or hydrated lime. Hydrated Class C fly ashes in Iowa are produced at sluice pond disposal sites at generating stations burning western sub-bituminous coals. They may be formed by dozing raw ash into the sluice pond where it hydrates to form a cementitious mass or they may be constructed as an engineered fill (above the sluice pond level) by placing the raw ash in lifts, followed by watering, compaction and subsequent hydration. The hydrated ash is typically mined by using conventional recycling-reclaiming equipment to pulverize the material where it is stockpiled on-site for use as an artificial aggregate. Research has been conducted on these materials, on an on-going basis, under the Iowa Fly Ash Affiliate Research Program since 1991. Test roads have been constructed using reclaimed fly ash as an aggregate base in Marshalltown (1994) and near Ottumwa (1995). They have been, and are, performing well. Based on extensive laboratory testing, this paper presents layer coefficients for reclaimed hydrated Class C fly ash bases for use in AASHTO thickness design for low volume roads and streets.

Christopher, B. R., Schwartz, C., and Boudreau, R. (2005). "Geotechnical Aspects of Pavements." FHWA NHI-05-037, National Highway Institute, Federal Highway Administration, U.S. Dept. of Transportation, Washington, D.C.

The manual covers the latest methods and procedures to address the geotechnical issues in pavement design, construction and performance for new construction, reconstruction, and rehabilitation projects. The manual includes details on geotechnical exploration and characterization of in place and constructed subgrades as well as unbound base/subbase materials. The influence and sensitivity of geotechnical inputs are reviewed with respect to the requirements in past and current AASHTO design guidelines and the mechanistic-empirical design approach developed under NCHRP 1-37A, including the three levels of design input quality. Design details for drainage features and base/subbase material requirements are covered along with the evaluation and selection of appropriate remediation measures for unsuitable subgrades. Geotechnical aspects in relation to construction, construction specifications, monitoring, and performance measurements are discussed.

Dawson, A. R., Kolisoja, P., Vuorimies, N., and Saarenketo, T. (2007). "Design of Low-Volume Pavements Against Rutting: Simplified Approach." Transportation Research Record: Journal of the Transportation Research Board, 1989, 165-172.

Roads that connect remote communities to each other and to urban centers are essential for community survival, yet they often must be funded from a small taxation base. Because of their thin, often unsealed, construction, the pavements forming these roads typically fail by rutting. A simplified means of designing pavements against rutting that is usable by engineers in these remote locations is proposed. The causes of rutting are identified, and simple methods of material assessment suitable for use by local road engineers having limited resources are discussed. An advanced testing and analytical approach is reported that uses repeated load triaxial testing of aggregates and nonlinear finite element analysis of chip-sealed pavements. The results are used to develop a permissible stress approach for design purposes. This approach uses simple stress analysis, by chart and PC-based computations, with readily available in situ evaluation of materials.

DOD (1985). "Pavement design for seasonal frost conditions." Technical Manual No. 5-818-2, Air Force Manual No. 88-6, Chapter 4, Departments of the Army and Air Force, Washington, D.C.

This manual presents criteria and procedures for the design and construction of pavements placed on subgrade or base course materials subject to seasonal frost action. The criteria are applicable to Air Force and Air National Guard airfields, and to roads. This manual is concerned with modes unique to frost areas. The principal non-traffic-associated distress modes are distortion caused by frost heave and reconsolidation, and cracking caused by low temperatures. The principal traffic-load-associated distress modes are cracking and distortion as affected by the extreme seasonal changes in supporting capacity of subgrades and bases that may take place in frost areas.

Helstrom, C. L., Humphrey, D. N., and Labbe, J. M. (2007). "Performance and Effectiveness of a Thin Pavement Section Using Geogrids and Drainage Geocomposites in a Cold Region." NETCR60, Department of Civil and Environmental Engineering, University of Maine, Orono, Maine.

Test sections were constructed in two portions of Maine Route 9 to investigate the use of geosynthetics for reinforcement and drainage for subbase courses that were 300 mm (12 in.) and 600 mm (24 in.) thick with 150 mm (6-in.) of flexible pavement. Four types of test sections were constructed: geogrid reinforcement, drainage geocomposite, drainage geocomposite with geogrid reinforcement, and control. Test sections using reinforcement geogrid have strain gages attached to the geogrid to measure induced forces. Some of the reinforcement sections have geogrid on subgrade whereas some have geogrid in the center of the subbase to evaluate the effects of geogrid location. Drainage geocomposite and control sections have vibrating wire piezometers to monitor porewater pressure in the subgrade and subbase course. Thermocouples were used to measure the depth of frost penetration. The results of falling weight deflectometer tests were used to backcalculate the effective structural number for each section. Reinforcement geogrid and drainage geocomposite increased the effective structural number by between 5% and 17% for sections with 300 mm (12 in.) subbase. However, they had no apparent effect for sections with 600 mm (24 in.) of subbase. The increase in backcalculated effective structural number that was produced by geogrid and/or drainage geocomposite in the 300-mm (12-in.) subbase sections could also be obtained by adding between 25 and 75 mm (1 and 3 in.) of subbase aggregate to an unreinforced section.

Holtz, R. D., Christopher, B. R., and Berg, R. R. (2008). "Geosynthetic Design and Construction Guidelines." FHWA-NHI-07-092, National Highway Institute, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

This manual is an updated version of the FHWA Reference Manual for the National Highway Institute’s training courses on geosynthetic design and construction. The update was performed to reflect current practice and codes for geosynthetics in highway works. The manual was prepared to enable the Highway Engineer to correctly identify and evaluate potential applications of geosynthetics as alternatives to other construction methods and as a means to solve construction problems. With the aid of this text, the Highway Engineer should be able to properly design, select, test, specify, and construct with geotextiles, geocomposite drains, geogrids and related materials in drainage, sediment control, erosion control, roadway, and embankment of soft soil applications. Steepened reinforced soil slopes and MSE retaining wall applications are also addressed within, but designers are referred to the more detailed FHWA NHI-00-043 reference manual on these subjects. This manual is directed toward geotechnical, hydraulic, pavement, bridge and structures, construction, maintenance, and route layout highway engineers, and construction inspectors and technicians involved with design and/or construction and/or maintenance of transportation facilities that incorporate earthwork.

Holtz, R. D., and Sivakugan, N. (1987). "Design charts for roads with geotextiles." Geotextiles and Geomembranes, 5, 191-199.

Design charts have been developed to determine the required aggregate thickness for geotextile-reinforced roads using the Giroud and Noiray procedure. The charts are for rut depths of 75, 100, 150, 200, and 300 mm, with tire pressures of 480 and 620 kPa for a standard design axle load of 80 kN. The charts can be used for the design of geotextile-reinforced unpaved roads, roadway stabilization aggregate, and for the first construction lift for embankments on very soft foundations.

Houlsby, G. T., and Burd, H. J. (1999). "Understanding the behavior of unpaved roads on soft clay." Geotechnical Engineering for Transportation Infrastructure: Theory and Practice, Planning and Design, Construction and Maintenance, Proceedings of the Twelfth European Conference on Soil Mechanics and Geotechnical Engineering, H. B. J. Barends, J. Lindenburg, H. J. Luger, L. de Quelerij, and A. Verrujit, eds., Taylor and Francis, Balkema, 31-42.

An approximate calculation, based on bearing capacity theory, is presented for the ultimate capacity of an unreinforced or reinforced unpaved road, idealized as a granular fill over clay. The calculation is calibrated against rigorous numerical analyses to determine an equivalent load-spread angle. The method is then compared with experimental results for unreinforced and reinforced roads in both plane strain and axial symmetry. Empirical methods are used for predicting the effect of repeated loading on the behaviour of the road, and the possible contribution of shakedown analysis is examined.

Houlsby, G. T., and Jewell, R. A. (1990). "Design of reinforced unpaved roads for small rut depths." 4th International Conference on Geotextiles Geomembranes and Related Products, D. Hoedt, ed., Balkema, Rotterdam, Netherlands.

Current design methods for reinforced unpaved roads on soft ground are based on the concept that the principal function of hte reinforcement is to act as a tensioned membrane. This is usually combined with an empirical increase of the allowable bearing capacity factor for the subgrade in the case of a reinforced road. A new analysis of unpaved roads is presented in which the tensioned membrane effect, which is any case insignificant at small rut depths, is not considered, and a rational calculation is made to determine the appropriate bearing capacity factor for the subgrade. The role of shear stresses on the reinforcement surface becomes of primary importance. Design charts are presented which allow the necessary depth of granular fill, and the required reinforcement tension to be determined.

Janoo, V. C., Barna, L. A., and Orchino, S. A. (1997). "Frost-Susceptibility Testing and Predictions for the Raymark Superfund Site." Special Report 97-31, US Army Corps of Engineers Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

This project was conducted to assist in predicting the effects of freeze–thaw cycling on silicon common granular fill during the freezing season. This material is being used as the subbase material in the proposed pavement structure at the Raymark Superfund site in Stratford, Connecticut. Based on the initial laboratory results of the Tilcon material performed at CRREL, the amount of fines passing the no. 200 sieve was found to be in the vicinity of 20%, of which approximately 14% was finer than 0.02 m. Results from the frost heave tests indicate that when the Tilcon material is saturated, based on the rate of heave, the material is classified a high to very high frost susceptible material. In the unsaturated condition, the material is classified as a low to medium frost-susceptible material. Computer simulations were run to predict the amount of frost heave and frost penetration that may be expected on this site during the freezing season. Results from the laboratory frost-susceptibility tests and computer simulations were then used to estimate the amount of cumulative damage to the pavement structure during its design life.

Shoop, S., Affleck, R., Haehnel, R., and Janoo, V. C. (2008). "Mechanical behavior modeling of thaw-weakened soil." Cold Regions Science and Technology, 52, 191-206.

Freeze–thaw action produces a loose, wet soil that undergoes large deformation when subjected to vehicle loads and is responsible for “thaw weakening” of pavement systems. Because of the difficulty and expense in large-scale experiments, a finite element analysis was desired for the detailed study of thaw weakening. Neither a material model for thawing soil behavior nor detailed test data for large strains on thaw-weakened soil were available. Therefore, both were developed and are presented here. The material model must be capable of capturing the major behaviors of thawing soil subjected to rapid loading from vehicles in a near-surface condition. A common subgrade soil from New England, which was used in experimental studies of full-scale road sections, was chosen to represent a typical frost-susceptible silty sand. The soil was subjected to a suite of saturated and unsaturated triaxial testing, duplicating the conditions measured during thaw. The triaxial test data was used to calibrate a modified Capped Drucker–Prager plasticity model. The thawed soil material model was validated using independent test data of direct shear on thawed samples. The validated model was then implemented in application simulations of moving vehicle loads (a rolling wheel) on paved and unpaved roads with freeze–thaw layering.

Shoop, S., Affleck, R., Janoo, V. C., Haehnel, R., and Barrett, B. (2005). "Constitutive Model for a Thawing, Frost-Susceptible Sand." ERDC/CRREL TR-05-3, Cold Regions Research and Engineering Laboratory, U.S. Army Engineer Research and Development Center, Hanover, New Hampshire.

A material model for soft, wet soil was generated to simulate the deformation behavior of thawing soil under vehicle loading on paved and unpaved roads. Freeze–thaw action produces a loose, wet soil that undergoes large deformation when subjected to vehicle loads. The soil modeled is a frost-susceptible fine sand, which was used in full-scale tests of paved and unpaved road sections in CRREL’s Frost Effects Research Facility (FERF). The soil was subjected to a full suite of saturated and unsaturated triaxial testing, using density, moisture, and loading conditions duplicating those experienced during the freeze–thaw testing in the FERF. Material parameters were generated for a capped Drucker–Prager plasticity model. These were calibrated in triaxial test simulations using the commercial finite element code ABAQUS. The material model was then implemented in several three-dimensional finite element simulations for validation and robustness. The model for Lebanon Sand was compared to the same model for other granular materials.

Shoop, S., Haehnel, R., Janoo, V. C., Harjes, D., and Liston, R. (2006). "Seasonal deterioration of unsurfaced roads." Journal of Geotechnical and Geoenvironmental Engineering, 132(7), 852-860.

Seasonal deformation of unsurfaced roads was observed over several years and was studied using pavement deterioration models and finite-element analysis. The Mathematical Model of Pavement Performance is a model designed for pavement deterioration prediction and was successfully used for seasonal deterioration modeling because of its flexibility in defining the pavement structure, properties, and seasonal impact. However, these types of models are designed for highways and are somewhat limited in soils characterization and manipulation of the forces at the road–tire interface. Therefore, a three-dimensional dynamic finite-element model of a wheel rolling over soil was applied to simulate local vehicle traffic on a secondary

unpaved road. These simulations were used to study the effects of vehicle speed, load, suspension system, wheel torque, and wheel slip on rutting and washboard formation. Modeling results are compared to field measurements and observations.

Terrel, R. L., Epps, J. A., Barenberg, E. J., Mitchell, J. K., and Thompson, M. R. (1979). "Soil Stabilization in Pavement Structures - A User's Manual." COT-FH-11-9406, Federal Highway Administration, Department of Transportation, Washington D.C.

This manual contains two volumes. Volume 1 covers the pavement design and construction considerations of soil stabilization, while Volume 2 covers the mix design considerations. The primary purpose of this manual is to provide background information for those engineers responsible for utilizing soil stabilization as an integral part of a pavement structure. Information is included which will allow the pavement design engineer to determine the thickness of stabilized layer(s) for a pavement in a specific climate and subjected to definable highway traffic. The construction engineer will find information on quality control, specifications and construction sequences. The materials engineer has been provided with information that will allow the determination of the type and amount of stabilizers that are suitable for a particular soil. The manual has not been written to endorse one type of a chemical stabilizer over another. Nor is it intended to provide the specific features of one manufacturer's products. Rather, it explains the general characteristics of chemical soil stabilization and offers a method for evaluating the benefits of chemical stabilization versus the conventional mechanical stabilization operations. A thorough study of the manual should enable the engineer to recommend where, when and how soil stabilization should be used. It may also act as an aid in solving problems that may arise on soil stabilization projects.

White, D. J., Harrington, D., Ceylan, H., and Rupnow, T. (2005b). "Fly Ash Soil Stabilization for Non-Uniform Subgrade Soils, Volume II: Influence of Subgrade Non-Uniformity on PCC Pavement Performance." IHRB Project TR-461; FHWA Project 4, Center for Transportation Research and Education, Iowa State University, Ames, Iowa.

To provide insight into subgrade non-uniformity and its effects on pavement performance, this study investigated the influence of non-uniform subgrade support on pavement responses (stress and deflection) that affect pavement performance. Several reconstructed PCC pavement projects in Iowa were studied to document and evaluate the influence of subgrade/subbase non-uniformity on pavement performance. In situ field tests were performed at 12 sites to determine the subgrade/subbase engineering properties and develop a database of engineering parameter values for statistical and numerical analysis. Results of stiffness, moisture and density, strength, and soil classification were used to determine the spatial variability of a given property. Natural subgrade soils, fly ash-stabilized subgrade, reclaimed hydrated fly ash subbase, and granular subbase were studied. The influence of the spatial variability of subgrade/subbase on pavement performance was then evaluated by modeling the elastic properties of the pavement and subgrade using the ISLAB2000 finite element analysis program. A major conclusion from this study is that non-uniform subgrade/subbase stiffness increases localized deflections and causes principal stress concentrations in the pavement, which can lead to fatigue cracking and other types of pavement distresses. Field data show that hydrated fly ash, self-cementing fly ash-stabilized subgrade, and granular subbases exhibit lower variability than natural subgrade soils. Pavement life should be increased through the use of more uniform

subgrade support. Subgrade/subbase construction in the future should consider uniformity as a key to long-term pavement performance.