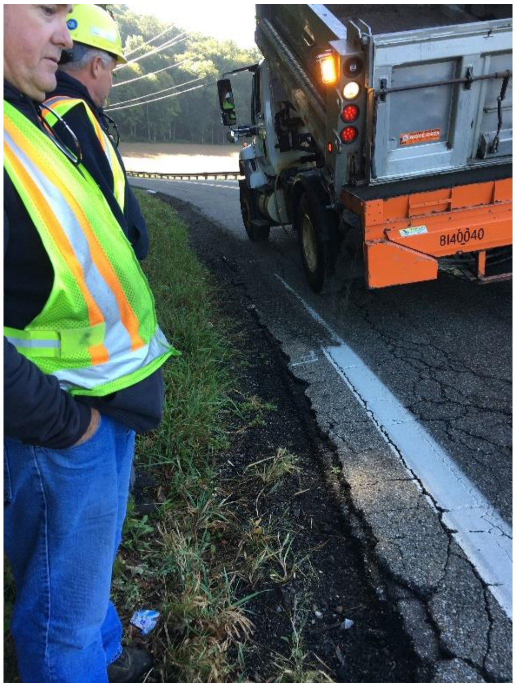
Evaluation of Post Flooding Shoulder Reconditioning



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16. Abstract

The Ohio Department of Transportation (ODOT) Holmes County Garage has to frequently maintain the shoulders of the hilly and curvy highways, which are prone to shoulder erosion and material loss due to floods or heavy rain. Currently, the problematic shoulders are maintained by simply replenishing with new aggregates, which is only a temporary fix. ODOT is seeking a permanent, easy-to-implement, cost- and time-effective solution to post-flood shoulder reconditioning. In this research, the current ODOT practice for shoulder reconditioning is evaluated by reviewing specifications, making site observations, discussing reconditioning with the maintenance crew, and conducting laboratory tests of the adopted materials. It was found that the currently adopted materials do not conform to those specified for shoulder reconditioning in CMS Item 617; the water content of the material is not well controlled, and the compaction of the placed materials is not sufficient. A comprehensive literature review was conducted, and four major types of promising permanent shoulder reconditioning techniques were identified: vegetation, chemical stabilization, mechanical stabilization and paving. Cost-benefit analysis was conducted for each technique, and a decision tree was developed to assist ODOT in choosing the most viable technique considering traffic type and volume, shoulder width, and drainage condition of the sites. It is recommended that quality control and assurance measures on material and compaction should be performed in order to better implement the current practice. It is also recommended that methods such as mechanical stabilization of the shoulder using geosynthetics, together with drainage measures, can be considered in the future to permanently prevent flood-induced shoulder erosion.

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Prepared in cooperation with the Ohio Department of Transportation
and the U.S. Department of Transportation, Federal Highway Administration

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Executive Summary

The Ohio Department of Transportation (ODOT) Holmes County Garage manages hilly and curvy highway routes, which are prone to shoulder erosion induced by flood or heavy rain. The current (ODOT) practice for reconditioning of shoulders is specified in its Construction and Material Specifications (CMS) Item 617: "Reconditioning Shoulders". The method simply involves the reestablishment of the shoulder by applying and compacting additional aggregates. This method is straightforward and easy to implement. However, the aggregate may simply erode away when the next flood comes. Several flooding events occur in this area each year, resulting in frequent maintenance and reoccurring expenses for shoulder reconditioning. ODOT is seeking a permanent, easy-to-implement, cost- and time-effective solution to post-flood shoulder reconditioning.

The objectives of this project are to:

1) Evaluate the current ODOT practice for reconditioning shoulders after flooding;
2) Conduct a literature review and develop matrices of existing strategies for shoulder reconditioning;
3) Conduct cost-benefit analysis for the identified strategies;
4) Recommend most viable strategies to ODOT Holmes County considering site condition, equipment, material, ease of deployment, and cost benefit and other factors.

To accomplish the research goals, the following tasks were conducted:

1) Review of the current and historic ODOT specifications on shoulder reconditioning;
2) Use of a questionnaire to find the current practices adopted by Holmes County Garage;
3) Site visits to areas with problematic shoulder sections;
4) Observation of current practice adopted by Holmes County Garage;
5) Laboratory testing of the materials used by Holmes County Garage;
6) Literature review to identify alternative shoulder reconditioning strategies;
7) Cost-benefit analysis of various shoulder reconditioning strategies; and
8) Development of decision tree aid ODOT in selecting an appropriate strategy.

The key findings include:

1) The problematic shoulder sections in Holmes County have different characteristics; five distinct categories can be made based on the site conditions including shoulder width, drainage condition and traffic condition. Recognizing the differences are critical when choosing appropriate reconditioning methods.
2) Overall, the current practices of shoulder reconditioning involve simply replenishing with materials specified in Items 304 or 411 or strengthening the shoulder with larger No. 1 aggregates; in some cases, the surface of the replenished shoulder is sealed using emulsions. Use of much larger No. 1 aggregates seems to work well at present time; however, the high cost limits its application, and only severe and critical problematic shoulder areas are repaired using No. 1 aggregates. Simply replenishing with Item 304 or 411 materials does not work well, and chip sealing provides only a temporary solution.
3) The implementation of Item 617 is evaluated and the following conclusions can be made:

a. The engineers confuse the materials specified for Item 617 with materials specified for Items 304 and 411. The specifications for these three items can be found in CMS Item 703. The gradations for the three materials are similar but not identical, as shown in Table 9.
b. The tested materials do not conform to that specified for Item 617. For one thing, the gradation is different in that the adopted materials consist of fewer particles passing the No. 30 (600 μm) sieve; for another, aggregate materials are blended with asphalt grindings for use in shoulder reconditioning, which is not specified in Item 617. Since asphalt grindings may provide extra binding between aggregate particles after compaction, it is expected to improve the reconditioning quality. However, the addition of grindings may change the compaction characteristics, and it is not clear how the grindings will affect the overall performance of the aggregates.
c. The water content of the tested materials is close to the optimum value; however, as indicated by the engineers, water content is typically not controlled, and the water content at the time of using depends on weather conditions.
d. The compaction of the placed materials is not well controlled. Currently, the materials are only compacted by using the dump trucks or graders used for placing the materials; typically, only two passes (instead of the specified four passes) of compaction are conducted. After compaction, there is no quality assurance measurement; it is highly probable that the compaction effort is not sufficient to achieve 98% of its maximum dry density.

4) Based on the literature review, six major types of shoulder reconditioning techniques are identified: reshaping, replenishing, vegetation, chemical stabilization, mechanical stabilization and paving. In addition, hydraulic measures and structural measures should also be considered for shoulder reconditioning. For each type of technique, there exist varieties in the material used. For example, chemical stabilization can be realized using cement, fly ash and other materials; mechanical stabilization can be realized using geotextile, geogrid or geocell. In addition, some methods may be combined: vegetation can be combined with mechanical stabilization, for example, and chip sealing can be combined with chemical or mechanical stabilization. Note that some of the identified methods, such as most of the chemical stabilization methods, do not work well based on the result of previous studies. Considering all of the above factors, the potentially effective shoulder reconditioning techniques are identified and summarized in Table 11. Each method is grouped and numbered, and the required materials and equipment for each method are listed.
5) Holmes County Garage engineers suggested the beneficial use of recycled tires for shoulder reconditioning. However, based on the survey and interviews conducted by the research team, no business model currently exists to realize the idea; even if a new business model is developed, the tire-based geocells may not be competitive in terms of cost when compared to commercially available geocells.
6) A cost-benefit analysis was performed, and the benefit-cost ratio for each potentially effective method is estimated. A summary is provided in Table 11.
7) Based on the traffic type, traffic volume, shoulder width, and drainage condition of the sites, a decision tree was developed to assist ODOT in choosing viable shoulder reconditioning methods in the future. The procedure of the decision tree is shown in Figure

5. For some cases, multiple options are available, and the final decision should be made considering the availability of equipment, materials and budget.

The research results lead to the following recommendations:

1) The engineers should differentiate materials specified for Items 304, 411 and 617. Only materials specified for Item 617 are recommended for shoulder reconditioning.
2) Quality control and quality assurance measures are recommended for implementation of Item 617. Specifically, the moisture-density relation of the materials should be determined through compaction tests. Before placement, the water content of the materials should be measured and adjusted to optimum moisture content; after placement, the materials should be sufficiently compacted to achieve at least 98% of maximum dry density. Dedicated compactors should be used; in addition to the weight requirement, four passes of compaction should be guaranteed.
3) In addition to Item 617, alternative methods such as vegetation, chemical stabilization, mechanical stabilization, paving, hydraulic measures, and structural measures can be considered for shoulder reconditioning. The selection of methods should be based on the characteristics of the pavement as assisted by the decision tree (Figure 5).

1. Project Background

Shoulders or berms are critical components of the roadway systems, since they provide lateral support for the pavement, provide space for drivers in emergencies, and serve as a recovery area when vehicles accidently leave the driving lanes. The quality of shoulders directly affects the health condition of the pavement and the safety of the traveling public. A major problem with shoulders is pavement edge drop-off, which refers to the vertical elevation difference between the pavement surface and the shoulder surface. Pavement edge drop-off can be caused by a variety of reasons including rain- or wind-induced erosion, irregular slopes caused by granular material degradation, vehicle off-tracking, or insufficient bearing capacity of subsurface soil under shoulders (White et al. 2007). Pavement edge drop-off poses a great risk for the safety of the public and has been identified as a primary cause of accidents on two-lane undivided highways (AASHTO 2008, Glennon 2005, Hallmark et al. 2006, Jensen and Uerling 2015). Therefore, inspection and maintenance of shoulders has become a mandatory and routine practice for roadway owners.

The Ohio Department of Transportation (ODOT) ODOT maintains shoulders along more than 49,250 lane miles of interstate, US and state route roadways. The current practice for reconditioning of shoulders is specified in ODOT's Construction and Material Specifications (CMS) Item 617: Reconditioning Shoulders. The method simply involves the reestablishment of the shoulder with additional aggregates and compaction. This method is straightforward and easy to implement. Maintenance crews with ODOT in Holmes County currently repair shoulders with additional aggregate when flooding occurs. However, the aggregate may simply erode away when the next flood comes. Several flooding events occur in this area each year, which results in frequent maintenance and reoccurring expenses for shoulder reconditioning. Furthermore, this issue is not unique to Holmes County and is actually a state-wide problem. Therefore, ODOT has initiated a research project to identify a permanent, cost- and time-effective solution to post-flood shoulder reconditioning that is easy to implement on a state-wide basis.

2. Research Context

2.1. Goals and Objectives of the Study

The goal of this study is to identify permanent solutions to post-flood shoulder reconditioning, which can result in cost savings, an increase in shoulder longevity and, in general, an improvement of current operations and safety of the traveling public. This report summarizes the key findings from Phase 1, which mainly involves an in-depth analysis of current processes and a review of the available literature.

The specific objectives for Phase 1 are to:

1) Evaluate the current ODOT practice for reconditioning shoulders after flooding;
2) Conduct a literature review and develop matrices of existing strategies for shoulder reconditioning;
3) Conduct cost-benefit analysis for the identified strategies;
4) Recommend most viable strategies to ODOT Holmes County considering site condition, equipment, material, ease of deployment, cost benefit, and other factors.

2.2. The Problem of Shoulder Drop-off and Erosion

Although pavement shoulders are on the edge of the roadways and are usually narrow and unpaved, their importance cannot be overlooked. Without stable shoulders, the main paved lanes lose effective lateral support and may experience premature distress; more importantly, poorly maintained shoulders pose a great safety risk to the traveling public because significant vertical differences between surfaces can affect vehicle stability and reduce a driver's ability to handle the vehicle (Hallmark et al. 2006). Iowa State University conducted a study on the safety impacts of pavement edge drop-off and found out that there is a relationship between potential edge drop-off–related crashes and the amount of edge drop-off along a segment that was 2.5 inches or more (Hallmark et al. 2006). This agrees well with current ODOT maintenance thresholds of 2.0 inches.

In its core, the shoulder drop-off problem results from the displacement of shoulder materials by one or more forces, such as traffic loads or water. The extent of the shoulder drop-off depends on the composition of the shoulder materials. In Ohio, shoulders are either paved or unpaved: paved shoulders have the same or similar composition as the roadway, while unpaved shoulders are either composed of unstabilized earth materials or stabilized materials. Unstabilized or granular shoulders, which are typically used for low-volume roads, are made of aggregates and onsite earth materials and are most prone to be damaged or eroded. Although a granular shoulder has a lower initial construction cost (by up to 70% compared to a paved shoulder according to White et al. (2007)), it typically adds more expense during its service life due to the need for more frequent maintenance. Key factors for achieving a high-quality aggregate shoulder include proper aggregate mix design, compaction techniques and construction methods (Butt et al. 1997). The ability of a granular shoulder to resist deterioration, which can result in shoulder erosion and drop-off, depends on its surface stability and strength. According to an unpublished survey of Virginia DOT maintenance managers concerning aggregate shoulder maintenance activities, it is believed that a shoulder should undergo maintenance approximately once every six months (Roosevelt 2005). This is consistent with the ODOT Holmes County Garage's practice of about twice per year.

Figure 1 illustrates common problems with granular shoulders, which include:

- Erosion by wind, rain and pavement surface drainage;
- Vehicle off-tracking;
- Settlement of soft underlying subgrade; and
- Irregular slope caused by granular material degradation.

Most relevant to this study is the rain- or flood-induced erosion of granular aggregates, which will be discussed in more detail in the next section. However, it should be noted that these factors can be correlated and can influence one another.

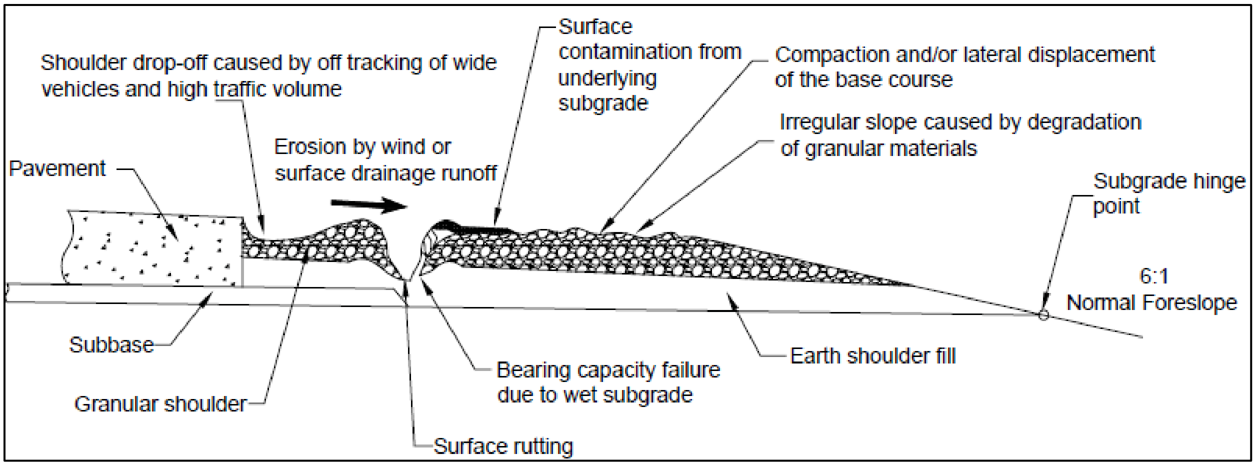


Figure 1 Common Granular Shoulder Problems (White et al. 2007)

2.3. Flood Induced Erosion of Aggregates: Important Factors

The erosion of aggregates occurs when the erosive forces exceed the resistance forces in the shoulder. Erosive forces are induced by flowing water, which is driven mainly by gravitational forces. Therefore, local topology, pavement and shoulder surface grades are critical influences on the velocity and volume of the storm water flow. Holmes County contains both hilly and curvy highway routes, which involve larger longitudinal and transverse slopes along and across the pavement sections, respectively. During a heavy rain event, such large slopes promote the channeling of flows toward the shoulders. Effective surface and subsurface drainage systems will channelize and relieve these flows without severely damaging the shoulder. However, a concentrated flow, if not effectively drained, will accelerate along or across the shoulders, inducing enormous erosive forces on the shoulder materials.

Resistance of the shoulder materials to erosion is mainly provided by gravity, frictional forces, and the interlocking of particles. Therefore, the particle size, particle shape, cohesion and compactness of the shoulder materials are important. Larger particles such as aggregates or crushed stones are usually placed on top of the original soils to increase the overall erosive resistance as well as the bearing capacity of the shoulder sections. ODOT CMS Item 703.18 specifies the materials for Items 410, 411 and 617. Crushed carbonate stone, gravel, air-cooled blast furnace slag, granulated slag, basic oxygen furnace slag, electric arc furnace slag, recycled Portland cement concrete, or recycled asphalt cement concrete are eligible for use in shoulder construction or reconditioning. The gradations for each material are also specified. It should be noted that the gradation can significantly contribute to erosional resistance. With a proper gradation, the voids between large particles are filled with smaller particles, thus increasing the interlocking forces; particles passing sieve No. 200 are categorized as fines, which may introduce cohesion to the soil mass and increase the erosional resistance. In addition, compaction is required after placing the granular materials to prevent the loss of contained moisture and increase the erosional resistance by improving the interlocking effects and friction between particles. Additional resistance may be provided by vegetative cover, which can stabilize the soil through the effective anchorage provided by its root system.

Ideally, for an unpaved and unstabilized shoulder section, if the surface slope is gradual, the drainage system works properly, gradation is appropriate and compaction is adequate, the shoulder should remain stable after flooding. However, this is not the case in practice because there are always inconsistencies or variabilities in materials and operations; and other factors may aggravate erosion of the aggregates. For example, off-tracking traffic may disturb the shoulder surface, loosen the aggregate materials and initiate the formation of ruts. In addition, even normal traffic levels may generate tremendous air flows that can degrade the shoulder materials. Moreover, irregular slopes caused by the degradation of granular materials may form concentrated flow channels, which can accumulate water and may promote further erosion.

In short, the factors affecting the erosion of shoulder aggregates include the following: local topology, pavement and shoulder grades, drainage condition, aggregate particle shape, size and gradation, cohesion of the shoulder material, compaction, traffic volume, and subgrade soil properties. In this research, these factors are evaluated to identify the collective reasons for erosion of aggregates in Holmes County.

3. Research Approach

To accomplish the research goals listed in **Section 2.1**, the following approaches are taken:

1) Review of the current and historic ODOT specifications on shoulder reconditioning;
2) Questionnaire for current practices adopted by Holmes County Garage;
3) Site visits to problematic shoulder sections;
4) Observation of current practice adopted by Holmes County Garage;
5) Laboratory test of the materials used by Holmes County Garage;
6) Literature review of alternative shoulder reconditioning strategies
7) Cost-benefit analysis
8) Development of decision tree

The aforementioned approaches are briefly discussed below and more details can be found in the appendices.

3.1. Review of current and historic ODOT specifications

ODOT Construction and Material Specifications (CMS) Item 617 ("Shoulder Reconditioning") provides specifications for shoulder reconditioning. The specification requires that any shoulder with more than a 2-in. drop-off should be reconditioned. The method adopted involves replenishing with additional aggregate materials and adequate compaction. The material should conform to CMS Item 703.18, where the material type and gradations are specified. Item 617 also specifies the requirements on shoulder preparation and aggregate spreading and compaction. The equipment required includes soil loosening tools (such as a power tiller or a backhoe with bucket teeth), blade or disc (for asphalt shoulder preparation), spreader, compacting equipment (such as a crawler-type tractor, tamping rollers, trench rollers, pneumatic tire equipment), and a water truck (which is optional and depends the moisture condition of the soils at the site).

In the last ten years, CMS underwent several modifications. The archives are reviewed and the specifications for Items 617 and 703.18 in different versions of CMS are compared (CMS 2005, 2008, 2010, 2013, 2016). Item 617 is quite consistent through the years, and the only notable change is in the 2013 version, where a description on how to compact the shoulders (using side-mounted rollers) is included when the shoulder is too narrow. It is clear that ODOT acknowledges the importance of shoulder compaction.

Note that Item 617 is similar to Item 411, “Stabilized Crushed Aggregates”. Item 617 and Item 411 are summarized in **Table 1**.

Table 1. Current ODOT Specified Shoulder Reconditioning Practice

Method	**Material**	**Equipment**	**Awarded contract average cost**	**Notes**
Item 617 “Shoulder Reconditioning”	703.18: Aggregates	Crawler-type tractors, tamping rollers, trench rollers, suitable pneumatic tire rollers, or other suitable equipment.	Shoulder reconditioning: \$2.75 / square yard. Shoulder preparation: \$0.3 / square yard. Compacted aggregate: \$50 / cubic yard.	>4 passes with roller > 6 ton; apply water if needed; This is the mostly used current practice; currently using limestone or grindings conforming to Item 411 or 304; Compaction effort is not sufficient in current practice; Need to replenish materials twice a year.
Item 411 “Stabilized crushed aggregate”	703.18: Aggregates	Self-propelled spreading machine (spreader box and pavers are allowed); crawler type tractor, tamping roller, trench roller, suitable pneumatic tire	\$50 / cubic yard	< 6 in./lift; 2 percent of the optimum moisture; 98% of maximum dry density; See above.

3.2. Survey

A questionnaire was prepared to obtain more details on the general shoulder reconditioning practices in Holmes County, as well as the actual implementation and quality control of the various steps stated in CMS Item 617.

The questions for evaluation of the current practices on shoulder reconditioning included:

1) Which areas in Holmes County experience the most frequent and severe shoulder erosion problems? Are the topography maps available for those areas?

   Answer:
   1.) *SR 83 15.1 mm Sheet flow flooding area.*
   2.) *SR 83 0-6mm Various hill locations*
   3.) *SR 557 2-5mm Various hill locations*
   4.) *SR 241 1-5mm Various hill locations*

   (Note: the research team later visited a total of eight sites including those listed above).

2) What are the daily traffic volumes in those areas?
   Answer: (Note: this question was not answered but the research team identified the daily traffic volumes from ODOT's traffic online survey report available via: http://www.dot.state.oh.us/Divisions/Planning/TechServ/traffic/Traffic_Survey_Reports/2014_Reports/HOL2014.PDF)

3) What types of drainage systems are used in those areas?
   Answer:
   Most of our roads are rural routes and just have a standard open ditch.

4) How often are the shoulders maintained?
   Answer:
   As needed, depends a lot on weather conditions. (Large rainfalls, flooding)
   The areas identified above with the exception of #1 have been done twice in last year.

5) What equipment and manpower are required to complete the maintenance work?
   Answer:
   Grader, broom, 2 or 3 Dump trucks, 2 pickup trucks. 6 or 7 HT's

6) How much time is required to recondition the shoulder in the abovementioned areas?
   Answer:
   Depends a lot on severity of areas, amount of material needed and if areas are spread out a lot. More info to come I have to open old work orders to obtain info

7) What is the typical cost/lane/mile for shoulder reconditioning?

Answer:
I just ran a report on a work order that we are currently working on three roads with hilly terrain so the work is spread out over a long distance. The cost per mile was $2,245.63/mile. I will get some comparisons when I open old work orders.

8) How is the gradation and quality of the supplied material ensured?
Answer:
We normally use 411 or 304 limestone and mix together with asphalt grindings. Our limestone is purchased from suppliers on the ODOT contract, I believe there are samples pulled by the testing dept. then it is considered approved source?
(Note: Here distinctions among materials for Items 411, 304 and 617 should be made. Their gradations are similar but not identical. Please see Table 9 in Section 4 for the comparison among materials for these three items.)

9) Has the problem shoulder been sufficiently loosened prior to placing additional aggregate material?
Answer:
No, we are normally filling in a washed out area.

10) How are the additional aggregates stored and spread?
Answer:
We stockpile at our garage when possible ahead of time to blend in grindings.

11) How are the additional aggregates compacted? Has the compaction been performed in multiple passes as indicated in the CMS item 617?
Answer:
We do not have a rubber tire roller, they roll in with the grader and or dump trucks.

12) What is the typical moisture condition of the site when reconditioning? Is applying water a common practice when the site is too dry?
Answer:
Moisture condition varies, no we are not really equipped to add water.

Through discussions with the Holmes County engineers, it was also learned that over the years, they had tried several other methods to strengthen, seal, or stabilize the shoulders. These methods include, for example, applying tack coat, prime coat, and chip seal. Such methods are in fact specified by ODOT and the corresponding Item numbers are 407, 408, and 422, respectively. Such specifications are summarized in **Table 2**.

In addition, ODOT also specified some other methods which can be used for erosion control on shoulders but were not implemented by Holmes County. These include Items 206, 659, 660, and 671. Note that such specifications are not designed for shoulder reconditioning. When implemented at the shoulder sections, some modifications are required. These specifications are summarized in **Table 3**.

The Holmes County garage also tried to use aggregate with a much larger size (e.g., No. 1) to strengthen some shoulder sections.

Table 2. Additional ODOT specified practices implemented by Holmes County for shoulder reconditioning

Method	Material	Equipment	Awarded contract average cost	Note
Item 407 “Tack coat”	702.04: Asphalt; 702.12: Non-tracking asphalt emulsion; 702.13: SBR Asphalt emulsion; 703.06: Cover aggregate	Cleaning equipment, spreader boxes and distributors.	$2 / gallon (binder) $50/ cubic yard (aggregate)	Used occasionally on shoulder sections; Not performing well and doesn’t last long (can hold up to several months).
Item 408 “Prime coat”	702.02: Asphalt material, MC-30, 70, 250; or 702.03: Primer 20 703.05 or 703.06: Cover aggregate No. 9	Cleaning equipment, spreader boxes and distributors.	$3.2 / gallon (binder) $50 / cubic yard (aggregate)	Used occasionally on shoulder sections; Not performing well and doesn’t last long (can hold up to several months).
Item 422 “Chip seal”	702.16: Polymer emulsified binder Type A 703.05: Aggregate washed limestone or washed dolomite 703.05	Spray bar, adjusting the nozzles for triple lap coverage; Type II pneumatic tire roller; Self-propelled spreaders with a variable width aggregate hopper; Power sweepers, pickup sweeper, rotary brooms.	$3.5 / square yard	Weather requirements: May 1 to September 15; not below 21 degrees. Currently not often used for shoulder sections in Holmes County.

Table 3. ODOT specified practices that have the potential to be implemented for shoulder reconditioning

Method	**Material**	**Equipment**	**Awarded contract average cost**	**Note**
Item 206 "Chemically stabilized subgrade"	712.04.B: Lime; 701.04: Cement.	Mechanical spreader, power driven transverse type mixer, vibratory footed roller at least of 10 tons; moisture control.	\$3.3 / square yard – For 14 inches' deep	Test rolling, spreading, mixing, compacting, curing, proof rolling, protection; Not used in Holmes County.
Item 659 "Seeding and mulching"	Lime, commercial fertilizer, topsoil, mulch (straw, wood fiber, compost), seeds, water 659.07 Kentucky bluegrass, Class 2.	Bulldozer, pneumatic or hydraulic planting machine; mower.	\$0.7-1.05 / square yard	Not rigorously applied for erosion control in the problematic areas; Engineers mentioned that the native grass and wild flowers will grow even not purposely planted.
Item 660 "Sodding"	Sod of well-rooted Kentucky bluegrass or Canadian bluegrass (QPL); Wood stakes, T-pins, round pins, galvanized poultry netting; Item 659 fertilizer and lime.	Excavator, hammer.	Reinforced - \$16.18/sq.yd. Staked – \$19.28/sq.yd. Unstaked – \$5.72/sq.yd.	Not rigorously applied for erosion control in the problematic shoulder areas.
Item 671 "Erosion control mat"	Item 660.02: Sodding; Item 712.11: Erosion control mats Type A; Fertilizer, lime, staples, pins, washers.	Staple/pin driver.	\$1.78 / square yard	Not used on shoulder sections in Holmes County.

3.2. Visit to sites with problematic shoulder sections

A total of eight sites in Holmes County were visited. The locations of the visited sites are marked on the map in Appendix 1. Photos for each site can also be found in Appendix 1. The characteristics of the problematic sections and the key observations are summarized in Table 4.

Table 4. Synthesis of problematic shoulder areas

Road	Section[a]	AADT[b]	Shoulder width	Guardrail?	Drainage?	Material	Observation	Category
SR-60	7.0–8.0	1,120	< 2 ft	No	No	304	Hill top, narrow shoulder	I
SR-754	1.0	2,570	< 2 ft	Yes	Ditch destroyed	No. 1, 304s,	Trough	
US-62	21.2	9,060	≈ 2 ft	Yes	No	No. 1, Emulsion	Slope next to guardrail	II
SR-557	7.0	3,310	> 2 ft	No	Yes	No.1	Buggy, Ditch, culvert	III
SR-557	4.4	930	> 2 ft	Yes	No	304, Emulsion	Buggy, Rutting, guardrail	
SR - 557	2.6	930	≈ 2 ft	Yes	Culvert, bad	No.1	Buggy, Culvert, trough area	IV
SR-83	4.5	2,800	> 2 ft	No	Ditch	304	Ditch exists, bearing capacity	V
SR-83	15.7	4,230	> 2 ft	No	No	304	No guardrail, sheet flow, vegetation	

[a] Sections are described using station numbers with units of mile.
[b] AADT is the abbreviation of Annual Average Daily Traffic. Data is available at http://www.dot.state.oh.us/Divisions/Planning/TechServ/traffic/Pages/Traffic-Count-Reports-and-Maps.aspx

According to the site conditions, the problematic shoulders in Holmes County can be categorized into five groups:

Category I involves narrow shoulders (< 2 ft) on hilly roadways. Such roadways typically have two lanes and low to moderate Annual Average Daily Traffic (1,000–3,000), and the roadway is located on one side of the hill so the road surface is not crown-shaped but has a single crossfall. Most of the time, there is also no dedicated drainage channels such as side ditches on the hill. Water directly from the rain fall, together with the runoff from the hill, has no way to go but to concentrate on the shoulder, inducing flow with higher velocity and eroding the shoulder materials more easily.

Category II involves wider shoulder sections (> 2 ft) on roadways with high AADT (> 9,000); typically, guardrails are installed at sections where the roadways are built on slopes.

Category III involves wider shoulders (> 2 ft) on roadways with buggy traffic. The AADT varies from section to section, but the buggy traffic is unique. Since the buggy traffic is slow and must make way for the faster automobiles, the buggy is often driven to the roadside so that the right buggy wheel often hits the shoulder area. Such frequent disturbance to the shoulder caused a significant rutting problem on shoulders covered with chip seal. On sections where chip seal is not used, such a disturbance caused more material to be lost by erosion.

Category IV involves culverts at the trough of a hilly roadway; there are no side ditches, so the runoff is concentrated on the shoulder area and it all flows to the trough area. At the visited site, the erosion was so severe that it created a large void surrounding the culvert, and the guardrail posts had begun to lose support and tilt away from the roadway.

Category V involves a wider shoulder (> 2 ft) on roadways where side ditches exist or roadways that are prone to sheet flow during flooding seasons. These sites usually have wider shoulders; but these shoulders are not as common as other Categories in Holmes county.

Based on the site visits, some general assessment of the performance of the current reconditioning methods can be made:

1) Overall, shoulders reconditioned based on Item 617 and Item 411 are still vulnerable to flood-induced erosion, and the Holmes County Garage typically reconditions the shoulders twice a year.
2) Shoulders strengthened by chip seal do not last long due to the initial low bearing capacity of the subbase for the shoulder; over time, the chip seal cracks and water is allowed to seep in, which softens the subbase and at the same time erodes fine materials. During flooding season, more and more shoulder materials will be washed away.
3) Shoulders reconditioned with large size aggregates (e.g., No. 1 aggregates) seems to be working well, at least for now. However, the cost involved is much higher than the materials specified in Item 314.
4) Regarding to the culvert region at the trough of hilly roadways (Category IV in Table 4), Holmes County temporarily installed some soil retaining plates (in fact, speed limit signs were used for this purpose) to keep the already insufficient aggregates from eroding. For the visited site, Holmes County is planning to reconstruct the culvert section.

3.3. Site observation of current shoulder reconditioning practice

To better evaluate the current practice, especially the implementation of the Item 617, the research team observed the shoulder recondition process at the SR 60 site shown in Table 4. Photos and videos were taken to document the equipment and procedures. As shown in Figure 2a, the road is located along a hillslope and the shoulder is very narrow with a width smaller than 2 ft. Vegetation is established on the hillslope but not on the shoulder section. Between the shoulder and the hillslope, there is no ditch or alternative drainage system. Obvious traffic rutting on the shoulder section can be observed, and the drop-off at the shoulder section is apparent. The reconditioning work begins by filling the drop-off sections with Item 314 materials from a dump truck (Figure 2b); a grader is then used to level the aggregate surface with the pavement (Figure 2c); the aggregate is then compacted with the grader tires for two passes (Figure 2d); after compaction, any excess materials are swept using a broom truck (Figure 2e). The completed shoulder section is shown in Figure 2f.

3.4. Laboratory test of the aggregate used in shoulder reconditioning

Materials used in shoulder reconditioning at the visited site were collected for laboratory evaluation. The following tests were conducted: 1) Water content determination; 2) Sieve analysis; and 3) Standard Proctor compaction. The test results are briefly summarized below, and detailed data can be found in Appendix 4.

1) Six samples were tested for water content determination; the average water content was found to be 5.18%.
2) The particle size distribution curve is shown in Figure 3. From the curve, the coefficient of uniformity (C_u) and the coefficient of curvature (C_c) can be determined. For the tested sample, C_u=7.64 and C_c=1.29; according to unified soil classification grading criteria, the material can be classified as well-graded gravel; according to AASHTO soil classification system, the material can be classified as A-1-a; according to ODOT CMS **Item 703, the material does not conform to that specified for Item 617. As shown in Table 5, the tested material contained fewer *particles smaller than 600 µm* than specified.**

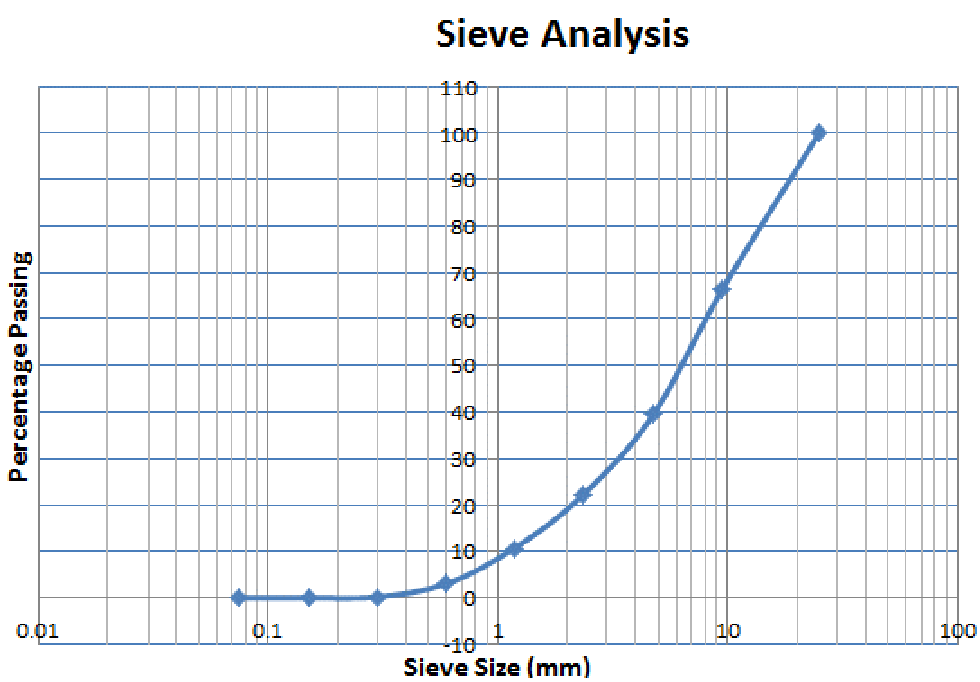


Figure 2. Particle size distribution curve for the tested sample

(a) (b) (c)

(d) (e) (f)

Figure 3. The shoulder recondition process adopted by ODOT Holmes County garage. (a) Before reconditioning; (b) Filling material; (c) Grading; (d) Compaction; (e) Cleaning; (f) After reconditioning

Table 5. Comparison of the sample gradation with that specified for Item 617

Sieve Size	Total Percent Passing	
	CMS Item 703.18 (for materials used in Item 617)	On site material
1 inch (25.0 mm)	100	100
¾ inch (19.0 mm)	30 to 100	--
⅜ inch (9.5 mm)	35 to 75	66.42
No. 4 (4.75 mm)	30 to 60	39.45
No. 30 (600 µm)	9 to 33	**3.03**
No. 200 (75 µm)	0 to 15	0

3) According to ODOT CMS Supplement 1015 ("Compaction testing of unbound materials"), Standard Proctor Method B is selected to determine the moisture-density relations of the sample. The result is shown in Figure 4. From the curve, it can be determined that the maximum dry density of the tested sample is 1,718 kg/m^3 and the optimum moisture content is 6%. Note that the in-situ water content is 5.18%, which corresponds to a dry density of 1,714 kg/m^3 given sufficient compaction effort, or 99.8% of the maximum dry density. It is always suggested to compact aggregates at its optimum moisture content so that 100% of the maximum dry density is achieved. However, due to the various uncertainties in practice, it is typically required to achieve 98% of maximum dry density. **This means that, if the materials are compacted with sufficient compaction effort, the in-situ water content is acceptable.** However, as observed in the field, the compaction was not performed according to the Item 617, which requires compaction equipment weighing at least 6 tons and a minimum of four passes. **While the grader used for compaction at the site weighed more than 6 tons, only two passes were performed.**

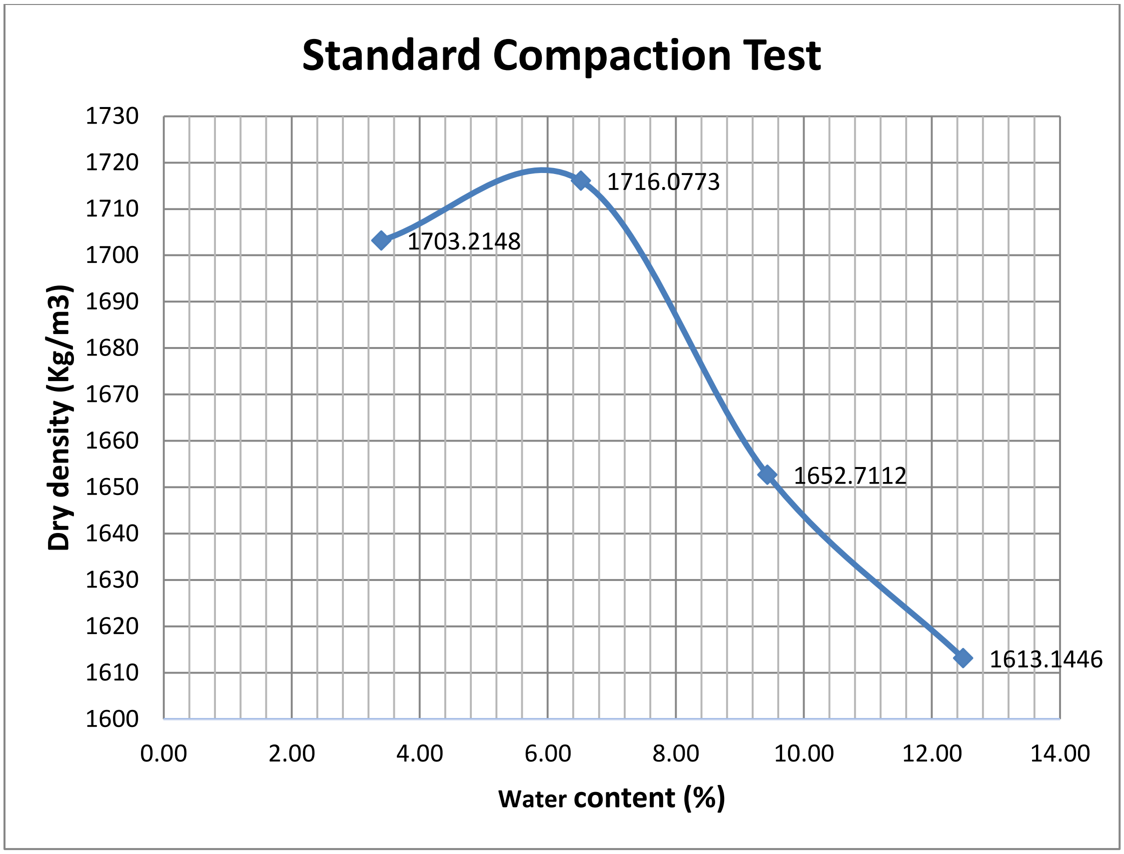


Figure 4. Moisture-density curve for the tested sample

3.5. Literature review

Reports from previous state or federal DOT projects on shoulder reconditioning were reviewed to identify alternative strategies. In addition, research papers or theses on this topic were reviewed. The literature review revealed that six main shoulder reconditioning techniques have been studied or adopted by state DOTs:

1) **Reshaping** (pulling) shoulders involves using equipment (usually a motor grader) to pull materials from the base of the shoulder slope back up to the pavement edge. The materials are then compacted using compactors such as a pneumatic tire roller.

2) **Replenishing** is a process similar to reshaping, but it is performed when there is more than a two-inch drop-off and when there are not enough materials left on the shoulder to reestablish its original shape and slope.

3) **Promoting growth of vegetation** is beneficial because it increases the shoulder's resistance to wind and water erosion. The root system of the vegetation helps to hold the aggregate in place under all climate and soil conditions.

4) **Chemical stabilization** of shoulder materials is another potential strategy for increasing resistance to erosion. The unbounded materials can be stabilized with chemical agents including cement, emulsion, salts, asphalt, and so on to increase its stability and extend the longevity of the pavement.

5) **Mechanical stabilization** mainly involves placing geosynthetic products to hold the aggregates in place. Different types of geosynthetic products such as geo-fabrics, geo-grids or three-dimensional geocells can be used.

6) **Paving the shoulder** is the ultimate solution to increase the bearing capacity and erosional resistance of the shoulder. Since the function of the shoulder is different from that of the pavement, the paved shoulder does not need to possess the same structure as the pavement. Based on traffic volume and the original bearing capacity of the subgrade, a different design on the shoulder section can be proposed. In order to save cost, reclaimed material such as recycled asphalt pavement (RAP) materials can be used.

A brief summary of the different methods for shoulder reconditioning is summarized in Table 6. A detailed review for each method can be found in Appendix 3.

Two additional measures can also be considered:

1) **Hydraulic measures.** The above methods are all used for the reconditioning of the shoulder from the perspective of improving the material strength or the erosional resistance. As discussed in Section 2.3, erosion occurs when the flow-induced erosive force exceeds the resistive strength of the material. There, it is equally important to reduce the erosive force, or the flow velocity, acting on the shoulder. The most efficient approach is to divert water away from the shoulder by means of ditches or other drainage measures. Such methods can be categorized as hydraulic measures.

2) **Safety edge.** The ultimate goal of shoulder reconditioning is to ensure the safety of the traveling public. Other structural methods, such as a **safety edge**, have proven to be a relatively easy and inexpensive countermeasure to steep pavement edges or drop-off. A safety edge is a 30- to 35-degree tapered asphalt wedge or fillet installed along pavement edges. "*The safety edge not only provides an angled and compacted transition that eliminates the abrupt drop-off, but it also provides for a stronger and more stable pavement edge, which makes it easier for drivers to maneuver their vehicles safely back onto the roadway. By offering a tapered, rather than vertical, transition between the paved surface and the unpaved shoulder, the safety edge is a low-cost means of improving safety on paved two-lane highways.*" (Moler, 2007).

Table 6. Summary of existing post-flooding shoulder reconditioning techniques

Technique	Material	Equipment	Effectiveness	Cost, time, labor	Ref.*
Reshaping	On-site materials	Motor grader, tractor broom, roller, etc.	Effective only for a few weeks up to a year under optimal conditions.	Quick, require minimum personnel and equipment.	[1]
Replenishing	Additional aggregates	Motor grader, dump trucks, tractor broom, front end loader, etc.	Lost granular materials should be added regularly (about once every 6 months).	Initial cost: $13,376/3ft-mile; Maintenance cost: $259/3ft-mile-year [2]; $2,370/3ft-mile-year [3]	[2], [3]
Vegetation	Vegetation		Vegetation increases shoulder stability in all climates and is the most practical and economical method available for reducing soil erosion.		[4]
Chemical Stabilization	Polymer emulsion	Road reclaimer, rollers, etc.	The stabilized granular section performed inadequately.		[5]
	Foamed asphalt (FA)	Road reclaimer, rollers, etc.	Effective for a short period of time.		[5]
	Soybean oil soapstock	Road grader, trucks for soapstock, water and sand	Not successful [5]; successful under certain conditions [8].		[5], [8]
	Portland cement	Road reclaimer, rollers, etc.	Edge drop-offs and erosion were observed after four months.		[5]
	15% to 20% Class C fly ash with the upper 12 in. of subgrade clay	Road reclaimer, pad foot roller, smooth wheel roller, etc.	Successful in improving both the short- and long-term performance; both California bearing ratios (CBR) and modulus increase significantly.		[5]

Table 6. Summary of existing post-flooding shoulder reconditioning techniques (Continued)

Technique	**Material**	**Equipment**	**Effectiveness**	**Cost, time, labor**	**Ref.***
Chemical Stabilization (Continued)	Soiltac and Centrophase AD	Road reclaimer, rollers, etc.	Do not increase shoulder stiffness or bearing strength (but were only tested on crushed run stone). Insufficient data to determine their effectiveness to improve a shoulder's short-term resistance to wind or water erosion.		[3]
	Lignosulfonates	Road reclaimer, rollers, etc.	No significant difference in performance between stabilized and control section.		[6]
	Reclaimed asphalt pavement (RAP) and Portland cement (PC)	Motor grader, dump trucks, rollers, etc.	Successfully stabilized the shoulders. The rehabilitated section held up for a period of 6 years.		[7]
Mechanical Stabilization	Geogrids were placed at the interface between subgrade and granular layer	Rollers, etc.	Considerably improved the performance of the shoulder test section and eliminated rutting.		[5]
	Artificial soil reinforcement (geosynthetic mesh and grid)	/	/		[4]
	Geo-cellular materials such as geo-block or geo-web	Staple driver, roller side compactor	Sediment erosion reduced by 200% (geo-block) or 47% (geo-web).		[9]
Paved Shoulder	Portland cement/asphalt, aggregates, etc.	Motor grader, dump trucks, rollers, etc.	Reliable performance and require much less maintenance effort.	Initial cost: $53,469/3ft-mile ; Maintenance cost: $259/3ft-mile-year; $76/3ft-mile-year	[2]

References*: [1] ODOT (2016); [2] Souleyrette et al. 2001; [3] Roosevelt, 2005; [4] Jensen and Uerling 2015; [5] White et al., 2007

[6] MaineDOT, 2007a; [7] MaineDOT, 2007b; [8] Guo et al. 2013.; [9] Shirmohammadi 2004

3.6. Cost-benefit analysis

Cost is usually the dominating factor when choosing a maintenance strategy. A cost-benefit analysis can assist the decision making process. In this research, a cost-benefit analysis was conducted for each viable shoulder reconditioning strategy.

The ratio of benefit to cost (B/C) is determined for the considered design life of the newly installed method. Take two alternative strategies I and II, for example. Both have associated initial costs (Ct_{ini_I}, Ct_{ini_II}), maintenance costs (Ct_{mt_I}, Ct_{mt_II}), maintenance intervals (T_I and T_{II}) and service life (N_I and N_{II}). The idea of a cost-benefit analysis can be simply explained as follows:

Assume L_{II} is larger than N_I, the total cost for implementing strategy II during its service life time N_{II} is:

Cost for strategy II during L_{II}: $Ct_{II} = Ct_{ini\_II} + Ct_{mt\_II} * (N_{II} / T_{II})$;

During the same time period L_{II}, the total cost for strategy I is:

Cost for strategy I during L_{II}: $Ct_I = (Ct_{ini\_I} + Ct_{mt\_I} * (N_I / T_I))*(N_{II} / N_I)$

When assessing if it is beneficial to replace strategy I with strategy II, Ct_I can be seen as the "benefit" since strategy I is no longer used and this cost is **saved**; and Ct_{II} can be seen as the "cost".

If (B/C) > 1, it is beneficial to replace strategy I with strategy II.

If (B/C) < 1, it is not beneficial to replace strategy I with strategy II.

In this study, strategy I is the current shoulder reconditioning method, while strategy II can be any of the alternative methods.

It should be noted that the above explanation is not rigorous, since the value of a dollar changes over time. Therefore, it is necessary to convert all future annual costs to the current worth using the following formula:

$$P = A \left[\frac{(1+i)^N - 1}{i\,(1+i)^N}\right]$$

where *P* = Present value; *A* = Annual Value; *i*= rate of interest; and *N* = Design Life

Assumptions used in cost analysis:
1) The current method of shoulder reconditioning is carried out twice a year;
2) The design, cost items and service life are assumed as shown in Table 7.
3) The unit cost for different items are assumed as shown in Table 8.
4) A treatment area is assumed to be 2 ft wide and 1 mile long.

In this section, only a brief introduction of the cost benefit analysis is included. Detailed calculation procedures can be found in Appendix 2. All the spreadsheet used for calculating the benefit/cost ratio for each alternative strategy can be found in a separate Appendix 2-2.

Table 7. Assumed design, cost items and service life for each alternative method

Method		Design and cost items (for shoulders of 2’ wide and 1 mile long)	Service life
A: Vegetation	A1: Seeding and mulching	Material, Installation, Maintenance (twice a year)	5 years
	A2: Sodding	Material, Installation, Maintenance (twice a year)	5 years
	A3: Erosion control mat (Type A)	Material, Installation, Maintenance (twice a year)	5 years
	A4: Turf reinforced mat	6” of aggregate base, material, installation, maintenance costs	10 years
B: Mechanical Stabilization	B1: Geocell only	6” of geocell and infilling aggregate, 1” of aggregate cover, rebar anchors, costs for material, installation and maintenance	10 years
	B2: Geocell with vegetation	6” of geocell and infilling aggregate, sod, rebar anchors, costs for material, installation and maintenance	10 years
	B3: Geocell with chipseal	6” of geocell and infilling aggregate, 1 layer of chipseal, rebar anchors, costs for material, installation and maintenance	10 years
C: Chemical Stabilization	C1: Fly ash and aggregate	Excavation of 14”, Fly ash mixing of 14”, 2” of top aggregate layer	10 years
	C2: chip seal on top of C1	Excavation of 14”, Fly ash mixing of 14”, 2” of top aggregate layer, 1 layer of chip seal	10 years
D: Paving	D1: Chip Seal	Costs for aggregate, binder and installation	2 years
	D2: Hot RAP (Item 401.04)	40% RAP, 60% virgin aggregate, 6”	15 years
	D3: AC (Item 251.03)	6” of AC	15 years
	D4: Safety edge	NA	NA
E: Hydraulic and Structural method	E1: Side Ditch with soft liner,	1–2ft wide + ditch erosional control mat	15 years
	E2: Catch basin or drop inlet	Precast reinforced concrete	15 years
	E3: Culvert side/wing wall	Precast reinforced concrete	15 years

Table 8. Unit cost for different items

S.N.	Item	Cost or value (with units)	References
1	Aggregate	\$50 / Cubic Yard	[1]
2	Shoulder preparation for ative soil	\$0.33 / square yard	[1]
3	Geocell	For 3” - \$0.50/Sq.ft. For 4” - \$1.05/Sq.ft. For 6” - \$1.50/Sq.ft.	[2]
4	Interest Rate	4% per annum	[3]
5	Maintenance for Geocell+Vegetation Method	\$350 per one time	
6	Vegetation Seed (Kentucky Bluegrass)	\$18.98/3 lb package	[4]
7	Vegetation Sod	\$0.3 / Sq.ft.	[5]
8	Rebar for Anchorage	\$2 / lb	[1]
9	Unit weight of Rebar	7850 kg/m^3 or 490 lb/ft^3	[6]
10	Pavement Repair	\$205 / cubic yard	[1]
11	Maintenance cost for Paved method	\$500 / year	
12	Excavation	\$10/cubic yard	[1]
13	Chip seal	\$3.5/sq. yard	[1]

[1] Previous summary of Contracts awarded by ODOT:
http://www.dot.state.oh.us/Divisions/ContractAdmin/Contracts/Pages/default.aspx
[2] Cost information obtained from different suppliers.
[3] Center for Transportation Research and Education, Iowa State University, 2711 South Loop Drive, Suite 4700, Ames, IA 50010-8664, June 2007.
[4] Supplied by Home Depot as of 01/03/2017.
[5] http://www.improvenet.com/r/costs-and-prices/grass-sod
[6] http://www.coyotesteel.com/assets/img/PDFs/weightspercubicfoot.pdf

3.7. Interview on potential use of recycled tires in shoulder reconditioning

One of the ideas proposed by the Holmes county engineers involves beneficial use of recycled tires for shoulder reconditioning. The idea is proposed because currently ODOT generates a considerable amount of waste tires every year, inducing a recurring disposal fee. The research team also proposed to use commercially available geocell to contain and strengthen the soil. The Holmes county engineers suggest to use ODOT waste tires to produce similar geocell structures locally.

The research team did a search of local businesses related to tire recycling and rubber production. Two approaches to produce tire based geocells are identified:

1) The first approach involves 12-step minimum treatment of the tires, such as cutting and stitching manually. Only a startup company called “MATIREAL” is leading the effort right now. The final product typically has very large cell size (5” by 10”) and is more suitable for parking lot construction rather than shoulder reconditioning since the shoulder in the problematic areas are typically narrow (2 ft in width).

2) The other approach involves reusing the rubber of the tires and molding it into a mat with three-dimensional (3D) cells. This process is more complex and expensive and, more importantly, it involves specialized equipment. The research team interviewed experts in local companies such as Akron Rubber Associates, RCA Rubber, Boomerang Rubber, Inc., Durable Corporation, R. C. Musson Rubber Co., Inc., Recycled Tire Mats, and Wooster Rubber, Ltd./Rubber Queen. In-depth discussions were held with RCA Rubber and Akron Rubber Associates.

   RCA Rubber manufactures floor mats that include clay to decrease flexibility, as pure rubber is very soft and flexible. RCA uses molding technique to produce mats with different textures and, theoretically, they can make 3D geocells as large as 3 ft by 5 ft. Occasionally, they use recycled tire crumb/powder as part of the raw materials. However, they do not accept scrap tires. Therefore, an intermediate company such as a tire recycling facility is needed. More importantly, only a very small portion of tire crumb (10%) can be used. The cost involved in transporting the tires to the recycling facility, the post-processing of the tires to rubber crumb, and the process of producing the geocells leads to a high cost of production of the geocells. Such cost is believed to be higher than the disposal fee and the sale price for commercially available geocells.

   Rubber Associates is a rubber molding company that specializes in producing custom molded rubber components. The representative at Rubber Associates thinks it is possible to mold the proposed products with dimensions of 3½ ft by 5½ ft. The shape form can have different designs including interlocking details. Similar to RCA, they do not accept scrap tires (since the tire rubber was vulcanized, it cannot be used directly for molding), and they use raw rubber to create their components. Rubber Associates can only include up to 5~10% of tire rubber crumb in the raw material.

   For raw materials, moldable unvulcanized rubber is \$0.6 per pound, while crumb rubber is about \$0.5 per pound. In addition to the raw material, to produce the 3D geocell, new molds are needed (at a cost of \$20,000 ~ \$30,000 per piece). Also, labor and overhead costs can be estimated as twice the cost of the raw material. Based on a simple cost analysis, the final cost for the 3D geocell will be higher than that of commercial geocells, which are mass produced.

   As commented by Denise Kennedy, a leading expert in the field of beneficial reuse of recycled tires, *"Tire reclamation and recycling" is a huge topic involving great many stakeholders from government, tire user, recycling facilities, processing facilities and end users."*

   If a complete production line for tire-geocell transformation already existed, then the demand for geocell can be easily met with economic benefit. However, it is apparent that such a complete production line is not established locally; therefore, the demand cannot be readily met, and the need does not justify the investment to establish such a line.

According to California Department of Resources Recycling and Recovery, tire-derived products typically have higher initial costs than competing products. As an example, tire-derived sidewalk tiles cost approximately $9 to $13 per square foot, while traditional rubber sidewalk tiles cost about $3 to $9 per square foot.

3.8. Development of the decision tree

When choosing the most viable shoulder maintenance strategies, a number of factors should be taken into consideration. A certain maintenance strategy can be selected and evaluated based on the following factors: importance and traffic volume of the particular shoulder section, site condition (such as on-site soil properties, topology, and existing drainage systems), improvement gained by the treatment, maturity of the technology, availability of equipment and materials, ease of implementation (labor, special expertise), initial cost, maintenance frequency and cost, and other factors.

Considering the fact that the visited sites may not cover all the possible problematic shoulder conditions in Holmes County, a more comprehensive decision tree is developed. This decision tree considers the major site specific conditions:

1) Whether buggy traffic is an issue
    a. Buggy wheels apply additional loading to the shoulder, considering the fact that the buggy wheels are typically very thin and the load is applied in a more concentrated way.
    b. In addition to erosion control, the shoulder needs to be strengthened to increase the loading bearing capacity.
2) Whether the site involves culverts at the trough of a hilly road
    a. In such regions, drainage is vital, and the best strategy is to channel the runoff from the shoulder to the side ditch, and route the water from the side ditch to the culvert itself through the use of catch basins or drop inlets.
    b. It would also be beneficial to install a side/wing wall to the culvert to retain the backfill surrounding the culvert.
3) Whether the shoulder is narrow or wide
    a. For wide shoulders or shoulders without guardrail, the construction space is sufficient and more methods can be adopted.
    b. For narrow shoulders or shoulders with a guardrail, the construction space is limited and only select methods can be adopted.
4) Whether the road is prone to sheet flow
    a. Sheet flow sections may be submerged in water, and chemical stabilization is not recommended.
5) Whether the roadway has high, medium or low traffic volume
    a. For roadways with high traffic volume, there is a higher chance that the traffic will drive on and disturb the shoulder section. Therefore, it is suggested to select methods which also improve the bearing capacity of the shoulder.
    b. For roadways with medium or low traffic volumes, more economical methods such as strengthening the shoulder with vegetation can be adopted.

4. Research Findings and Conclusions

This research resulted in the following findings:

1) The problematic shoulder sections in Holmes County have different characteristics; five distinct categories can be made based on the site conditions including shoulder width, drainage condition and traffic condition. Recognizing these differences is critical when choosing appropriate reconditioning methods.
2) Overall, the current practice of shoulder reconditioning involves simple replenishing with materials specified in Items 304 or 411 or strengthening the shoulder with larger No. 1 aggregates; occasionally, the surface of the replenished shoulder is sealed using emulsions. Use of much larger No. 1 aggregates seems to work at the present time, but its high cost has limited its application; only severe and critical problematic shoulder areas are repaired using No. 1 aggregates. Simple replenishing with Item 304 or 411 materials does not work well, and chip sealing is only a temporary solution.
3) The implementation of Item 617 was evaluated, and the following conclusions can be made:
    a. The engineers confuse materials specified for Item 617 with materials specified for Items 304 and 411. The specifications for these three items can be found in CMS Item 703. The gradations for the three materials are similar but not identical, as shown in Table 9.

Table 9. Gradations for materials used for Items 304, 411 and 617

Sieve Size	Total Percent Passing		
	CMS Item 703.18 (for materials used in Item 304)	CMS Item 703.18 (for materials used in Item 411)	CMS Item 703.18 (for materials used in Item 617)
2 in (50 mm)	100		
1 ½ in (37.5 mm)		100	
1 inch (25.0 mm)	70 to 100	75 to 100	100
¾ inch (19.0 mm)	50 to 90	60 to 100	30 to 100
⅜ inch (9.5 mm)		35 to 75	35 to 75
No. 4 (4.75 mm)	30 to 60	30 to 60	30 to 60
No. 30 (600 µm)	9 to 33	7 to 30	9 to 33
No. 200 (75 µm)	0 to 15	3 to 15	0 to 15

The physical properties are also slightly different for these three materials, as shown in Table 10.

Table 10. Physical Properties specified for materials used in Items 304, 411 and 617.

	Total Percent Passing		
	CMS Item 703.18 (for materials used in Item 304)	CMS Item 703.18 (for materials used in Item 411)	CMS Item 703.18 (for materials used in Item 617)
Percent of wear, Los Angeles test, maximum (CCS or crushed gravel)	50 %	--	--
Loss, sodium sulfate soundness test, maximum	15%	15%	--
Percent by weight of fractured pieces (one or more faces), minimum	90%		90%
Gravel used, portion retained on a No. 4 (4.75 mm) sieve (one or more faces) minimum crushed	--	40%	--
Maximum plasticity index of material passing No. 40 (425 µm) sieve	--	6%	--
Content of shale and shaly material, maximum percentage by weight	5.0%	5%	12%
Content of chert, that disintegrates in 5 cycles of the soundness test, maximum percentage by weight	5.0%	--	--

b. The tested materials do not conform to that specified for Item 617. For one thing, the gradation is different in that the materials used consist of fewer particles smaller than No. 30 (600 µm); for another, aggregate materials are blended with asphalt grindings for use in shoulder reconditioning. Since asphalt grindings may provide extra binding between the aggregate particles after compaction, it is expected to improve the reconditioning quality; however, the addition of grindings may change the compaction characteristics, and how exactly the grindings will affect the overall performance of the aggregates is not clear.

c. The water content of the tested materials used are close to the optimum value. However, as indicated by the engineers, the water content is typically not controlled, and the water content at the time of use depends on weather conditions.

d. The compaction of the placed materials are not well controlled. Currently, the materials are only compacted using dump trucks or graders used for placing the materials; typically, only two passes (instead of the specified four passes) of compaction are conducted. After compaction, there is no quality assurance measurement; it is highly probable that the compaction effort is not sufficient to achieve 98% of the material's maximum dry density.

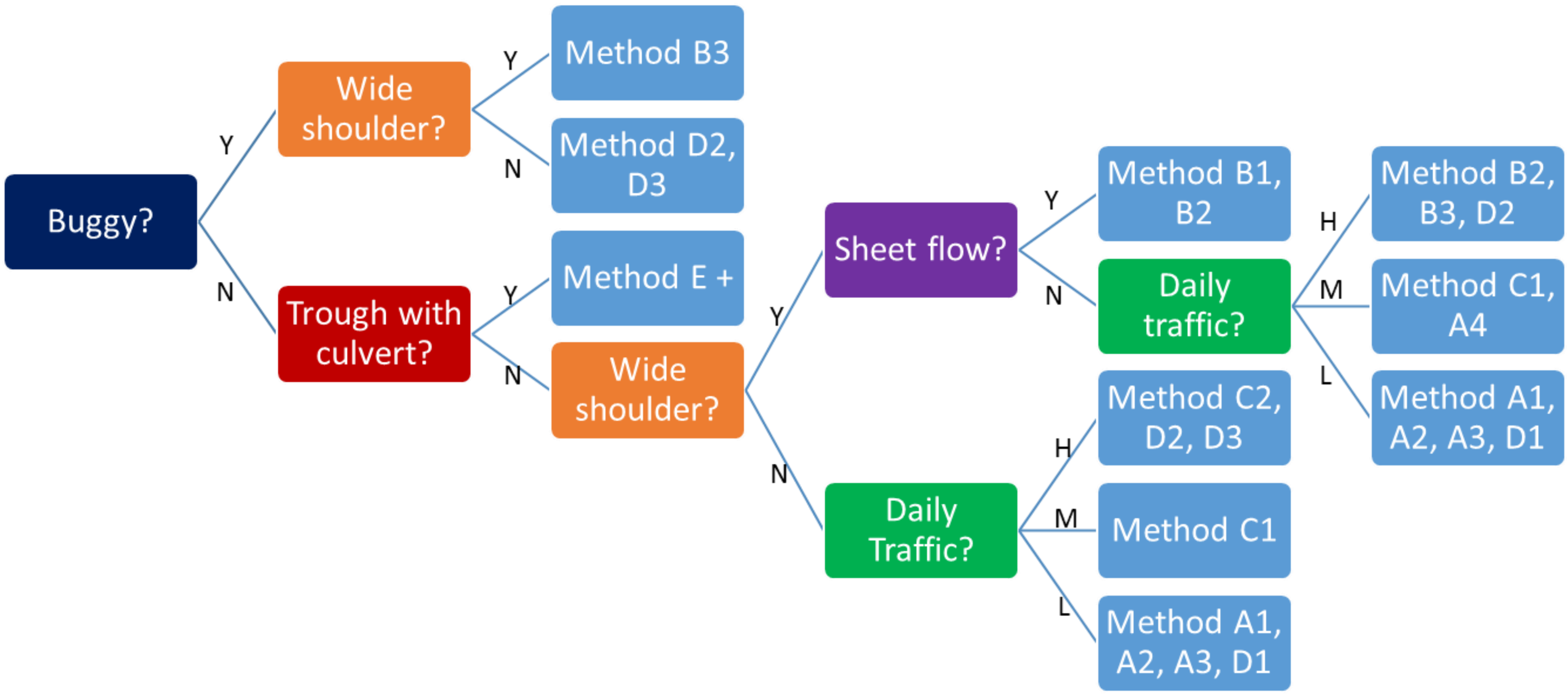
4) Based on literature review, six major types of shoulder reconditioning techniques are identified: reshaping, replenishing, vegetation, chemical stabilization, mechanical stabilization and paving. In addition, hydraulic measures and structural measures should be considered for shoulder reconditioning. For each type of technique, there exists variety in the material used. For example, chemical stabilization can be realized using cement, fly ash and other materials; mechanical stabilization can be realized using geotextile, geogrid or geocell. In addition, some methods may be combined. For example, vegetation can be combined with mechanical stabilization, and chip sealing can be combined with chemical or mechanical stabilization. Note that some of the identified methods, such as most of the chemical stabilization methods, do not work well based on the results of previous studies. Considering all above factors, potentially effective shoulder reconditioning techniques are identified and summarized in Table 11. Each method is grouped and numbered, and the required materials and equipment are summarized.

5) Based on a cost-benefit analysis, the benefit-to-cost ratio for each potentially effective method is estimated. The results for this analysis are also listed in Table 11.

6) Based on the traffic type, traffic volume, shoulder width, and drainage condition of the sites, a decision tree was developed to assist ODOT in choosing viable shoulder reconditioning methods in the future. The procedure of the decision tree is shown in Figure 5. For some cases, multiple options are available, and the final decision should be made considering the availability of equipment, materials and budget.

Table 11. General summary of the potential methods

Method		Material	Equipment	B/C
A: Vegetation	A1: Seeding and mulching	Suggested grass: Kentucky bluegrass Mulch; fertilizer and lime	Dozer, pneumatic or hydraulic planting machine; mower;	4.08
	A2: Sodding	Sodding, pins, wood stakes, T-pins, round pins, galvanized poultry netting; Item 659 fertilizer and lime	Excavator, hammer; mower;	1.01
	A3: Erosion control mat	Item 660.02: Sodding Item 712.11: Erosion Control Mats Type A Fertilizer, lime, staples, pins, washers	Staple/pin driver, mower;	3.27
	A4: Turf reinforced mat	Seed, fertilizer, lime, turf reinforced mat, staples and pins, hammers; topsoil/aggregate mix	Excavator, hammer; mower;	2.60
B: Mechanical Stabilization	B1: Geocell only	Geocell, aggregate, stakes, pins,	Staple driver, roller	1.73
	B2: Geocell with vegetation	Geocell, aggregate/topsoil mix, stakes, pins, seeds, fertilizer, lime	Staple driver, roller, planting machine, mower	1.57
	B3: Geocell with chip seal	Geocell, aggregate, stakes, pins, binder, aggregate	Staple driver, roller side compactor	1.53
C: Chemical Stabilization	C1: Fly ash and aggregate	Fly ash/nature soil mixture, aggregate	Excavator, mixer, side compactor,	3.25
	C2: Chip seal on top of C1	Fly ash/nature soil mixture, aggregate, binder	Excavator, mixer, distributor, side compactor,	2.60
D: Paving	D1: Chip seal	Binder, aggregate	Distributor, side compactor	2.34
	D2: Hot RAP (Item 401.04)	Binder, aggregate, RAP	Distributor, paver, side compactor	1.67
	D3: AC (Item 251.03)	AC	Distributor, paver, side compactor	0.69
	D4: Safety edge	AC	Distributor, paver, side compactor	NA
E: Hydraulic and Structural methods	E1: Side ditch with soft liner	Aggregate, and materials in A	Excavator and equipment in A	Cost: $15k-$20k
	E2: Catch basin or drop inlet	Catch basin, drop inlet, aggregate backfill, drainage pipes	Excavator, compactor	
	E3: Culvert side/wing wall	Precast culvert with side walls; or precast wing walls, aggregate	Small crane, compactor	



A1: Seeding and mulching; **A2**: Sodding; **A3**: Erosion control mat; **A4**: Turf reinforced mat; **B1**: Geocell only; **B2**: Geocell with vegetation; **B3**: Geocell with chipseal; **C1**: Fly ash and aggregate; **C2**: chip seal on top of C1; **D1**: Chip Seal; **D2**: Hot RAP (Item 401.04); **D3**: AC (Item 251.03); **D4**: Safety edge; **E1**: Side Ditch with soft liner; **E2**: Catch basin or drop inlet; **E3**: Culvert side/wing wall

Figure 5. The decision tree for selection of most viable shoulder reconditioning strategy based on site conditions

5. Recommendations for Implementation of Research Findings

Based on the results of this research, the following recommendations are made:

4) The engineers should differentiate materials specified for Items 304, 411 and 617. Only materials specified for Item 617 are recommended for shoulder reconditioning.
5) Quality control and quality assurance measures are recommended for implement of Item 617. Specifically, the moisture-density relation of the materials should be determined through compaction test. Before placement, the water content of the materials should be measured and adjusted to optimum moisture content. After placement, the materials should be sufficiently compacted to achieve at least 98% of maximum dry density. Dedicated compactors should be used; in addition to the weight requirement, four passes of compaction are required.
6) In addition to Item 617, alternative methods such as vegetation, chemical stabilization, mechanical stabilization, paving, hydraulic and structural measures can be considered for shoulder reconditioning. The selection of methods should be based on the characteristics of the pavement as assisted by the decision tree (as presented in Figure 5).
7) For the visited sites, the recommended permanent solutions are listed in Table 12.

Table 12. Recommended permanent solutions for the visited sites

Category	**Characteristics**	**Reason for material loss**	**Recommendation**
I	Located in hilly areas, Shoulder are narrow (< 2 ft), AADT is normally low to moderate, there may be existing guardrail which limits the construction space, no dedicated drainage system	High runoff velocity; No drainage system for the runoff.	**Method D: Paving**
II	High traffic volume, narrow to moderate shoulder width	Low bearing capacity, traffic disturbance, high runoff velocity.	Bearing capacity needs to be improved; **Method B: Mechanical stabilization**
III	Buggy traffic area, moderate to wide shoulder area	Buggy wheel caused rutting.	Bearing capacity needs to be improved; **Method B: Mechanical stabilization**
IV	Trough area with culvert, limited shoulder space, runoff drainage is limited	High runoff velocity; No drainage system for the runoff.	Drainage needs to be improved; **Method E: Hydraulic and structural**
V	Wide shoulder, sheet flow area	Sheet flow submerging, low bearing capacity, traffic disturbance.	**Method B**: **Mechanical stabilization** **Method A4: Turf reinforced mat**

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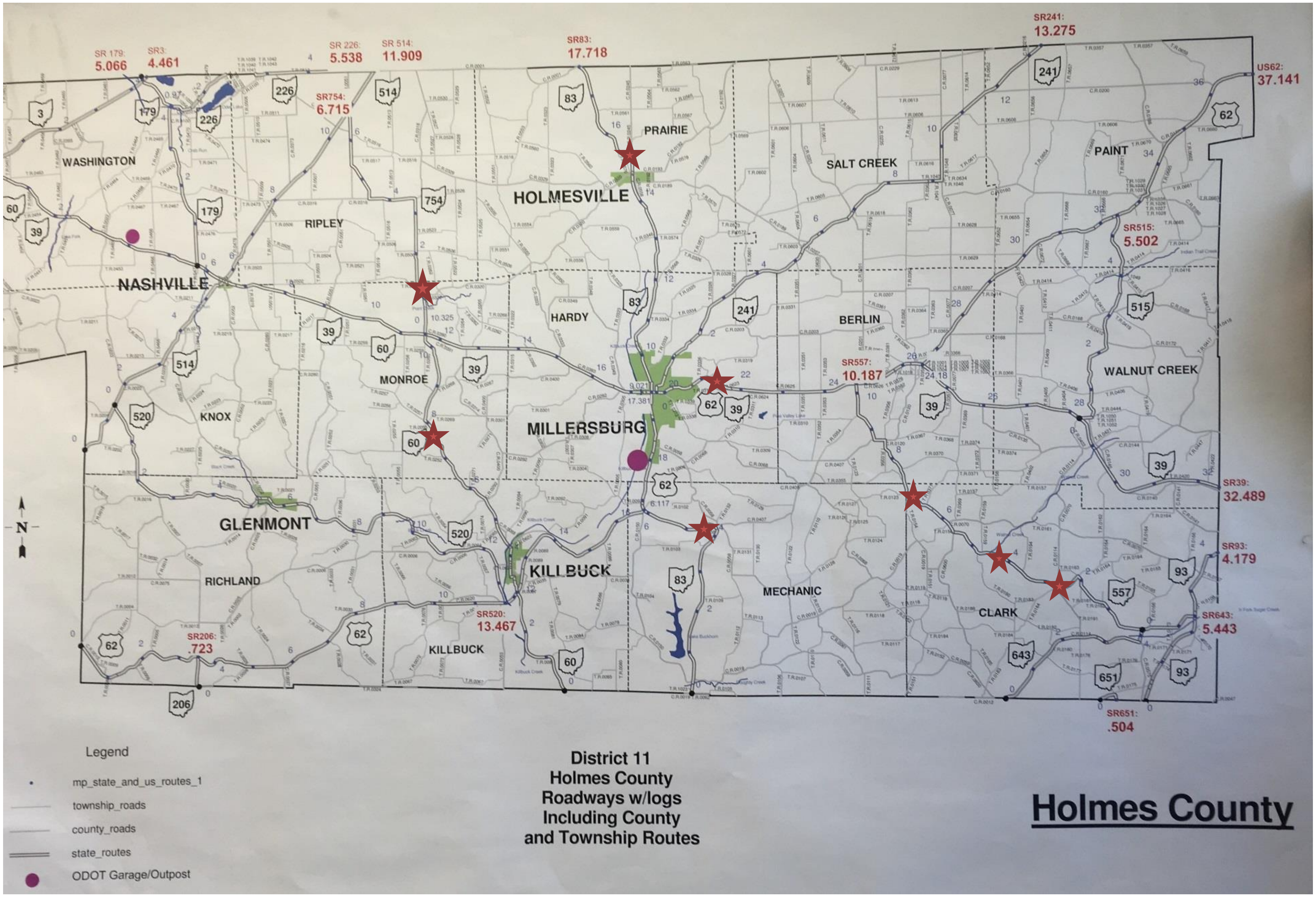
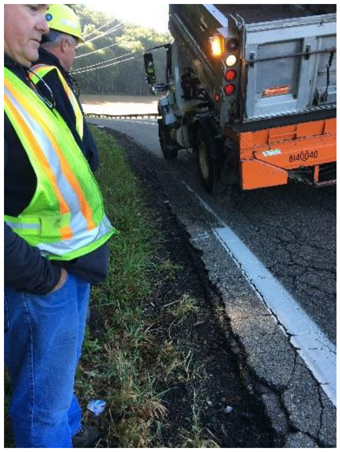
Appendix 1 Site visit maps and Photos



Site 1: SR-60, Station 7-8

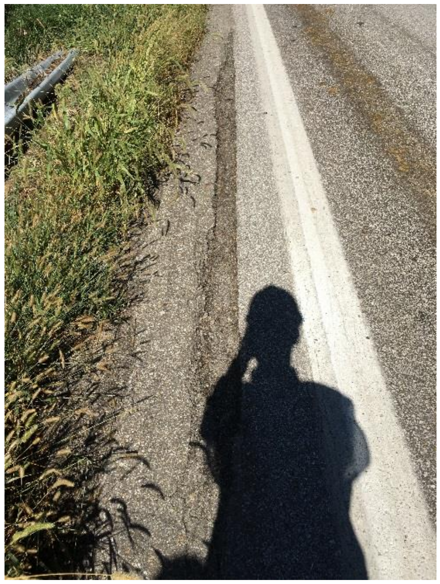
Site 2: SR-754, Station 1.0



Site 3: SR-39 or US-62, Station 21.2

Site 4: SR-557, Station 7.0 (buggy)

Site 5: SR-557, Station 4.4 (Buggy) (emulsion)



Site 6: SR-557, Station 2.6 (Trough, Culvert)

Site 7: SR-83, Station 4.5 (south of garage)




Site 8: SR-83, Station15.7 (sheet flow area)

Appendix 2 Cost-Benefit Analysis

Example Cases
A) Current Method:

This method consists of adding additional aggregates to the shoulder. The aggregates are compacted by four passes of the spreader truck.

Assumptions used in cost analysis:

1) The current method of shoulder reconditioning is carried out twice a year;
2) A lump rate of aggregate of $50/CY is used; this cost includes the material, labor and equipment; the cost information is obtained from the ODOT awarded contracts;
3) A treatment area is assumed to be 2 ft wide and 1 mile long.

Cost Calculation:
Length of Shoulder considered = 1 mile = 1760 yard
Width of Shoulder = 2 feet = 0.6666 yard
Thickness of aggregate in shoulder = 2 inches = 0.0554 yard
So, Volume of aggregate required = 1760 * 0.6666 * 0.0554 cubic yards = 64.996 cu.yards.
Rate of aggregate = $ 50/ CY.
Hence, Cost for current method = Volume * Rate = 64.996 * 50 = $ 3249.81

B) Geocell Method

Design: Three types of geocells are considered based on their heights. They are geocells with height of 3 inches, 4 inches and 6 inches. The geocells are infilled with the aggregates followed by an inch of aggregate top cover. The surface of the top cover is prepared and vegetation is planted on top of it, as shown in Figure A2-1.

Special requirement: To prevent the shifting of geocells from their original position, the anchors (rebar) are provided at certain locations. Based on the “Design and Installation Guidelines for Erosion Control” by Envirogrid, rebar with lengths of three times the height of geocells and one J-hook per square yard of geocell are used.

Aggregate usage: About half the volume of the aggregates required for the infill is available locally. Hence, only cost of 50% of new aggregates is included in the calculation.

Vegetation: Vegetation can be grown on the top layer either by sowing the seeds or by laying the vegetation sod. **Kentucky Bluegrass** is selected based on the accessibility and climatic conditions of Ohio. The initial cost for installation varies with the method adopted for growing the vegetation.

Maintenance: It is assumed that the geocell system requires two times of routine maintenance with an average maintenance cost of $350.00 per time.

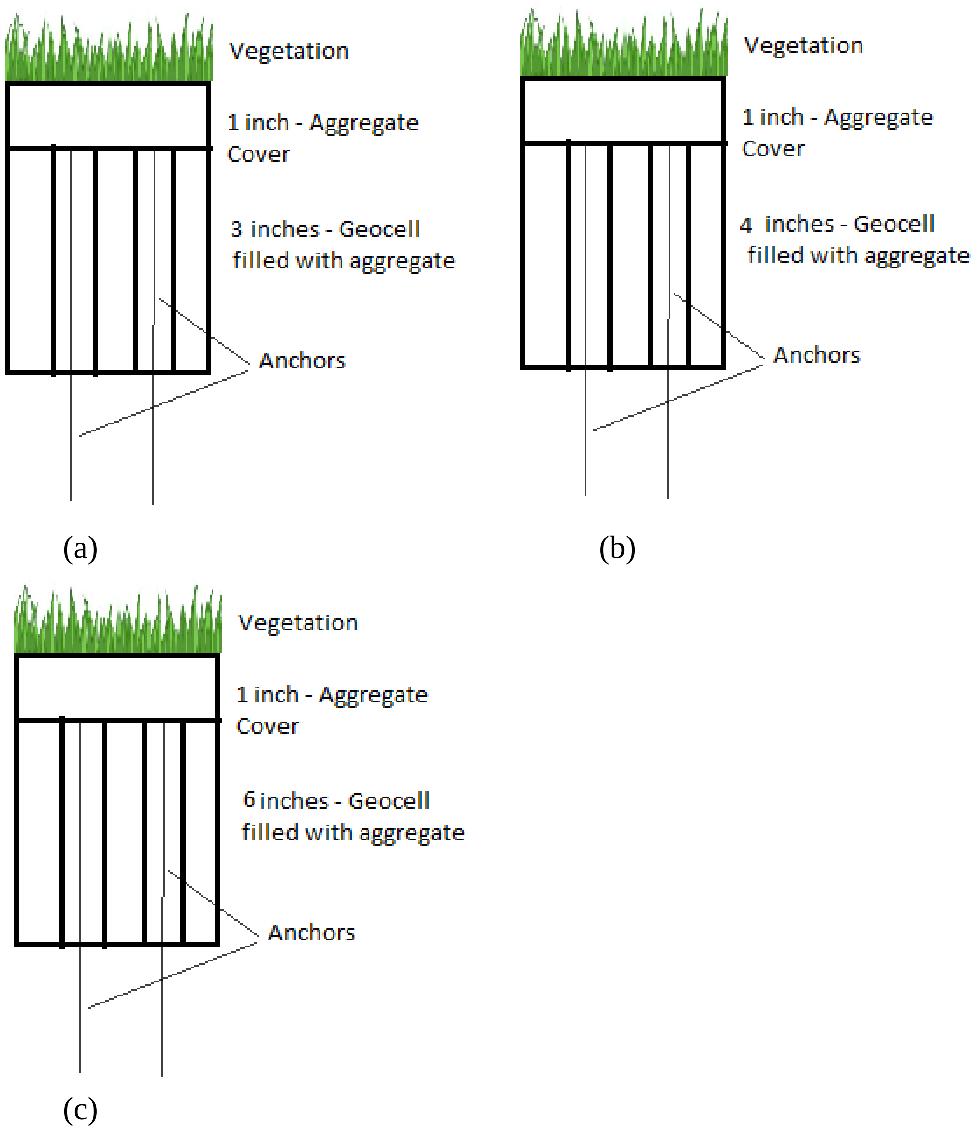


Figure A2-1. Design of geocell reinforced shoulder: (a) 3 inches- Geocell (b) 4 inches-Geocell and (c) 6 inches-Geocell

A sample spreadsheet is provided to showcase the calculation of the cost for geocell system with vegetation sod (Table 3); Assuming a service life of 10 years for the geocell system, the cost-benefit analysis is illustrated in Table A2-2.

Table A2-1: Sample cost calculation for Geocell with vegetation sod

	Thickness of Geocell = 6" Width of shoulder = 2' Thickness of top cover filled with aggregate = 1" So, total thickness of aggregate = 7"				
A)	Excavation:				
	Volume for excavation of 1-mile long, 2-ft wide and 7-in depth			227.5	Cu. Yards
	Unit price for excavation			10	$/ Cu. Yards
	Total cost for excavation			**2275**	$
B)	Aggregate:				
	For Volume of Aggregate in 1-mile length of shoulder on a single side:				
	Width of shoulder =	2	ft	0.6666	yard
	Thickness of aggregate used=	7	in	0.1939	yard
	Length of shoulder =	1	mile	1760	yard
	Volume of aggregate required			227.5	Cu. Yards
	Price of compacted aggregate per cubic yard			50	$/Cu.Y
	cost of aggregate for shoulder reconditioning per mile			**13649**	$
	cost of 50% aggregate for shoulder reconditioning per mile			**6824. 5**	$
B)	Geocell:				
	Total area to be covered by geocell			1173.216	Sq. yard
	Total area to be covered by geocell			10558.94	Sq. ft.
	Price of geocell			1.5	$/Ft2
	Cost of geocell			**15838.416**	$
C)	Vegetation:				
	Total area to be covered by vegetation (Kentucky Bluegrass)			10558.94	Sq. ft.
	Price of vegetation (Kentucky Bluegrass) sod			0.3	$/Ft2
	[source: http://www.improvenet.com/r/costs-and-prices/grass-sod]				
	Cost of vegetation (Kentucky Bluegrass) sod			**3167.68**	$
D)	Cost for Anchorage Rebars			**2094**	
	Hence, total cost for shoulder reconditioning per mile= Cost of Aggregate + Cost of Geocell + Cost of Vegetation Sod + Cost of Anchorage Bars **27,925.13** $				

Table A2-2: Sample cost-benefit analysis considering a service life of 10 years for the geocell system

	Cost benefit analysis considering a service life of 10 years				
1)	Cost of installing new method =				$27,925.13
2)	Cost of existing method =				$3,249.81
	Maintenance is carried out twice in a year				
	So, Cost of existing method per year =				$6,499.62
3)	Considering Maintenance cost for geocell and vegetation=				$350.00
	Maintenance is carried out twice in a year				
	So, maintenance cost per year=				$700.00
	Now,				
	Converting all costs to present worth				
		S.N.	Present value	Remarks	
		1)	$27,925.13	Installation Cost	
		2)	$52,717.71	Benefit	
		3)	$5,677.63	Maintenance Cost	
	So,				
		Total cost =		$33,602.76	
		Total Benefit =		$52,717.71	
			Benefit cost ratio	1.57	

From Tables A2-1 and Tables A2-2, the initial cost for geocell system with vegetation rod cover is $27,925.13/mile for two-feet-wide shoulders. This cost is much higher than the initial cost of $3,249.81/mile for Item 617 (i.e., replenishing). But since the geocell system requires much less maintenance work, the benefit to cost ratio considering a service life of 10 years is 1.57, which means it is more cost effective comparing to the traditional method in the long run.

Note that some cost items such as maintenance cost are assumed since there is no available data; also the service life of 10 years is also assumed. Once the data is available, the spreadsheet can be easily updated to reflect the changes.

The spreadsheets developed for calculating the benefit/cost ratio for each identified method in Table 11 is attached as Appendix 2-2.

Appendix 3 Literature review

A3.1 Vegetation

The vegetation along the roadway shoulder reduces the erosion as the roots hold the aggregate in position under all climatic and soil conditions. In Texas, establishment of vegetation is usually included in the TxDOT's construction contracts for road maintenance projects. Establishing vegetation on highway shoulders may be the most practical and economical method available for reducing soil erosion (Jensen and Uerling 2015).

A clear zone along the roadside, 6 feet or more wide and without any vegetation, was common practice until late 1980s. However, this has led to erosion and actually caused them to have to maintain the edges continuously for drop-off problems. Eventually the maintenance personal realized that vegetation at the pavement edge protects the edges from erosion, wind, and rain, and thus solves more problems than it causes. Establishment of vegetation is considered as a part of rehabilitation or new project, where the contractors are required to cover the base crown with top soil and establish vegetation at the pavement edge during the backfilling operation.

The major factor that affects the growth of vegetation is rainfall. In the case of Nebraska, road shoulders in the southeastern one-third of Nebraska are mostly vegetated due to sufficient rainfall. Shoulder maintenance work with vegetation includes placing soil or aggregates along the pavement edge to increase shoulder elevation and stabilize the soil or recovering material that has moved away from the pavement edge. The selection of vegetation species depends on many factors like time required for vegetation to establish and permanence.

Some seed mix specified for the Sandhills region of Nebraska is shown in Figure below:

Species	Minimum Purity (percent)	Lbs. of PLS/acre
Perennial ryegrass – Linn	85	7
Slender wheatgrass	85	5
Western wheatgrass – Rodan, Rosana, Barton, Flintlock	85	5
Kentucky fescue	85	3
Blue grama – NE, KS, CO, MN	30	2.5
Sideoats grama – Pierre, Butte	75	4
Sand dropseed (Sporobolus cryptandrus)	90	0.2
Sand lovegrass – NE-27, Nebraska native	90	1
Purple prairie clover – inoculated	90	0.2
Rye	90	16

A3.1.1 Temporary Seeding

They provide erosion control by planting appropriate rapidly growing annual grasses or small grains. They should be applied on exposed soil where additional work (grading, etc.) is not scheduled for more than 21 days. Whereas, permanent seeding should be applied if the areas will be idle for more than one year. Proper applications of temporary seeding help to achieve erosion control efficiencies greater than 90%.

Specifications
for
Temporary Seeding

Table 7.8.1 Temporary Seeding Species Selection

Seeding Dates	Species	Lb./1000 ft2	Lb/Acre
March 1 to August 15	Oats Tall Fescue Annual Ryegrass	3 1 1	128 (4 Bushel) 40 40
	Perennial Ryegrass Tall Fescue Annual Ryegrass	1 1 1	40 40 40
	Annual Ryegrass Perennial Ryegrass Creeping Red Fescue Kentucky Bluegrass	1.25 3.25 0.4 0.4	55 142 17 17
	Oats Tall Fescue Annual Ryegrass	3 1 1	128 (3 bushel) 40 40
August 16th to November	Rye Tall Fescue Annual Ryegrass	3 1 1	112 (2 bushel) 40 40
	Wheat Tall Fescue Annual Ryegrass	3 1 1	120 (2 bushel) 40 40
	Perennial Rye Tall Fescue Annual Ryegrass	1 1 1	40 40 40
	Annual Ryegrass Perennial Ryegrass Creeping Red Fescue Kentucky Bluegrass	1.25 3.25 0.4 0.4	40 40 40
November 1 to Feb. 29	Use mulch only or dormant seeding		

Note: Other approved species may be substituted.

A3.1.2 Permanent Seeding

Permanent vegetation is used to stabilize soil, prevent sediment pollution, reduce erosion, reduce runoff by promoting infiltration, and provide stormwater quality benefits offered by dense grass cover.

Table 7.10.2 Permanent Seeding

Seed Mix	Seeding Rate		Notes:
	Lbs./acre	Lbs./1,000 Sq. Feet	
General Use			
Creeping Red Fescue Domestic Ryegrass Kentucky Bluegrass	20-40 10-20 20-40	1/2-1 1/4-1/2 1/2-1	For close mowing & for waterways with <2.0 ft/sec velocity
Tall Fescue	40-50	1-1 1/4	
Turf-type (dwarf) Fescue	90	2 1/4	
Steep Banks or Cut Slopes			
Tall Fescue	40-50	1-1 1/4	
Crown Vetch Tall Fescue	10-20 20-30	1/4-1/2 1/2-3/4	Do not seed later than August
Flat Pea Tall Fescue	20-25 20-30	1/2-3/4 1/2-3/4	Do not seed later than August
Road Ditches and Swales			
Tall Fescue	40-50	1-11/4	
Turf-type (Dwarf) Fescue Kentucky Bluegrass	90 5	2 1/4 0.1	
Lawns			
Kentucky Bluegrass Perennial Ryegrass	100-120	2 2	
Kentucky Bluegrass Creeping Red Fescue	100-120	2 1-1/2	For shaded areas

Note: Other approved seed species may be substituted.

A3.1.3. Selection of optimum grass for erosion control in Ohio

Characteristics of perennial cool-season grasses in the Northeast:

Table 1. Characteristics of perennial cool-season grasses in the Northeast.

Grass	Seedling vigor	Tolerance to soil limitations			Winter survival rate	Tolerance frequency	Relative maturity[b]
		Dry	Wet	Low pH[a]			
Kentucky bluegrass	M[c]	L	M	M	H	H	Early
Orchardgrass	H	M	M	M	M	H	Early-medium
Perennial ryegrass	H	L	M	M	L	H	Early-medium
Reed canarygrass	L	H	H	H	H	H	Medium-late
Smooth bromegrass	H	H	M	M	H	L	Medium-late
Tall fescue	H	M	M	H	M	H	Medium-late
Timothy	M	L	L	M	H	L	Late

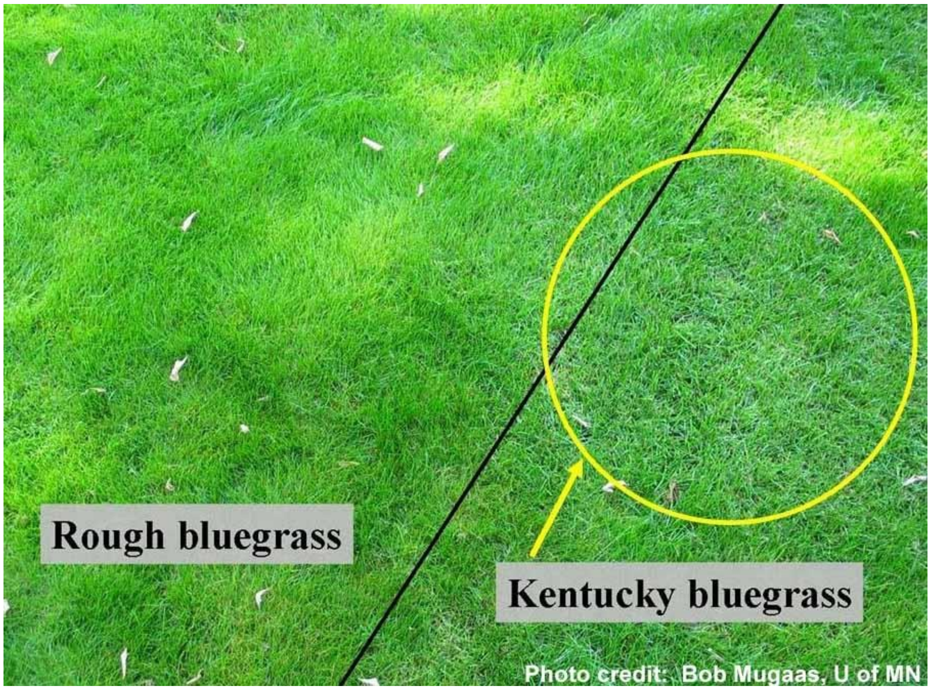
[a]pH of 6.0
[b]Maturity characteristic refers to relative time of seed head appearance in the spring, which will depend not only on species but also on variety.
[c]L = low, M = moderate, H = high

Findings from Texas study:

- Many districts sow Buffalo grass or Bermuda grass (in some districts) along the highway shoulders as the last step of rehabilitation or repair.
- The varieties of burmuda grasses available till date do not have the cold tolerance. Thus, they require special care to survive Ohio winters.
- Buffalo grass can tolerate extreme drought and extreme temperatures, once they are established. However, they are only occasionally planted in Ohio as low maintenance plant.

Characteristics of Kentucky Bluegrass:

- Seedhead stems are 18 to 24 inches tall, but can be 4 to 6 inches in height when used for grazing.
- Because of its dense, vigorous turf forming habit, it is considered as an excellent for erosion control.
- It can be used alone or as a mix with legumes or other grasses for erosion control.



- They are best adapted to well-drained, fertile, medium-textured soils of limestone origin. However, they perform satisfactorily on poorly drained and heavy-textured soils.
- The optimum temperature for forage production is between 60 °F and 90°F. However, they can survive extreme temperatures.
- They should be cut low going into winter, especially where heavy snow cover is expected.

Characteristics of Tall Fescue:

It was widely used in the past as a forage and erosion control plant since it is easy to establish and long lived under harsh conditions and mistreatment. However, it is realized that the presence of endophytic fungus in this grass may be harmful to the wildlife.

References:

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A3.2. Turf reinforced Mats

A3.2.1. TERMs Vs PERMs

TERMs refer to temporary erosion and revegetation materials and PERMs stand for permanent erosion and revegetation materials. TERMs consist of temporary nature materials which facilitate vegetative establishment, then degrade. They are suitable for areas where vegetation alone can provide adequate long term erosion protection. But, for those areas where vegetation alone cannot provide adequate long term erosion protection, and require reinforcement, PERMs are required to be applied.

Vegetation established along with the geosynthetic materials provide better way for erosion and sediment control. This reinforced vegetation provides 'permanent' medium to high flow resistance. The biotechnical composite materials below represent some Permanent erosion and revegetation materials (PERM):

-UV stabilized fiber roving systems (FRSs).
-Erosion control revegetation mats (ECRMs).
-Tuff reinforcement mats (TRMs).
-Sports turf geofibers.
-Vegetated geocellular containment systems (GCSs).
-Vegetated concrete block systems.

A3.2.2. TRM Vs ECRM

Turf reinforcement consists of flexible three dimensional geosynthetic matrix, which retains seeds and soil, stimulates seed germination and accelerates seedling development to protect soil from erosion. The better performance has resulted in the widespread practice of turf reinforcement as an alternative to concrete, rip rap and other armor systems.

TRMs are installed first, then seeded and filled with soil while ECRMs are seeded prior to installation. In general, **TRMs** provide sufficient thickness and void space to permit soil filling, the development of vegetation within the matrix and long term performance than **ECRMs**. The nature of installation shows that TRMs can provide more vegetative entanglement and long term performance whereas denser ECRMs may provide superior temporary erosion protection.

A3.2.3. Fiber Roving System:

They consist of material formed from fibers drawn from **molten glass** and gathered into strands to form a single ribbon. They provide moderate erosion protection. The use of such fiberglass roving has been declining these days due to carcinogenic effects and is being replaced by environmentally friendly polypropylene roving.

A3.2.4. Geocellular containment systems (GCSs):

GCSs look like a large honeycomb and stabilize the soil by confining in a series of three dimensional cells up to 20 cm deep. The cells are laid into position and backfilled with sand or gravel depending upon application. The soil-backfilled cells are then seeded and fertilized for revegetation. Vegetated GCSs limit the flow velocity to 2 to 3 m/s and sustain scouring under high flow velocities (Chen & Anderson, 1986). They may be also filled with concrete or gravel to create a hard armor system in case of higher flow conditions.

A3.2.5. Concrete block systems:

They consist of prefabricated concrete panels which may be attached to and laid upon a woven or non-woven geotextile. They may be subdivided into three groups: non-tied interlocking blocks, cable-tied blocks, or in-situ concrete (Hewlett *et al.*, 1987). The entire erosion control section may be manufactured, trucked to the job site and placed as a unit in certain cases. The concrete blocks accommodate bending and torsion.

The long term erosion control may be accomplished more rapidly when the vegetation becomes established more rapidly. Flow resistance is the most important parameter in an engineering design before, during and long after vegetative establishment. So, the materials having long term flow resistance should be selected based upon longevity of the material.

Flow duration should be taken into account while selecting the control measure and materials. Generally, a major precipitation will produce significant flow velocities with durations lasting hours or days--not minutes. This duration of flow will reduce the erosion resistance of a vegetated surface.

References:

M. S. Theisen, "The Role of Geosynthetics in Erosion and Sediment Control", 1992.

William D. Lawson, And M. Shabbir Hossain, Best Practices for Pavement Edge Maintenance Research Report, May 2004.

Jensen and Uerling, Mitigating Pavement Edge Drop off, Nebraska Department of Roads, 2015.

A3. 3. Chemical methods

A3.3.1 Findings from "Stabilization Selection Guide for Aggregate and Native- Surfaced Low Volume Roads" by US Department of Agriculture

S. N.	Method	Typical Use	Equipment	Life Expectancy	Erosion Control	Cost
1	Chloride	Dust suppressant	Haul vehicles, spreader or tanker with spray bar, grading equipment, water truck and pneumatic tire roller	CaCl2 (3 to 6 months- 71%; and 6 to 12 months- 21%) MgCl2 (3 to 6 months- 33 %; and 6 to 12- months 42 %)	reduce the amount of erosion compared to an untreated unbound surfacing	Supply Price: \$360 to \$450/Mg (\$400 to \$500/ton) Supply+Install Price: \$0.30 to \$0.60/m2 (\$0.25 to \$0.50/yd2) for surface treatment
2	Clay Additives	Dust suppressant, soil stabilizer	tanker or water truck with spray bar, grading equipment, and roller	2 to 4 years	reduce the erodibility of the unbound roadway surface by binding surface particles together	Supply Price: \$145 to \$181/Mg (\$160 to \$200/ton) Supply+Install Price: \$10.60 to \$14.10/m3 (\$8.10 to \$10.80/yd3) for an aggregate stabilized with clay
3	Electrolyte Emulsions	Dust suppressant, soil stabilizer	tanker or water truck with spray bar, grading equipment, and roller	3 to 5 years, some treated surfaces still in service after 15 years or more	reduce the erodibility of the unbound roadway surface	Supply Price: N/A Supply+Install Price: \$0.40 to \$0.80/m2 (\$0.35 to \$0.70/yd2)
4	Enzymatic Emulsions	Dust suppressant, soil stabilizer	tanker or water truck with spray bar, grading equipment, and roller	5 to 7 years, some treated surfaces still in service after 12 years or more	reduce the erodibility of the unbound roadway surface	Supply Price: N/A Supply+Install Price: \$2.40 to \$4.80/m2 (\$2.00 to \$4.00/yd2) for mixing to a depth of 150 mm (6 in.)
5	Synthetic Polymer Emulsions	Dust suppressant, soil stabilizer	Tanker or water truck with spray bar, disc or rotary mixer, grading equipment, and roller.	6 months to 1 year for dust suppression; 5 to 10 years for stabilization applications	reduce the erodibility of the unbound roadway surface	Supply Price: \$0.80 to \$4.25/L (\$3.00 to \$16.00/gal) Supply+Install Price: \$2.40 to \$14.30/m2 (\$2.00 to \$12.00/yd2) for mixing to a depth of 150 mm (6 in)
6	Tree Resin Emulsions	Dust suppressant, soil stabilizer	tanker or water truck with spray bar, disc or rotary mixer, grading equipment, and roller	6 months for dust suppression applications; 5 to 10 years or more for stabilization applications	reduce the erodibility of the unbound roadway surface	Supply Price: N/A Supply+Install Price: \$21.40 to \$53.60/m2 (\$18.00 to \$45.00/yd2) for 50 mm (2 in) thick stabilized aggregate layer

Reference: Stabilization Selection Guide for Aggregate and Native- Surfaced Low Volume Roads, US Department of Agriculture, Forest Service, National Technology and Development Program, March 2009.

A3.3.2 Chemical additives

Terrasil and Zycobond

Terrasil is organo silane, water dissolvable, bright and warmth steady, receptive soil modifier that is used to waterproof soil subgrade. The Characteristics of Terrasil are:

- wipes out narrow ascent and water entrance from top
- reduces water penetrability of soil bases while keeping up 100% vapor porousness
- reduces expansively and free swell
- keeps up dry CBR under wet conditions
- holds quality of road bases and expands imperviousness to deformation by keeping up frictional values between residue and controls disintegration of soils.

Zycobond is acrylic co-polymer that holds soil particles as well as help in dust suppressant. It is mixed with Terrasil solution for one step waterproofing and bonding of compacted soils. It bonds the soil particles to resist soil erosion in side shoulders and slopes. Furthermore, it enhances quality of soil layer, increases quick drying of soil layers/ earth road after downpours, reduces undulations and low maintenance costs.

From economy perspective advantage, the usage of Terrasil (0.041%) + zycobond (0.020%) is fascinating and provides the support in improvement of road development. Also, it is found that the quality of subgrade soil is enhanced consequently expanding the load carrying limit of pavement.

Reference:

Nandan A. Patel1, C. B. Mishra2, D. K. Parmar3, Saurabh B. Gautam4, Subgrade Soil Stabilization using Chemical Additives, July-2015.

Calcium Chloride for Base Stabilization

Procedure:

1) Scarify the existing granular surface.
2) Select and add aggregate as needed.
3) Add 75% calcium chloride by weight of aggregate. Spray a 35% solution of liquid calcium chloride evenly over the road.
4) Mix all materials.
5) Compact the surface uniformly.
6) Add 0.25% calcium chloride by weight of aggregate to seal the surface.

Findings from “Surface Aggregate Stabilization with Chloride materials”:

1) Economic benefits of stabilization are greatest on projects well suited for stabilization, that have high traffic volumes, and that have high costs for aggregate replacement.
2) The average initial performance period for the treated sections lasted eight times longer than the untreated sections
3) Average speed on treated sections was 37 miles per hour and the average speed on untreated sections was 26 miles per hour for the 2- year period.

4) Visual observations indicate treated sections reduced the dust by approximately 90 percent, thus reducing inhalation health hazard.
5) No distinct difference in performance existed between the four different products: magnesium chloride liquid, calcium chloride liquid, and calcium chloride solid at 77- and 94-percent salt concentration.
6) Chloride stabilization does not improve resistance to surface erosion or pothole formation. Road crown is the primary deterrent to the formation of potholes and surface erosion.

References:

Steve Monlux, Michael R. Mitchell, Surface Aggregate Stabilization with Chloride materials, December 2006.

Calcium Chloride – The essential element for roads, Peters Company, http://www.peterschemical.com/calcium-chloride-the-essential-element-for-better-roads/

Pitch emulsion for Erosion Control of Road Shoulders

1) effective at sealing granular shoulders and prevents erosion for minimum of two years.
2) forms wind and water-proof barrier.
3) reduces short and long term maintenance costs from new aggregate, grading crews and equipment and from asphalt repairs while improving safety
4) Custom lengths of spray bar ensure the entire shoulder area is reached in the most economical manner with no over-spray

A3.3.3 Case studies involving chemical stabilization of shoulder for erosion control

Roosevelt (2005) investigated the effectiveness and potential cost benefit of using two soil stabilizers (Soiltac and Centrophase AD) with crusher run stone shoulder material. The soil additive is deeply mixed with the aggregate and properly compacted on 500-ft highway sections following the procedure outlined by Bushman et al. (2005). This process is generally known as full-depth reclamation (FDR). However, the preliminary experimental test results indicated that soil stabilizers mixed with crusher run stone neither increased its stiffness nor prolonged the period of its optimum strength. ***The experimental data are insufficient to judge if these soil stabilizers help increase the resistance of granular shoulders to water- or wind-induced erosion.*** The authors recommended conducting an additional study of soil stabilizers as a short-term solution to shoulder erosion. The cost benefit analysis conducted by Roosevelt (2005) indicated that the use of soil stabilizers is ***not*** a cost-effective alternative to proper design or preventive maintenance practices as originally proposed. As a result, this study suggests designing shoulders in accordance with the anticipated traffic load. Based on the cost analysis study by Souleyrette et al. (2001), the Virginia DOT adopted a policy to pave all shoulders on new construction projects when the anticipated average daily traffic (ADT) exceeds 2000.

White et al. (2007) evaluated the performance of several chemical stabilizers including polymer emulsion, foamed asphalt with fly ash, soybean oil, and Portland cement. The results indicated that stabilization of a granular surface using Portland cement, polymer emulsions, and soybean oil showed improvement in stability. By conducting a cost estimate analysis, however, it demonstrated that the monetary benefits of the reduced granular shoulder maintenance costs are ***small*** in comparison to the required investment. But the authors also pointed out that the investment in shoulder improvements would certainly result in an improved level of service, greater safety, and other benefits that are more difficult to quantify.

Maine DOT (2007a) conducted a study to investigate the effectiveness of utilizing lignosulfonate, a non-toxic by-product of the paper manufacturing process, for gravel shoulder stabilization. It was found that both experimental and control sections performed very well after being exposed for two years. The experimental section only showed a slight reduction of erosion lines, and the Maine DOT Maintenance Department decided to regrade the shoulders of the experimental section. In the same year, Maine DOT (2007b) conducted a project that investigated the effectiveness of using Portland cement together with recycled asphalt pavement (RAP) milled from the highway to stabilize and reinforce the shoulders adjacent to existing concrete slabs. The rehabilitated shoulders were shown to have held up for 6 years. However, the unit cost for this project is ***very high*** (about $389,400/mi). Still, this method is considered as a viable alternative based on the specific requirement for shoulder preservation and stabilization.

In summary, chemical stabilization can improve the stability and erosional resistance of the granular shoulders ***only if*** the proper gradation, mixture and process are ensured. In addition, chemical stabilization is usually a ***costly*** process and may not be worth the investment.

References:

- Bushman, W., Freeman, T., and Hoppe, E. (2005). "Stabilization techniques for unpaved roads." *Transportation Research Record: Journal of the Transportation Research Board*(1936), 28-33.
- Maine DOT, T. R. D. (2007a). "Utilizing lignosulfonates for gravel shoulder stabilization." MaineDOT Transportation Research Division.
- Maine DOT, T. R. D. (2007b). "Shoulder rehabilitation using Portland cement and recycled asphalt pavement." MaineDOT Transportation Research Division.
- Roosevelt, D. S. (2005). "Use of Soil Stabilizers on Highway Shoulders." Virginia Department of Transportation 36 p.
- Souleyrette, R., McDonald, T., Hans, Z., Kamyab, A., Welch, T., and Storm, B. (2001). "Paved shoulders on primary highways in Iowa: An analysis of shoulder surfacing criteria, costs, and benefits." Office of Traffic and Safety of the Iowa Department of Transportation.
- White, D. J., Mekkawy, M., Jahren, C. T., Smith, D., and Suleiman, M. (2007). "Effective shoulder design and maintenance." Iowa Highway Research Board; Iowa Department of Transportation.

A3.4. Mechanical Stabilization:

Mechanical stabilization of the shoulders involves placing geo-synthetic products (meshes and grids) to hold the aggregates in place. Geosynthetics are widely used as the construction materials for geotechnical and environmental applications in most parts of the world. They constitute manufactured materials, new products and they provide solutions to routine and critical problems alike. Generally, geosynthetics used for soil reinforcement include geotextiles (particularly woven geotextiles), geogrids and geocells.

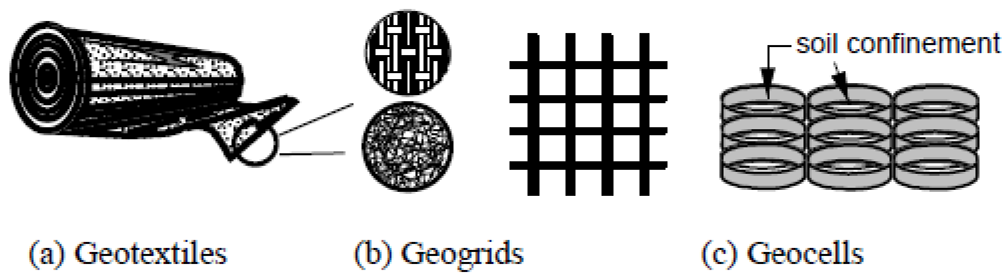


Figure 1: Geosynthetics commonly used for soil reinforcement (Bathurst 2007)

Geotextiles are flexible and permeable fabrics, which may be woven, nonwoven, knitted or stitch-bonded fibers or yarns. They are permeable enough to allow the flow of fluids through them and are usually made from synthetic polymers which do not decay under biological and chemical processes. . The geotextile should allow the movement of water while retaining the soil fines or sand particles without clogging or plugging. There are generally two approaches of using geotextile in the design of temporary and unpaved roads. The first assumes the use of geotextile as separator only while the second consider it’s possible reinforcing effect.

Geogrids have uniform longitudinal and transverse elements that allow direct contact between soil particles on either side of the sheet. They offer soil layer with higher resistance to penetration by limiting the downward movement of aggregates larger than the mesh openings.

Geocells are relatively thick, three-dimensional networks and their polymeric strips are joined together to form interconnected cells that are infilled with soil and sometimes concrete. They confine the infill materials within a three-dimensional framework, creating a composite layer with increased strength.

The method of mechanical stabilization is generally expensive to be used for stabilizing shoulders on minor roads. However, it may be useful for shoulder stabilization on roads with high traffic volumes.

A.3.4.1. The Role of Geosynthetics in Erosion and Sediment Control

Geosynthetics have found its use from the late 1950s and it has now become the backbone of the erosion and sediment control industry. There are various geosynthetic materials currently used for temporary as well as long term erosion and sediment control.

Temporary solution products: hydraulic mulch geofibers, plastic erosion control meshes and nettings, erosion control blankets and silt fences.

Long Term solution products: high performance turf reinforcement mats, geocellular confinement systems, erosion control geotextiles and fabric formed revetments.

The long term erosion control may be accomplished more rapidly when the vegetation becomes established more rapidly. Flow resistance is the most important parameter in an engineering design before, during and long after vegetative establishment. So, the materials having long term flow resistance should be selected based upon longevity of the material.

Flow duration should be taken into account while selecting the control measure and materials. Generally, a major precipitation will produce significant flow velocities with durations lasting hours or days--not minutes. This duration of flow will reduce the erosion resistance of a vegetated surface.

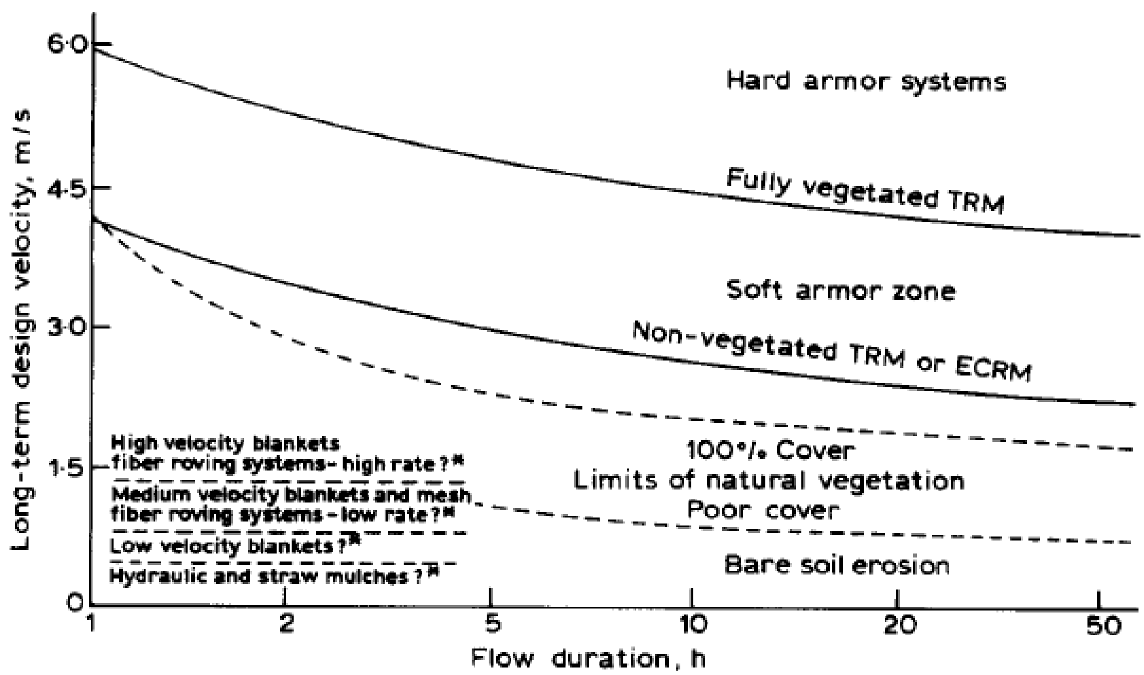


Fig. 1. Recommended maximum design velocities for various erosion control materials. *No known published data for flows exceeding 0·5 h.

The above figure combines cumulative research for several erosion control materials and tries to group categories of erosion control materials into their cost effective design. Thus, the designer will have an idea about performance guidelines from the time a material is installed to when it becomes fully vegetated.

Reference:

- M. S. Theisen, “The Role of Geosynthetics in Erosion and Sediment Control”, 1992.

A.3.4.2. Case Studies involving Geosynthetics for stabilization of unpaved shouders

1) Field observations on stabilization of unpaved roads with geosynthetics

In this paper, the performance comparison of an unreinforced section, three sections with different geotextiles, and a section with geogrid on an unpaved road on soft ground are described. It also suggest some ways to select the type of geosynthetic for particular type of construction based on separation and reinforcement. The test section consists of following properties:
Subgrade soil - soft clayey silt of undrained shear strength 40 kPa(approximately).
Base course layer thickness - 0.25 m to 0.5 m and compacted to a dry density 96% (approx.) of the maximum dry density.

The measurements of rut depth and base course layer thickness in the channelized wheel path, cross-sectional profiles of the road surface and of the deformed geosynthetic, and strain in the geosynthetic, with a cumulative number of vehicle passes were considered for comparing the performance.

The unreinforced section developed an initial rutting that is independent of base course layer thickness. Analytical approach of Giroud and Noiray (1981) greatly over predicts the number of vehicle passes to develop a 5 cm rut. Thus, they are applicable to unpaved roads that do not experience compaction of the gravel base course layer during trafficking.

The trafficability increases after the application of geosynthetics. On thin base course, separation of particles appear to very important for maximizing the potential benefit of a geosynthetic inclusion whereas, on thick base course, reinforcement becomes more important for an efficient mobilization of tensile strength through interlock and stiffness. **Thus, geotextiles outperform geogrid on thin base course and geogrid outperform geotextile on thick base course.**

2) Large scale tests on geosynthetic reinforced unpaved roads subjected to surface maintenance

This paper basically deals with the study of reinforcing the unpaved roads on poor subgrade using geosynthetics. In this test, a non woven **geotextile and a geogrid** were installed at the fill-subgrade interface that serves as reinforcing layer. Three cyclic loading stages were applied up to a rut depth in each test as well as monotonic loading tests were also carried out for comparisons. The test results show that the reinforced section with geosynthetic performed markedly better than the unreinforced section. The higher value of Traffic Benefit Ratio (TBR) was obtained which varied between 2.3 and 9.2, depending on the type of reinforcement and loading stage considered. **Geogrid reinforced section has the larger TBR** value than the geotextile reinforced section. The vertical stress and vertical strains in the subgrade were significantly reduced after the application of reinforcement. Moreover, the load spreading angle increased from 25^0 for the unreinforced road to 43^0 and 48^0 for the geotextile and for the geogrid reinforced roads, respectively.

Monotonic loading tests on unreinforced and on geogrid reinforced Tests show that **gravel breakage was significantly less in tests on geogrid reinforced road** in this test than under cyclic loading tests.

Also, the cost-effectiveness study suggest the use of geogrid reinforcement since it reduces the maintenance works which can yield to important savings in the overall cost of the road though initial cost of the reinforced unpaved road is higher.

3) Comparative Analysis of Geosynthetic Reinforced, Biologically Engineered Vegetation Road Shoulder Stabilization to Conventional Methodologies

In this research, the geo-block and geo-web materials were used to evaluate the effectiveness of the biologically engineered and geosynthetic reinforced road shoulder regarding its ability to reduce runoff and erosion. The project also performed a preliminary cost analysis regarding the implementation of new design as compared with the existing design procedures. The control section and experimental section were prepared for each test.

The results obtained from the tests performed for each design is given with respect to its own control section:

Table: Summary of results obtained from two capstone design projects.

	Geo-block Design	Geo-web Design
Storm intensity (in/hr)	11	5.3
Direct surface runoff (DSR)	Reduced 42%	Reduced 83%
Sediment erosion (TSS)	Reduced 200%	Reduced 47%
Percent vegetative cover	100% cover	100% cover
Load stabilization	Successful	*

* Due to size limitations in the testing pans, this data is inconclusive; however, the manufacturer's specifications indicate that geo-web is able to adequately support an 80-psi load.

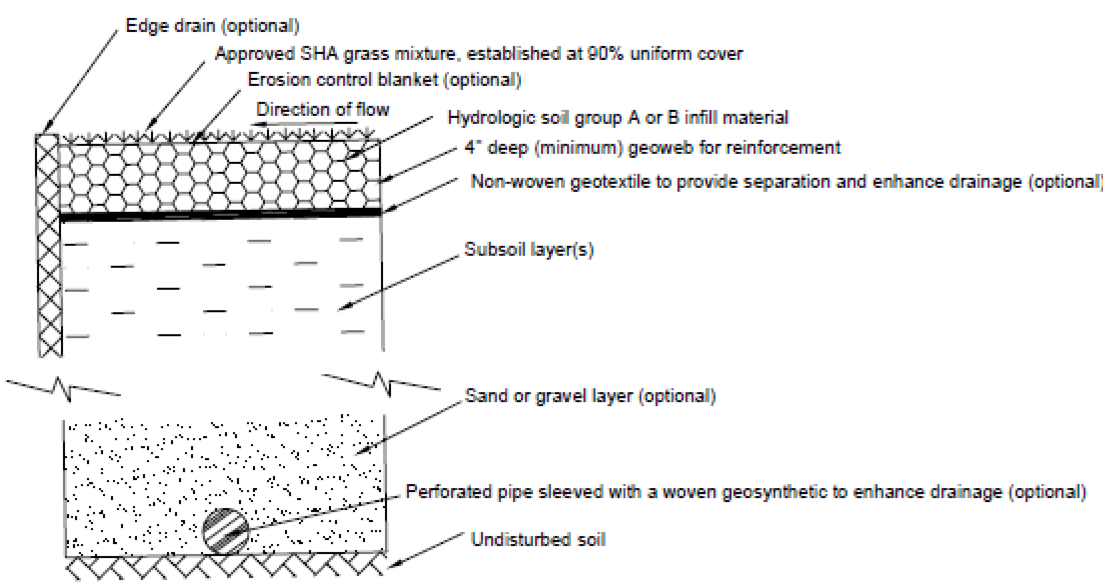


Figure: Profile of a composite geoweb road shoulder backfill system.

The results obtained from this study showed that geosynthetic reinforced, biologically engineered road shoulder stabilization has a significant advantage over the conventional methods. **The experiments conducted also showed that this design could be cost effective and reduced the runoff and erosion greatly. The initial cost to install this system is high which may be between two to seven times that of the practices currently in use, but with this system, the design life maintenance and environmental degradation costs are perceived to be minimal, unlike those of the existing practices in use.**

4) Use of Geocell as A Reinforcing Material for Unpaved Road Sections:

In this paper, the effectiveness of planar and geocell layer in reinforcing aggregate bases constructed over weak subgrade is investigated. CBR tests were carried out under static loading and in field studies, moving vehicle load was simulated at uniform speed of 20 Kmph for a maximum of 250 passes. The studies show that the effectiveness of geocell is dependent on its aspect ratio and the density of the infill material.

The experimental studies suggest that **geocells are more effective than planar reinforcements** and maximum benefit using geocell can be obtained at an aspect ratio between 1 to 1.67. Even an aspect ratio of 0.25 had considerable improvement over unreinforced test sections in the field tests. Thus, it is concluded that geocells are effective as a reinforcing material because of its confining action and its effectiveness depends on aspect ratio, the type of infill material and the strength of the reinforcing material used for its formation.

5) Critical Appraisal on Utilization of Geocell for Improving the Unpaved or Earthen Shoulder:

Geocells are placed at sub base, in-filled with soil material, and compacted and are mainly used for confinement of granular material. They reduce rutting or permanent deformations under traffic loading by providing lateral and vertical confinement and increasing the bearing capacity as well as wider stress distribution.

Figure: Close view of geocell pockets.

The study shows that geocell reinforcement is proved to be a versatile method in terms of its cost effectiveness and it prevents the lateral spreading of soil on the application of load by providing all round confinement to the materials. Also, it is found that the geocell layer increases the bearing capacity of the infill materials up to three times compared to unreinforced soil.

6) Stabilization of Unpaved Shoulders on Moderate and Weak Subgrade Using Geosynthetics

This paper presents the investigation for two types of geosynthetic products, geocell and geogrid, for their application for stabilization of unpaved shoulders on moderate and weak subgrade. The effectiveness of geocell and geogrid in improving the structural capacity of base courses was investigated by comparing the permanent deformations and vertical interface stresses between unreinforced and reinforced test sections. Two benefits of using geosynthetics as identified in the study are:

1) Confinement of the subgrade soil between and beyond the wheel areas, and
2) Reduction of the pressure applied by the wheels on the subgrade soil.

Traffic Beneficial Ratio (TBR) is used to evaluate the benefits provided by geosynthetic reinforcement. It is defined as the the ratio of the number of cycles, at a specific permanent deformation, for the test section with geosynthetic reinforcement to that without over the same subgrade condition.

i.e. $TBR = \frac{\text{Nreinforced}}{\text{Nunreinforced}}$

The calculated TBR at different deformations are listed in the table below:

Table: TBR at Different Permanent Deformations Provided by Geosynthetics

Section			TBR at Permanent Deformation (mm)		
Subgrade CBR	Base course	Reinforcement	25	50	70
3%	AB-3	Geogrid	1.9	2.0	2.6
5%	AB-3	Geogrid	3.6	3.9	
3%	Mixture	Geogrid	2.1	2.7	3.8
5%	Mixture	Geogrid	1.8	4.8	
5%	Mixture	Geocell	51.4		

This shows that the geosynthetic-reinforced mixture bases had a larger number of load cycles than the conventional aggregate base. Therefore, aggregate can be replaced with the geosynthetic-reinforced mixture in the application of unpaved shoulders or roads.

In the design of unpaved roads, aggregate bases are preferred because they are more effective to support loads. A thinner geosynthetic-reinforced base course is needed than an unreinforced base course to achieve the same performance (i.e., same tolerable permanent deformation). **As geocell can provide better lateral confinement, geocell is more effective in improving the**

performance of the soil-aggregate mixture base than geogrid. Since geogrid costs less than geocell, geogrid is considered as more cost-effective when aggregate base is used.

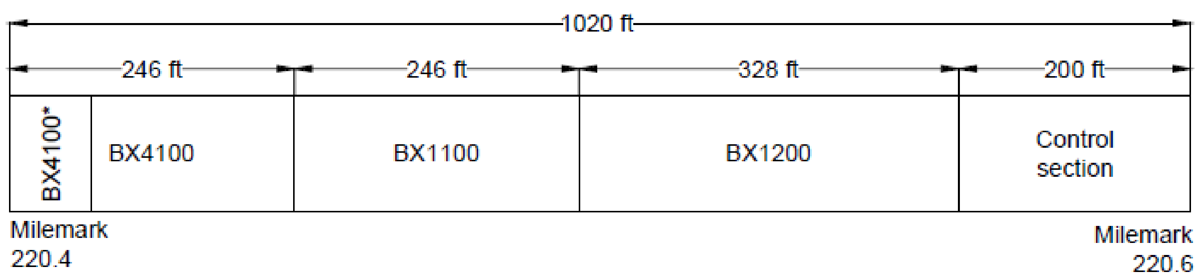
7) Test Section: Geosynthetic Stabilization of Granular Shoulder:

The problematic shoulder section, experiencing severe rutting due to soft subgrade conditions, was identified by driving a fully loaded dump truck (47,040 lb.) over the shoulder section and then measuring the rut depth at pre-identified locations along the wheel path, conducting CIV tests, and DCP tests. Three geogrid types, Tensar BX1200, BX1100, and BX4100, were selected to stabilize the shoulder section approximately 1,020 ft. long and 8 ft. wide. The first 200 ft. control section was left unstabilized. Following the control section was a long section stabilized with BX1200 geogrid (328ft). Two sections, each 246 ft. long, followed the BX1200 section and were stabilized with either BX1100 or BX4100.

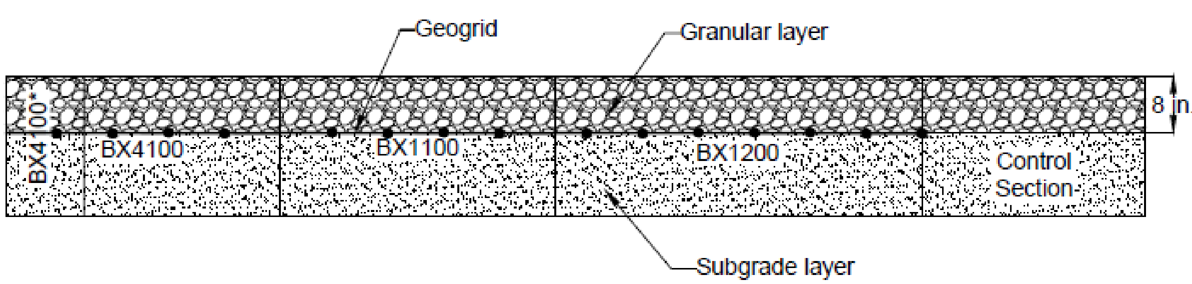
Table :Mechanical properties and costs of the selected geogrids

Geogrid	Aperture stability (Kg-cm/deg)	Aperture dimension (in.)		Cost per yd^2, installed ($)
		MD[a]	XMD[b]	
BX 1200	6.5	1.0	1.3	3.50–3.75
BX 1100	3.2	1.0	1.3	2.50–2.75
BX 4100	2.8	1.3	1.3	1.50–1.75

[a] MD: Machine direction
[b] XMD: Cross machine direction



(a) Plan view



(b) Cross section

Figure : Proposed test sections

Field Reconstruction Process:

1) The top granular layer contaminated with clay was removed from the underlying subgrade layer.
2) The virgin aggregate was placed on the pavement next to the test section.
3) The subgrade was leveled using a skid loader and then compacted using a pneumatic roller.
4) The geogrid pieces were cut to 8 ft. wide to match the width of the stabilized area.
5) The geogrids were rolled over the soft subgrade layer.
6) The geogrids were overlapped about 2 ft. in the direction of spreading the aggregate.
7) The new crushed limestone was spread over the geogrid and compacted with a pneumatic roller.
8) The thickness of the new granular layer was large near the pavement edge and it goes on decreasing with increasing distance from the pavement edge. The thickness was about 8 in. near the pavement edge and at about 8 ft. from the pavement edge , the geogrids were covered by 1 to 2 in. of rock.

Observations:

There were no signs of shoulder rutting on the stabilized Sections but the control section started to develop rutting one month after construction. Different tests were conducted to check whether the geogrids provided adequate strength or not. Plate load test carried out immediately after construction and at 3 months and 10 months, showed that the E values goes on increasing for the stabilized section. The lowest E and highest soil deflection values were measured at the control section. Among the three geogrids used, the section stabilized with the BX1200 geogrid produced the highest E value and lowest soil deflection, whereas the BX4100 geogrid section produced the lowest E value and highest soil deflection. However, all three geogrids were adequate for this purpose. Moreover, CBR values determined from DCP testing significantly increased for the upper 8 in. after 3 months. Some geogrids were exposed at the end section after certain time and it caused reduction in the strength provided. So, the entire geogrid should be covered with 6 to 8 in. of crushed limestone to prevent any damage to the grid from traffic or maintenance operations.

These tests also confirm that, in the case of existing shoulder sections overlying soft foundations, geogrid stabilization is proved to be an effective technique for alleviating shoulder rutting.

References:

- David White, Mohamed Mekkawy, Charles Jahren, Duane Smith, and Muhannad Suleiman, Center for Transportation Research and Education, Iowa State University, 2711 South Loop Drive, Suite 4700, Ames, IA 50010-8664, June 2007.

A.3.4.3. Commercially available Products

Table A3-1 A summary of commercially available geocells which can be potentially used for shoulder reconditioning

	Vendor	Product	Website	Location	Distributor in Ohio	Contact number/ Email	Model
1	DuPont	GroundGrid	http://www.landscapediscount.com/Ground-Grid-DuPont-p/dpgg-5055.htm	Washington		(800) 524-4161 support@landscapediscount.com	DPGG-5055
2	DuPont	GroundGrid	http://www.landscapediscount.com/Ground-Grid-DuPont-p/dpgg-50110.htm	Washington		(800) 524-4161 support@landscapediscount.com	DPGG-50110
3	IWT/Cargo-Guard	Envirogrid	http://iwtcargoguard.com/products/envirogrid-cellular-confinement-system	New Jersey	-	609-971-8810	
4	Invisible Structure. Inc.	Gravelpave2	http://www.invisiblestructures.com/gravelpave2.html	Colorado	330-644-0114	303-233-8383 800-233-1510 sales@invisiblestructures.com	
5	Presto	Geopave	http://www.prestogeo.com/geopave_porous_pavement	Wisconsin	Meredith Brothers (Columbus) - 614-258-4991	1-920-738-1328 1-800-548-3424	
6	Presto	Geoweb	http://www.prestogeo.com/load_support	Wisconsin	Meredith Brothers (Columbus) - 614-258-4991	1-920-738-1328 1-800-548-3424	GW20V GW30V

Table A3-1 A summary of commercially available geocells which can be potentially used for shoulder reconditioning (Continued)

	Vendor	**Product**	**Website**	**Location**	**Distributor in Ohio**	**Contact number/ Email**	**Model**
7	Contech	EnviroGrid® Geocell	http://www.conteches.com/products/erosion-control/temporary-and-permanent/envirogrid-geocell#4580600-description	OHIO	Contech Engineered Solutions	800-338-1122 info@conteches.com	EGA20 EGA30 EGA40
8	HANES Geo Components	TerraCell® Cellular Confinement	http://hanesgeo.com/Catalog/FeatureComparison?id=1082	OHIO	Hanes Geo components	888.239.4539 336.747.1600	TerraCell® 140 TerraCell® 175 TerraCell® 280
9	Purus North America	ECORASTER E50 – HEAVY DUTY	http://purus-northamerica.com/products/ecoraster/	Toronto, Canada	Purus North America Inc.	800-495-5517 905 376-1749	E50
10		Ecoraster Bloxx	http://purus-northamerica.com/products/ecoraster-bloxx/	Toronto, Canada	Purus North America Inc.	800-495-5517 905 376-1749	

Detailed descriptions of the commercially available geosynthetics:

1) DUPONTTM PLANTEX® GROUNDGRID®:
Requirements:

- The ground must be dug out to a depth of 2-3/4" - 3". This will allow for the grid height 2" plus a 3/4" - 1" aggregate filling layer (respectively 4-3/4" - 5" for grid height 4").
- Always add a filling layer of gravel of 3/4" to 1" on the filled grid. This layer may consist of decorative gravel.
- **Infill Material - Aggregate**

Application / Load	Typical sub-base thickness in inches
Occasional heavy traffic	from 6" to 20"
Light traffic	from 4" to 16"
Public paths/bridleways	from 2" to 6"
Domestic garden paths	from 2" to 5"

2) Geopave:

Table 2 Base and Infill Recommendations

		AGGREGATE Pavements	
AGGREGATE Surface		**BASE Material**	**INFILL Material**
		Porous Aggregate	**Porous Aggregate**
A		The base material shall be a clean, crushed aggregate with a particle range from **0.375 in to 1.0 in (10 mm to 25 mm)** with a fines content less than 5%. The aggregate shall be compacted to 95% Standard Proctor Density. After compaction, the surface shall be uniform with no protrusions from larger aggregate particles.	The infill material shall be a clean, crushed aggregate with a particle range from **0.375 in to 0.5 in (10 mm to 13 mm)** and a fines content less than 5%. Round stone should not be used.
		VEGETATED Pavements	
VEGETATED Surface		**BASE Material**	**INFILL Material**
		Aggregate/Topsoil Mix	**Aggregate/Topsoil Mix**
B		The aggregate/topsoil engineered base material ensures proper moisture retention and the nutrient component required to maintain healthy vegetative root growth. The aggregate/topsoil engineered base shall consist of a homogenous mixture consisting of 1) a clean, crushed aggregate blended with 2) pulverized topsoil and 3) a void component generally containing air and/or water. This homogenous mixture will promote vegetative growth and provide required structural support. The aggregate portion shall have a particle range from **0.375 in to 1.0 in (10 mm to 25 mm)** with a **D_{50} of 0.5 in (13 mm).** The percentage void-space of the aggregate portion when compacted shall be at least 30%. The pulverized topsoil shall equal 33% of the total volume and be added and blended to produce a homogenous mixture prior to placement. The mixture shall be compacted to 95% Standard Proctor Density.	The aggregate/topsoil engineered infill material shall consist of a homogenous mixture consisting of 1) a clean, crushed aggregate with 2) pulverized topsoil and 3) a void component generally containing air and/or water. This homogenous mixture will promote vegetative root growth and provide required structural support. The aggregate portion shall have a particle range from **0.375 in to 0.5 in (10 mm to 13 mm)**. The percentage void-space of the aggregate portion shall be at least 30%. The pulverized topsoil shall equal 33% of the total volume and be added and blended to produce a homogenous mixture prior to placement. Choice of vegetation shall be determined based upon local climate and proposed use with the aggregate/topsoil mix and a vegetated surface. Infrequent/occasional passes are recommended for vegetated surfaces.
	NOTE: The base and infill materials are different gradations for both Aggregate and Vegetated pavements.		

Table 3: Base Depth Recommendations for the GeoPave® Unit				
LOAD DESCRIPTION[1]	DEPTH OF BASE		DEPTH OF BASE	
	AGGREGATE		ENGINEERED AGGREGATE / TOPSOIL[3]	
	CBR[2] 2 – 4	*CBR[1] >4*	*CBR[2] 2 – 4*	*CBR[2] >4*
Heavy Fire Truck Access & H/HS-20 loading. Typical 110 psi (758 kPa) maximum tire pressure. Single axle loadings of 32 kips (145 kN), tandem axle loadings of 48 kip (220 kN). Gross vehicle loads of 80,000 lbs (36.3 MT).	6 in (150 mm)	6 in (150 mm)	Not Recommended	Not Recommended
Light Fire Truck Access & H/HS-15 loading. Typical 85 psi (586 kPa) maximum tire pressure. Single axle loadings of 24 kips (110 kN). Gross vehicle loads of 60,000 lb (27.2 MT).	6 in (150 mm)	4 in (100 mm)	Not Recommended	Not Recommended
Utility & Delivery Truck Access & H/HS-10 loading. Typical 60 psi (414 kPa) maximum tire pressure. Single axle loadings of 16 kips (75 kN). Gross vehicle loads of 40,000 lbs (18.1 MT).	4 in (100 mm)	2 in (50 mm)	4 in (100 mm)	2 in (50 mm)
Cars & Pick-up Truck Access. Typical 45 psi (310 kPa) maximum tire pressure. Single axle loadings of 4 kips (18 kN). Gross vehicle loads of 8,000 lbs (3.6 MT).	2 in (50 mm)	None[4]	2 in (50 mm)	None[4]
Trail Use. Loading for pedestrian, wheelchair, equestrian, bicycle, motorcycle and ATV traffic.	None[4]	None[4]	None[4]	None[4]

3) Gravelpave2:
Requirements:

- Base Course: Sandy gravel material from local sources commonly used for road base construction
- (recycled materials such as crushed concrete or crushed asphalt are NOT acceptable).
- Gravel Fill: Obtain clean, washed, fine decorative gravel, must be sharp and angular (not rounded) stone
- Subgrade Preparation: Excavate area allowing for unit thickness, the engineered base depth (where required), and 0.5 inch (1.25 cm) for 0.25 inch (6mm) gravel overfill and slight recession to contain gravel.
- Base Preparation: Place engineered base in lifts not to exceed 6 inches (150 mm), compacting each lift separately to 95 percent Modified Proctor.

4) Geoweb:

- Cell infill materials:
  - Cell infill material shall be sand.
  - Cell infill material shall be crushed aggregate with a maximum particle size of 2 inches (75 mm) with a fine content less than 10%.

- Cell infill material shall be concrete with a minimum strength of 3000 psi and air content of 2 to 4% in accordance with ACI and ASTM standards.
- Cell infill material shall be an engineered fill consisting of topsoil and aggregate mixture for vegetated surfaces.

- Requirements:
  - Engineered infill shall be a mix of topsoil and aggregate having a homogeneous mixture of a clear crushed aggregate having an AASHTO #5 or similar designation blended with pulverized topsoil and a minimum 30% void space for air and/or water.
  - The mixture will promote vegetation growth and provide structural support.
  - The aggregate portion shall have a particle range from 0.375 to 1.0 inches (9.5 to 25 mm) with a D50 of 0.5 inches (13 mm).
  - The percentage void space of the aggregate portion when compacted shall be at least 30%.
  - The pulverized topsoil portion shall equal 25% of the total volume. The topsoil shall be blended with the aggregate to produce a homogeneous mixture.
  - Once placed, the engineered fill shall be compacted to a 95% Standard Proctor.
  - E. Infill material shall be free of any foreign material.
  - F. Clays, silts and organics are not acceptable infill material.
  - G. Infill material shall be free-flowing and not frozen when placed in the Geoweb sections.

5) EnviroGrid® Geocell:

The *EnviroGrid Structural/Growth Infill* (Infill) material shall be composed of an aggregate and growing medium blend meeting the following requirements:

- Aggregate 1. The aggregate shall be durable, with 95+% of its fascia split or broken
- The aggregate shall meet the following gradation and void ratio requirements

	Cell Depth	**Particle Range**	**D $_{50}$**	**Void Ratio**
EnviroGrid EGA20	4″	0.5″ – 1.25″	0.75″ - 1.0″	≥ 30%
	6″	0.5″ – 2″	0.75″ – 1.25″	≥ 30%
	8″	0.5″ – 2″	0.75″ – 1.25″	≥ 30%
EnviroGrid EGA30	6″	0.5″ – 2″	0.75″ – 1.25″	≥ 30%
	8″	0.5″ – 2″	0.75″ – 1.25″	≥ 30%

A.3.5. Paved Shoulders

A.3.5.1. Iowa study

According to Souleyrette et al. (2001), although paved shoulders are generally much safer than unpaved shoulders, they are not always the proper solution. They are considered to be cost effective if,

- For partially paved shoulders, vehicles per day (VPD) = 1500 – 2000
- For full-width paved shoulders, VPD > 3000

In 1995, the Iowa DOT determined that a 3 ft. paved shoulder became cost effective, when an average daily traffic (ADT) exceeds 2,100 (Souleyrette et al. 2001).

Initial Construction and Maintenance Costs:

Initial cost of constructing granular shoulder is less as compared to that of paved shoulder (about 70%), however, the maintenance cost is much higher than paved ones. Maintenance cost for granular shoulders averaged about $259/lane-mile, while the maintenance cost of paved shoulders averaged about $76/lane-mile (Souleyrette et al. 2001).

Table 1. Summary of granular and paved shoulder costs in Iowa for calendar year 2000 (Souleyrette et al. 2001)

Shoulder type	Cost type	Width	Cost ($)
Paved (ACC)	Initial	3 ft	53,469 / mile
Granular	Initial	3 ft	13,376 / mile
Paved (ACC)	Initial	6 ft	106,938 / mile
Granular	Initial	6 ft	26,752 / mile
Paved (ACC)	Restoration	-	5.69 / s.y.
Granular	Restoration	-	1.43 /s.y.

Improvements for Aggregate Shoulders:

For upgrading from granular shoulders to paved shoulders, the Iowa DOT has two standards: one for non-NHS routes (generally under 3,000 AADT) and one for NHS routes (generally over 3,000 AADT). **The project is carried out as part of a rehabilitation project, when a granular shoulder is upgraded to a paved shoulder, and involves an HMA overlay of the traffic lanes. Since the overlay will be carried onto the shoulders, the total required minimum thickness includes the thickness of the overlay**.

Non-NHS highways receive 2 ft. widening units that are at least 8 in. thick while NHS highways receive 4 to 6 ft. widening units that are at least 6 in. thick.

Immediately after the first lift of hot mix is placed next to the pavement, the risk of structural failure is greatest. For example, a 2 in. base course would need to be placed next to the pavement across the width of the widening unit, if a 4 in. overlay is planned and a shoulder is intended to be 6 in. thick (NSH Standards). This 2 in. base course may not be able to withstand the loads of truck traffic before the total thickness of 6 in. is provided, which requires a minimum thickness of 3 in. for the hot mix base course. When this is done, a slightly thicker shoulder than the minimum requirements will result, since the overlay must be kept at the specified overlay thickness. In this example, the resulting shoulder will be 7 in. thick.

A.3.5.1. Saving cost for paved shoulder using reclaimed asphalt pavements (RAP)

An approach to reduce the cost of paved shoulder is to beneficially use the reclaimed materials such as RAP. *"Prairie Contractors in Louisiana has had success modifying, placing and compacting Hot-Rap shoulders that last a decade or more. Rather than merely placing crushed rock or reclaimed concrete that could be a safety hazard for straying traffic, the company makes a mix that incorporates the best of recycling and safety."* (ASPHALTPRO 2014)

Application of low-cost shoulder mix known as Hot-Rap:

- Originally, Hot-Rap was a blend of crushed aggregate base and sand, with an asphalt content of 2.5 percent.
- Nowadays, lesser quality and higher quantity (40 to 50 percent) can be used in the mix.
- Prepared at around 250 degrees F and placed on the shoulder at widths of 1 to 4 feet using a side spreader.
- Compacted with three passes of 12-ton steel wheel roller and some handwork is done to taper the outside edge to match the existing slope.
- Initial cost is higher than using crushed stone but saves the maintenance cost greatly since the material doesn't wash away.
- Mix is durable that they even look good after nearly 15 years.
- Prevent erosion around turnouts, drainage structures and also on the steep front slopes of ditches.
- Moreover, asphalt shoulder with high qualities of RAP save lives.

References:

- Souleyrette, R., McDonald, T., Hans, Z., Kamyab, A., Welch, T., and Storm, B. (2001). "Paved shoulders on primary highways in Iowa: An analysis of shoulder surfacing criteria, costs, and benefits." Office of Traffic and Safety of the Iowa Department of Transportation.
- Center for Transportation Research and Education, Iowa State University, 2711 South Loop Drive, Suite 4700, Ames, IA 50010-8664, June 2007.
- ASPHALTPRO (2012) "How to Compact High RAP, Sloped Shoulders", http://theasphaltpro.com/how-to-compact-high-rap-sloped-shoulders/
- ASPHALTPRO (2014) "How to Make Hot-RAP" http://theasphaltpro.com/how-to-make-hot-rap/
- User Guidelines for Waste and Byproduct Materials in Pavement Construction, Publication Number: FHWA-RD-97-148, Federal Highway Administration Research and Technology, US Department of Transportation. [Link:https://www.fhwa.dot.gov/publications/research/infrastructure/structures/97148/rap132.cfm]

Appendix 4 Lab test data

Water Content Determination:

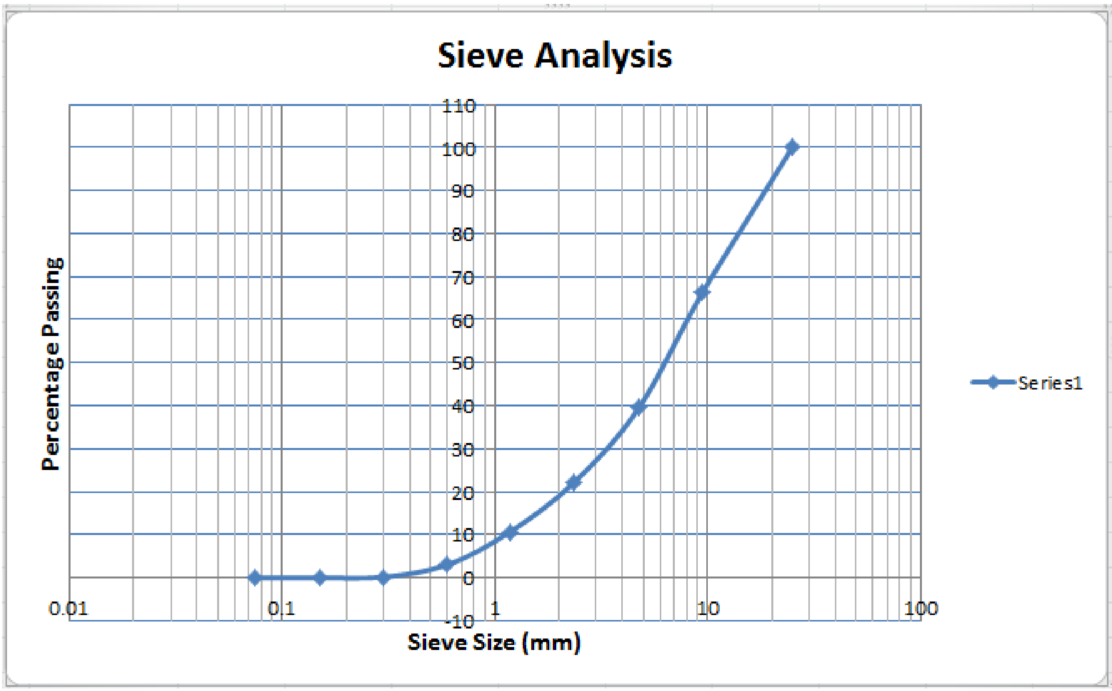
Sample	Wt. of empty container (gm)	Bulk wt. of sample with container (gm)	Dry wt. of sample with container after oven drying (gm)	Wt. of water (gm)	Dry wt. of sample without container (gm)	Water content (%)
A1	31.6	165.1	157.9	7.2	126.3	5.70
A2	31.9	169	161.6	7.4	129.7	5.71
A3	33.7	157.1	150.9	6.2	117.2	5.29
A4	34	142.7	136.8	5.9	102.8	5.74
B1	28.7	129.2	125	4.2	96.3	4.36
B2	29.6	131.5	127.3	4.2	97.7	4.30
					Total	31.10
					Average	5.18

Hence, average water content from these samples = (31.10/6) =5.18%

Sieve Analysis:

Weight of sample taken = 1000 gm

Sieve Size	Wt. retained (gm)	% wt. retained	cumulative % wt. retained	% passing
25mm	0	0	0	100
9.5mm	335.8	33.58	33.58	66.42
4.75mm	269.7	26.97	60.55	39.45
2.36mm	172.6	17.26	77.81	22.19
1.18mm	115.3	11.53	89.34	10.66
600 μ	76.3	7.63	96.97	3.03
300 μ	28.5	2.85	99.82	0.18
150 μ	1.8	0.18	100	0
75 μ	0	0	100	0
	1000	100		



Coefficient of Uniformity (Cu) = D60/D10
From the Graph,

D60=	8.02
D10=	1.05
So, Cu=	7.64

Coefficient of curvature (Cc)= (D30^2)/(D30*D10)
From the Graph,

D30=	3.3
So, Cc=	1.29

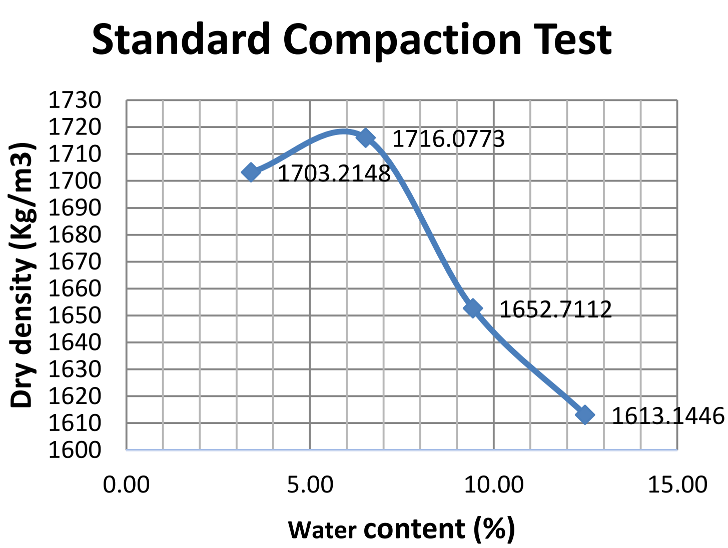
Standard Proctor Compaction Test:

Sieving of sample	Weight (gm)	% of total Weight
Retained on 3/4"	5864.7	23.42
Retained on 3/8"	3898.3	15.57
Retained on 4.75mm	6281.1	25.09
Passed through 4.75mm	8994.9	35.92
	25039	

Method B of Standard Compaction Test was selected. The sample passing through 3/8" sieve was collected for the test. The sample was then placed in the oven for 24 hours for complete drying. The first test sample was prepared with 4% water content and it was compacted on the mould in three layers. Each layer was compacted with 25 number of blows. The 2nd, 3rd and 4th test sample was prepared with 7%, 10% and 13% water content respectively.
Weight of Empty mould without collar = 4307.1 gm.
Volume of mould = 943 cm^3.

Wet wt. of sample + Wt. of cont. (gm)	Dry wt. of sample + Wt. of cont. (gm)	Wt. of empty cont. (gm)	Dry wt. of sample(gm)	Wt. of water(gm)	water content (%)
115.4	112.4	24.1	88.3	3	3.40
108.7	104.1	33.5	70.6	4.6	6.52
124.6	116.8	34.1	82.7	7.8	9.43
176.2	159.8	28.5	131.3	16.4	12.49

Bulk wt + mould(gm)	Bulk Wt.(gm)	Bulk density (gm/cc)	Bulk density (Kg/m3)	water content	dry density (Kg/m3)
5967.8	1660.7	1.7611	1761.0817	3.40	1703.2148
6030.8	1723.7	1.8279	1827.8897	6.52	1716.0773
6012.6	1705.5	1.8086	1808.5896	9.43	1652.7112
6018.3	1711.2	1.8146	1814.6341	12.49	1613.1446



From above graph,
Maximum dry density = 1718 Kg/m3
Optimum Moisture Content = 6%

Hence, the aggregate can be compacted to a maximum dry density of 1718 Kg/m^3 at the water content of 6%.