DEPARTMENT OF TRANSPORTATION

Pothole Prevention and Innovative Repair

Mihai Marasteanu, Principal Investigator
Department of Civil, Environmental, and Geo- Engineering
University of Minnesota

April 2018

Research Project
Final Report 2018-14

LRRB
LOCAL
ROAD RESEARCH
BOARD

To request this document in an alternative format, such as braille or large print, call 651-366-4718 or 1-800-657-3774 (Greater Minnesota) or email your request to ADArequest.dot@state.mn.us. Please request at least one week in advance.

Technical Report Documentation Page

1. Report No.	2.	3. Recipients Accession No.
2018-14		

4. Title and Subtitle	5. Report Date
Pothole Prevention and Innovative Repair	April 2018
	6.
7. Author(s) Debaroti Ghosh, Mugur Turos, Marcella Hartman, Rose Milavitz, Jia-Liang Le, Mihai Marasteanu	8. Performing Organization Report No.
9. Performing Organization Name and Address Civil, Environmental and Geo- Engineering University of Minnesota, Twin Cities 500 Pillsbury Drive, Minneapolis, MN	10. Project/Task/Work Unit No. CTS #2016007 11. Contract (C) or Grant (G) No. (c) 99008 (wo) 191
12. Sponsoring Organization Name and Address Minnesota Local Road Research Board Minnesota Department of Transportation Research Services & Library 395 John Ireland Boulevard, MS 330 St. Paul, Minnesota 55155-1899	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes

http:// mndot.gov/research/reports/2018/201814.pdf

16. Abstract (Limit: 250 words)

Pothole repairs continue to be a major maintenance problem for many highway agencies. There is a critical need for finding long-lasting, cost-effective materials and construction technologies for repairing potholes.

This research effort investigates critical components associated with pothole formation and pothole repair and proposes solutions to reduce the occurrence of potholes and increase the durability of pothole repairs. The components include investigating and documenting pavement preservation activities, experimental work on traditional repair materials as well as innovative materials and technologies for pothole repairs, stress analysis of pothole repairs to identify whether certain geometric configurations are more beneficial than others, evaluating cost analyses to determine the effectiveness of various repair methods. A number of conclusions and recommendations were made.

Potholes are mainly caused by the delayed response to timely fixing common pavement distresses. The state of Minnesota has a number of preservation strategies that are available and have been successfully used. Recommendations are made to improve these strategies using documents made available as part of new Every Day Counts, EDC-4, initiative.

Currently, there are no required specifications for patching materials. Mechanical testing can be used to select patching materials based on the estimated durability of the pothole repair, such as short-, medium-, and long-term. A number of new materials and technologies are available for more durable solutions for winter pothole repairs, however, they require additional heat source and are more expensive.

17. Document Analysis/Descriptors		18. Availability Statement	
Potholes (Pavements), Pavement maintenance, Pavement distress, Patching		No restrictions. Document available from: National Technical Information Services, Alexandria, Virginia 22312	
19. Security Class (this report)	20. Security Class (this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	129	

Pothole Prevention and Innovative Repair

FINAL REPORT

Prepared by:

Debaroti Ghosh
Mugur Turos
Marcella Hartman
Rose Milavitz
Jia-Liang Le
Mihai Marasteanu
Department of Civil, Environmental, and Geo- Engineering
University of Minnesota

April 2018

Published by:

Minnesota Department of Transportation
Research Services & Library
395 John Ireland Boulevard, MS 330
St. Paul, Minnesota 55155-1899

ACKNOWLEDGMENTS

The financial support provided by the Minnesota Department of Transportation and the Local Road Research Board is gratefully acknowledged.

The guidance and logistical support to obtain the pothole repair materials, provided by the project technical advisory panel, and in particular by the project champion, Todd Howard, are acknowledged.

Also acknowledged is the Unique Paving Materials Corporation for providing two of the pothole repair materials investigated in this study.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Pothole repairs continue to be a major maintenance item in the budget of many highway agencies. Despite considerable progress made in pavement materials and pavement mechanics, pothole repair remains an area in which little progress has been made. In this research effort, some of the critical components associated with pothole formation and pothole repair are investigated, and solutions that can reduce the occurrence of potholes and increase the durability of pothole repairs are proposed.

First, a literature review was performed to summarize national and international efforts on providing solutions to managing potholes and to preventing the initiation and development of potholes through pavement preservation activities. There is general agreement that pothole formation is caused by the delayed response to fixing common pavement distresses in the initial phase of their development. The most common distress related to pothole formation is cracking. Once cracks form, and are not repaired, water infiltrates into the pavement surface layer and accelerates the damage process through various mechanisms, ranging from stripping to freeze-thaw cycles. A proactive pavement preservation approach represents a viable solution that can significantly reduce the presence of potholes.

Then, the finite element method was used to determine whether certain geometric configurations (round vs. square, etc.) can reduce the stresses that develop in pothole materials and at the interface with the old pavement and then provide recommendations. Based on the numerical simulations performed, it was concluded that circular-shaped potholes minimize stress concentrations near the boundary of the potholes and can increase the durability of pothole repairs. Circular pothole repairs also represent the best construction option to uniformly fill the pothole with repair material and compact it; the repair material cannot easily flow into shapes with corners.

Extensive laboratory experimental work was performed next using both traditional materials as well as summer patching materials modified with graphite nano-platelet (GNP) additives. It was found that cold mixtures used for winter patching, which do not require heating for placing and compaction, have poor mechanical properties and are expected to require frequent re-repairs, especially in winters with many freeze-thaw cycles. Winter patching materials, that require an external source of heat for placing and compaction, have significantly better mechanical properties and are expected to last longer. However, they are more expensive and require specialized equipment and training. Pothole repairs performed in late spring and summer with hot mix asphalt are the most durable and may last for more than one winter season. In situations with high traffic, resurfacing of the road section might be more cost-effective than patching potholes in summer.

In Chapter 5, the main causes for premature failure of pothole repairs were investigated, and proactive pavement preservation techniques that can delay the initiation of potholes and reduce or eliminate the formation of significant pothole occurrence were identified. The investigation included life-cycle analyses to determine the cost effectiveness of asphalt pavement pothole repair methods. All life-cycle analyses demonstrated that cheaper materials and methods are more cost-effective in the short run however, the

more expensive and durable repair methods provide substantially higher effectiveness in the long run. The benefits are even higher if user costs are considered in the analysis. It was also found that a number of new materials and innovative technologies are available to provide more durable solutions for winter pothole repairs, which represent the most challenging situation. All three techniques and materials documented in this investigation, GAP, infrared heating, taconite mixture and microwave heating, require an external energy source to obtain the final product. The use of GNP additives show promising benefits for summer patching since they increase the compaction level. The addition of GNP additive may provide benefits for winter pothole repair since they can be heated significantly by application of microwave energy, similar to the effect observed in taconite aggregates.

Finally, a summary of the work performed followed by the most relevant conclusions and recommendations were provided. The research team was not able to make long-term recommendations for better patching strategies, materials and methods, since no cost and performance information was available to document current pothole repairs in Minnesota. It was recommended that a simple tracking system of pothole repair activities be developed and implemented.

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Pothole repairs continue to be a major maintenance item in the budget of many highway agencies, and for these agencies, the annual appearance each spring of potholes is a major public relations concern. This is especially true when repairs are short-lived and the same areas are repaired repeatedly. In spite of considerable progress made in pavement materials and pavement mechanics, pothole repair remains an area in which little progress has been made. Clearly, there is a need for long-lasting, cost-effective materials and construction technologies for repairing potholes.

1.2 OBJECTIVE

The main objective of this research effort is to investigate some of the critical components associated with pothole formation and pothole repair in order to propose solutions that can reduce the occurrence of potholes and increase the durability of pothole repairs. The components addressed include pavement preservation activities that could be used to prevent the initiation and formation of potholes, investigating and documenting the use of traditional as well as innovative materials and technologies used for pothole repairs, and performing a stress analysis of pothole repairs to identify whether certain repair shapes are more beneficial than others.

1.3 ORGANIZATION OF THE REPORT

First, a literature review is performed to summarize national and international efforts on providing solutions to managing potholes and to preventing the initiation and development of potholes through pavement preservation activities.

Then, a rigorous stress analysis is performed to determine if certain geometric configurations (round vs. square, etc.) can reduce the stresses that develop in pothole materials and at the interface with the old pavement and provide recommendations.

Chapter 4 details the extensive laboratory experimental work performed on traditional and new materials and innovative pothole repairs methods. This includes the use of graphene nano-platelet (GNP) additives to summer patching materials.

In Chapter 5, an investigation is performed to summarize the main causes for premature failure of pothole repairs and to identify proactive pavement preservation techniques that can delay the initiation of potholes and reduce or eliminate the formation of significant pothole occurrence. The investigation also includes the use of life-cycle cost analyses to determine the cost-effectiveness of asphalt pavement pothole repair methods. A summary of the work performed in this investigation followed by the most relevant conclusions and recommendations are provided in Chapter 6.

CHAPTER 2: LITERATURE REVIEW

This literature review summarizes recent national and international efforts on providing solutions to preventing the initiation and development of potholes and, once developed, repairing them.

2.1 WHY DO POTHOLES FORM?

Pothole formation is mainly caused by the delayed response to fixing common pavement distresses in the initial phase of their development. The most common distress related to pothole formation, is cracking, that can be the result of different failure mechanisms. For example, top down cracking occurs along wheel paths due to considerable traffic loading and it is related to asphalt mixture stiffness and fatigue characteristics. Bottom up cracking occurs in thin asphalt pavements, usually in the form of longitudinal cracks. Once cracks form, and are not repaired, water infiltrates into the pavement surface layer and accelerates the damage process through various mechanisms, ranging from stripping to freeze-thaw cycles. If distresses are repaired promptly, or water can be rapidly removed out of the pavement system, pothole formation can often be delayed and even avoided.

Although most distresses occur at the pavement surface, in many cases their causes stem from problems related to the foundation of the pavement structure, which are very difficult and expensive to fix. In these cases, prompt repairs can only delay the appearance of potholes and not prevent their occurrence. Only a combination of a solid structural pavement system and timely preservation activities can completely avoid the formation of potholes.

2.2 POTHOLE REPAIR METHODS

Some of the most common repair method are presented below and are described in most references related to pothole practice and research. The choice of the method to be used is mostly dictated by budget constraints.

A throw and go patch is placed by merely filling the pothole with patching material, without any preparation of the repair area or special compaction efforts. It is the simplest and quickest repair method, however, it generally does not perform well over time and, therefore, is a temporary solution.

The throw and roll is another temporary patch method. The pothole is filled in the same manner as the throw and go method, but then the patch is rolled over by a truck tire, which compacts the patch material. This method takes slightly more effort than the throw and go, and the repair has better performance, so this method is very commonly used.

Semi-permanent patching requires pothole preparation. The pothole is cleaned of water and debris, and the edges of the pothole are cut back to existing pavement material. Patching material is placed in the hole and compacted with vibratory equipment.

The edge-seal method begins by using either the throw and roll or semi-permanent techniques, but after the patch has set, its edges are sealed with a sealant or tack material.

Spray injection uses pneumatic spray equipment to first clean the hole of water and debris, then inject either hot-asphalt or emulsion-based materials into the hole. The high pressure placement compacts the patching material during installation, so no further compaction is necessary. Spray injection provides a safer option for patch placement.

In recent years, a number of attempts were made to investigate the use of innovative materials and technologies for pothole repairs, which could provide long term cost effective solutions for long lasting repairs. A team led by UCLA is developing a nano-molecular resin that infiltrates already compacted aggregate-cement mixtures. The resin hardens to form a cage-like mesh throughout the mixture, which can potentially improve load bearing capacity, compressive shear-load strength, adhesion to patch walls, water resistance, and decrease appearance and propagation of alligator cracking. The project is in its early stages, but in the later stages researchers will deploy the new materials to street test sites [1].

The Natural Resource Research Institute (NRRI) has recently completed a report regarding the use of taconite-based materials in pothole repair [2]. The study examined two repair options. The first involved using Rapid Patch, a material developed by NRRI. Rapid Patch is a fast-setting, taconite based, petroleum-free and Portland cement-free compound that can be activated by either water or a chemical solution. The compound contains a blend of taconite fine aggregate and magnetite concentrate, a powdered inorganic activator and a liquid activator. Rapid Patch seems to be best suited for rigid and moderately deep repairs in Portland cement concrete roads. The compound can set in less than 15 minutes and be drivable in 30 minutes. The formulation can also be adjusted so set times match summer or winter temperature conditions.

NRRI has also developed a repair method that utilizes a 50 kW microwave and taconite aggregate. The microwave heats the repair materials, and the magnetite in the taconite aggregate enhances microwave absorption. The existing pavement is also heated so that it becomes part of the repair itself, and creates a very strong bond. This method is best for hot mix asphalt pavements and works at all temperatures, even extremely cold. Repairs can be completed in under ten minutes, and increasing microwave power to 75 or 100 kW shortens the heating time proportionally, which could decrease installation time. With this method, repairs will likely only need to be performed once, eliminating costs of repeated repairs necessary with other methods. According to the authors, repairs performed on Hwy 53 in March 2013 were “still largely intact and well bonded to the pavement” 2.5 years after installation, comparable to semi-permanent/permanent repairs.

In 2009, Caltrans Maintenance group partnered with UC Davis to test a new pothole repair equipment, the Python Pothole Patcher (PHP) [3]. They found the PHP produced either long term or permanent patches, depending on how clean the pothole was before placement. Also, a moderate quality patch could be placed very quickly (to minimize traffic disruptions), and a high-quality patch could be produced if more time was available. The team plans to continue research in an effort to launch the PHP to full-scale deployment.

2.3 COMMON PRACTICES BY COUNTRY

United States

The Federal Highway Administration Report No. FHWA-RD-99-168 *Materials and Procedures for Repair of Potholes in Asphalt-Surfaced Pavements* is a Manual of Practice intended to be used by highway maintenance agencies and their contractors [3]. The authors state that the decision process for pothole repairs is based on several factors including: level of traffic; time until scheduled rehabilitation or overlay; availability of personnel, equipment, and materials; safety concerns; rideability. Materials and repair procedures are the two main factors for quality repairs. Materials, labor and equipment are main cost contributors. However, the authors recommend that user-delay costs and other lane-closure costs must be also considered and balanced to optimize cost-effectiveness.

One of the most comprehensive reports documenting pavement patching practices in US and also other countries is the recently published NCHRP "Pavement Patching Practices, A Synthesis of Highway Practice" [4]. In the survey of state and local U.S. agencies, included in the report, it was found that engineering judgement is the main driving factor of maintenance decisions. Public outreach and standardized guidance were also noted to be important components. It was also found that repair operations mainly occur during either winter or spring. Winter repairs most often occur during snow melt periods to avoid having to plow or place salt or abrasives.

The throw and go method was found to be one of the most commonly used methods due to its high production rate. However, this method should be replaced by the throw and roll technique, which also has a high production rate (only 1-2 additional minutes per patch) but produces superior results. Semi-permanent, spray-injection, and edge-seal methods are also commonly used by agencies, however less so than the throw and go and throw and roll methods. The NCHRP survey found that about half the respondents use automated equipment. These three methods generally produce higher quality repairs, with higher costs. Semi-permanent and edge-seal techniques require additional effort and have a lower production rate, leading to increased labor costs. Spray injection has a higher production rate and lower material costs but an increase in equipment costs.

The NCHRP survey found that hot-mix asphalt is the number one material used for patching. However, cold mix materials are still common in practice because they can be transported more easily than hot mixes, and are generally widely available.

United Kingdom and Ireland

The NCHRP synthesis [4] also included a survey of agencies in the United Kingdom and Ireland. Visual inspection was found to be the number one trigger for patching, and safety was the second. Public complaints were not a main source for patching initiation, possibly due to lack of communication between agencies and the public. The survey found that the UK has a much lower occurrence compared to U.S of scaling, spalling or cracking as a trigger to patching, and attributed this to a lower amount of concrete pavement.

Ninety two percent of survey respondents indicated that "patching is a major part of their maintenance operations," accounting for between 8-50% of the total maintenance program (excluding motorways, which are built and maintained at higher standards). UK agencies tend to follow specifications, plans or guidelines for patching more often than the US. Patch tracking is performed by 54-62% of UK/Ireland respondents. Seventy-two percent of UK respondents do not implement QC/QA procedures during patch placement; however, 63% monitor patch performance after installation.

In general, practices in the UK and Ireland were found to be very similar to practices in the US. Potholes are the main distress feature needing patching, and 72% of agencies reported performing patching themselves (compared to 88-92% in the US). About half of the respondents use automated equipment, and hot asphalt mix is the most commonly used patching material.

The Netherlands

In the Netherlands maintenance initiation occurs based on either failure or condition based criteria; forecasting maintenance needs based solely on user-based criteria has not proven to be possible [5]. Road usage is however used for budgeting and planning purposes.

Maintenance is classified into short, medium and long term. Short term considers the immediate two years, medium considers 2-5 years into the future, and long term maintenance covers the period beyond five years. Periodic maintenance refers to repairs that occur less frequently, such as overlays, surface treatments, mill and replace, and double surface treatments. Intervals for periodic maintenance are based on assessment of road sub-base, soil conditions, and road classification.

The Dutch allocate large budgets for annual/routine maintenance, reasoning that the repair of small features will inhibit damage progression. Annual maintenance may include crack sealing, slurry seals, surface treatments and localized mill and replace. Commonly, roads will be 60% covered by minor repairs before periodic maintenance occurs [5].

South Africa

The Council for Scientific and Industrial Research (CSIR) published a comprehensive technical guide that documents the causes, identification, and repair of potholes [6]. The 2009/2010 summer rainfall in South Africa caused the development of an excessive number of potholes, leading to an increased concern and a deeper look into the causes of potholes and potential improvements in maintenance and repair procedures. The main reasons for the increase in pothole occurrence during 2009/2010 season were found to be insufficient maintenance, unusually wet conditions, and lack of proper pothole repair.

Most roads in South Africa are asphalt, with a typical thickness of 25-50 mm, compared to average thicknesses of 100 mm in northern countries. Single and double surfacing seals are common surfacing types. These seals are flexible and able to withstand moderate amounts of deflection over a fair amount of time before cracking occurs. However, their performance is dependent on underlying layers. Therefore, once cracking begins (which almost always occurs as top down cracking), water will be able to infiltrate the lower layers, quickly propagating additional surface cracking and leading to damage, including potholes, over large areas of the pavement.

The CSIR technical guide recommends using a decision process to classify the cause of a pothole and determine the appropriate repair action. The guide also mentions the importance of determining the amount of moisture that may be present in the subgrade, which includes noting the presence of water-loving vegetation since it can indicate excessive water in the area.

The South African National Roads Agency Ltd (SANRAL) uses notice or sign boards to distribute the phone number of a 24/7 hotline where potholes can be reported. This is considered to be the most effective system currently in use. This method can be most successful by ensuring the public is aware of the hotline, and that reported repairs are attended to in a timely fashion. This may require having properly trained maintenance crews available on a stand-by basis.

Regular road inspections may also be useful, however can be costly and time consuming. The CSIR guide provides a field assessment form that can be used to standardize inspection procedures. The form includes the following sections: Road Number, Location, Surfacing type, Layers Affected, Crocodile Cracking, Surface Deformation, Subgrade Saturated, Stabilized Base, Carbonation of Base, Action, and Comments.

The CSIR guide outlines pothole repair preparation as follows:

1. Mark area needing to be patched. Area marked should include the entire failed area as well as some competent material surrounding it. If any associated defects have occurred such as cracks, they also should be within the marked region.
2. Use straight lines since they are more easily cut.
3. Use a diamond saw to cut surface.
4. Excavate area with a spade or jackhammer
5. For larger patches of 1 meter in length or more, area should be rectangular, with sides parallel to the road. For smaller patches, a diamond shaped patch pointing in the direction of traffic (longitudinal along the road) has been found to be most effective. Depth of the repair area depends on the cause of the pothole and the type of material being repaired.
6. Place geosynthetic crack sealing strip along the edge of the excavated area. Bitumen emulsion can be placed below the strip for adhesion as well as over the strip to help waterproof the strip. This procedure will help decrease the chance that a crack will form along the joint between the existing road and the patch.
7. Thoroughly clean repair area, removing all loose debris and unsound material.

The CSIR guide classifies repairs by depth (shallow, medium-depth and deep), and whether they occur solely in the surface seal or extend into underlying asphalt layers. Shallow asphalt repairs are for potholes up to 75-100 mm in depth that occur in only an asphalt layer. After pothole preparation, the entire hole should be treated with a bitumen emulsion tack coat. Then the asphalt (either hot or cold mix) should be placed in layers no thicker than 75 mm. Layers should be compacted separately. Once the patch is complete, it should be checked with a level to confirm it is without depressions or unevenness, and is at least level with the existing road, or 5-10 mm above the existing road to allow for additional compaction cause by traffic loading.

Medium depth asphalt repairs are treated in the same manner as shallow repairs, however in order to minimize asphalt needs and costs, the hole may first be filled with crushed stone, natural gravel or treated gravel. The filler material should be as similar as possible to the existing subbase material, and should be compacted to the same density. Before placing the filler, the sides of the hole should be moistened to increase adhesion of the material to the walls of the hole. Filler should be placed in layers less than 100 mm, and each layer should be compacted using hand tamping or a plate compactor. Special care should be taken to ensure each layer is compacted evenly, all the way to the edge of the repair area. Once all filler is placed and compacted, the top layer should be coated with bitumen emulsion.

Deep asphalt repairs are needed when structural failure at depth has occurred (usually due to either excessive water in lower layers or poor quality materials). Local alligator cracking is often present and a good indication that deep repair will be needed. Before repair begins, it is necessary to first address the source of water. Sub-soil drains may be used if appropriate. If is not possible to address the water source, then repair materials must be treated with cement or bitumen emulsion to decrease moisture susceptibility. However, this will likely not result in long term repair, simply because the surrounding existing material is likely to fail due to the continued presence of water. Once the hole is properly prepared, repair procedures follow those described above for medium-depth repairs.

Cold mix asphalt is most commonly used for small pothole repair, while hot mix is used for larger repairs. Both mixes are used in conjunction with a tack coat to improve bonding with the existing road. Due to the cost of asphalt, it is recommended that the repair area be mainly filled with natural gravel, cemented material, or bitumen treated materials, and asphalt be used just in the upper portion of the repair area. Material from the side of the road has been used in the past due to the ease of procurement. However, it is rarely successful and therefore never recommended.

2.4 POTHOLE REPAIR PERFORMANCE

The number of comprehensive studies documenting the performance of pothole repairs is relatively reduced. One of the earlier studies is a report by FHWA performed in the early 90’s to evaluate which combinations of materials and patching procedures produce the most cost-effective approach [7].

Potholes were placed from March 1991-February 1992 and monitored every 1, 3 and 6 months until November 1995. Lifespan and distress type were recorded and compared to laboratory values.

The throw and roll technique was found to be as effective as the semi-permanent technique, when using similar materials. The spray-injection technique performance was comparable to control patches at all sites, however, it was found to be dependent on operator experience. Patch life was longer than expected, with 56% of patches surviving till the end of the study.

The study produced the following recommendations:

- "Use high-productivity operations in adverse weather." Speed of patch placement should be the main concern when placing patches in cold weather or heavy precipitation. Throw and roll and spray injection techniques are recommended for quick, high quality results. The throw and roll technique should be performed using high quality materials. Spray injection patches should be placed and maintained by a well experienced technician.
- Using the highest quality materials will reduce the need for re-patching and be more cost effective in the long run than repeated repair.
- Operation cost calculations should factor in safety and user delay costs.
- Compatibility of aggregate and cement should be tested. Small scale testing on cold mixes should be performed to confirm material compatibility.

In *Development of Preventive Maintenance Decision Trees Based on Cost-Effectiveness Analysis,* Wei and Tighe compiled the life span and cost data presented in Table *2.12*.1[8]. The last column divides the total cost of the repair by the number of years the repair survives. Of the techniques listed, hot-mix patch treatments are the most cost effective pothole repair. However, the throw and roll and edge-seal techniques are not listed. Additionally, the lifespan listed for spray patches is shorter than expected. Perhaps this cost data was specific to a particular machine or asphalt mix, and is not representative of all spray patch options. It is also interesting to note the potential increase in costs with the progression of deterioration. If cracks are repaired at an early stage, they can be treated with a rout and seal technique for a relatively nominal cost ($62.50 per lane/km/year). If however the road is allowed to deteriorate to a point where full surface treatments are required, cost will be at least $1000 per lane/km/year.

Table 2.1: Average life span and cost of patch types.

	Treatment	Life (years)	Cost ($CA/lane/km)	Cost/Year
Crack Treatments				
	Rout and Seal	6	$375	$62.50
	Crack Sealing	3	$3,375	$1,125.00

Pothole Treatments	Hot-Mix Patch	5	$1,246	$249.20
	Machine Hot-Mix Patch	4	$1,386	$346.50
	Mill and Patch 10%	6	$2,450	$408.33
	Mill and Patch 20%	7	$4,900	$700.00
	Spray Patch	2	$3,375	$1,687.50
Full Surface Treatments	Chip Seals	5	$5,738	$1,147.60
	Fog Sealing	3	$3,038	$1,012.67
	Microsurfacing	7	$8,438	$1,205.43
	Slurry Seals	5	$6,075	$1,215.00
	Thin Hot-Mix Overlay	7	$11,756	$1,679.43
	Thin Cold-Mix Overlay	5	$8,438	$1,687.60
	1 Lift Overlay	7	$26,250	$3,750.00

Presented in *Durability Analysis of Pothole Patching Mixture in Snowy Cold Region*, Kaito et al. performed a study focused on potholes in snowy cold regions [9]. In these regions, pavement is often wet, either from snow melt or from water spray treatments used to melt snow and clean pavements. The increased presence of water increases pothole occurrence. This often leads to emergency repairs performed during winter or early spring months. According to this study, cut-back asphalt is regularly used in minor pothole repairs, since it is easy to handle and store. However, in snowy cold regions, even these materials do not always perform properly when placed in extreme environmental conditions such as lower temperatures and the presence of water. Additionally, limited time for repairs (due to inability to close roads for long periods of time) may also lead to lower quality patch performance.

The study analyzed potholes generated on national roads from June 2007 to February 2008 and used a Weibull deterioration hazard model to statistically estimate pothole lifespan in snowy cold regions and evaluate patching material durability. The potholes were repaired with “ordinary-temperature” patching materials. Data analyzed included inspection records, observation data after repair, and basic information on paved roads. In the model, the lifespan of a patching mixture was defined as the time between placement of the patch and the recurrence of a pothole in the same spot. The following factors were assessed in the model to determine their contributions to the generation of potholes:

- Repeated generation of potholes (used as a qualitative parameter)
- Surface material
- Existence of water-spray device
- Water removal before patch placement
- Dirt removal
- Tamping method
- Large vehicle traffic amount

Kaito et al. found that pothole generation was most dependent on ruts, structure, surface materials, and the device used to spray water for snow removal. These factors accounted for “over twofold differences in durability of patching mixtures.” Also, “repairing work conditions” had a greater impact on pothole lifespan than structural conditions, in particular whether water and dirt were removed before patch placement.

Lifespan of patches placed in September, January and February were found to be 10-25 days, which is significantly lower than those placed during other months (60-100 days). This difference was attributed to the presence of water. It was determined that current patching materials do not perform well under severe weather conditions in snowy cold regions, particularly when water is present.

2.5 SURVEY ON CURRENT POTHOLE REPAIR PRACTICES IN MINNESOTA

A survey using Qualtrics software was distributed to MnDOT maintenance superintendents and local engineers to obtain current pothole repair practices. A total of 41 responses were collected and are presented in Appendix 1. The main conclusions from the survey are as follows:

- Most respondents listed the recurrence of original failure mechanism as a main mechanism of repair failure. Commonly recurring failures are due to either structural causes or to the inability to remove sources of moisture, such as poor drainage or water conduits below the asphalt surface.
- Public complaints were the number one trigger for repair activities, while pavement condition parameters part of management program were second.
- The main factors responsible for pothole formation were found to be the weather and the wearing course condition.
- Crack sealing and patching are the most common preservation activities, followed by chip seals.
- Throw and roll is the number one repair method used.
- Hot asphalt mix is the number one material used.
- When asked in what areas respondents would like to spend more money (if more were available), staffing, equipment, and materials were evenly chosen.

CHAPTER 3: POTHOLE STRESS ANALYSIS

3.1 INTRODUCTION

In this task, numerical simulations were performed to determine if certain geometric configurations (round vs. square, etc.) are more favorable in reducing the stresses that develop in pothole materials and at the interface with the old pavement and to determine a set of desirable material properties for long lasting pothole repairs.

3.2 LITERATURE REVIEW ON COMPUTER SIMULATIONS FOR POTHOLE REPAIRS

A literature search found no published reports on stress analysis of pothole repairs. Surprisingly, only a few published references were found on the more general topic of stress analysis of repairs in other engineering structures. One example is detailed below.

Filled potholes are similar to micro-inclusions in steel on a much larger scale. Yang et al. [10] simulated micro-inclusions in steel rudder arms for ships. Two dimensional plane stress finite element modeling was performed using the commercial software ANSYS. The "fish-bone" structure of inclusions was simplified to round, square, isosceles trapezoid, rhombus and pentagon shapes. Inclusions were modeled with different elastic moduli $E_2 = 0.5E_1$ and $E_3 = 1.5E_1$ where E_1 is the elastic modulus of the matrix material and E_2 and E_3 are the elastic moduli of the inclusion. Circular shaped inclusions in a square plate of 100 µm by 100 µm were modeled first. Circles had diameters ranging from 5 µm to 35 µm. The plate was loaded in uniaxial tension. It was observed that the maximum and minimum stresses always occurred at the interface between the matrix and the inclusion. When $E_2 = 0.5E_1$ the maximum stress occurred in the matrix material on the sides of the circle perpendicular to the loading and the minimum stress occurred in the inclusion on the top and bottom of the circle, nearest the loading. When $E_3 = 1.5E_{1,}$ the maximum stress occurred in the inclusion on the edges of the circle closest to the load and the minimum stress occurred in the matrix material along the sides of the circle. It was shown that the change of the diameter of the circle had little effect on the magnitude or distribution of the stresses.

Yang et al. also modeled inclusions shaped as a square, isosceles trapezoid, rhombus and pentagon. Each shape had approximately the same area. It was observed that in general, the locations of maximum stress occurred on the interface between the boundary and the inclusion with each shape inclusion. As with the circle, the maximum stresses occurred in the matrix when the elastic modulus of the inclusion was less than the elastic modulus of the matrix and in the inclusion when the elastic modulus of the inclusion was greater. The stress concentration increased when the difference between the elastic moduli of the matrix and the inclusion increased. It was also observed that the distribution of stresses within the inclusion depended on its shape. The circular inclusion had uniform stress in the horizontal direction and one of the lower maximum stresses. The pentagon had the most inhomogeneous stress concentration. The pentagon and square had the highest maximum stress.

Additionally, it was seen that the stresses increase linearly with increase in applied load, a well-expected consequence of elasticity.

3.3 STRESS ANALYSIS OF POTHOLES

Pavement sections containing three different shaped potholes, round, square and diamond, were modeled using finite element analysis to determine the effect of geometry on the stress concentrations around the pothole. The potholes were loaded in tension as shown below in Figure 3.11. Dimensions, material properties, and loading were kept constant over all simulations for comparison purposes.

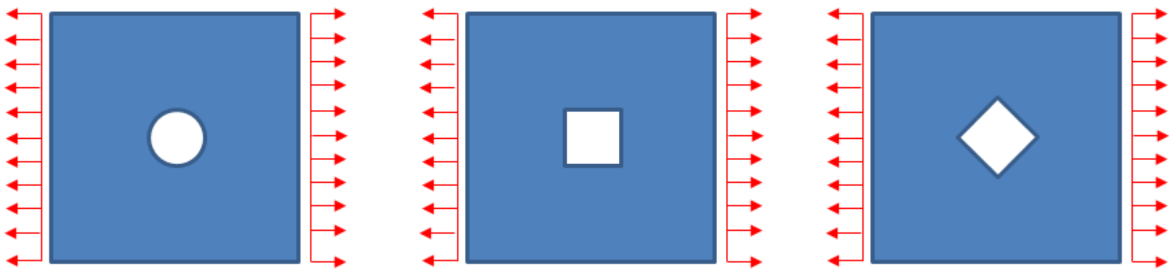

Figure 3.1: Pothole model geometry and loading

The pavement sections were modeled as two-dimensional planar shells using the commercial finite element analysis software Abaqus/CAE version 6.11. Due to the symmetry of loading and specimen geometry, quarter sections with symmetry boundary conditions were used. Each quarter section was modeled as a 1 in thick, 200 in by 200 in square with a hole of 12-in radius. The models are shown in Figure 3.2. The existing asphalt was modeled as an elastic material with a Young's modulus of 1000 ksi and a Poisson's ratio of 0.35. The bottom edge of each model was given y-symmetry boundary conditions (y = 0, no x and z rotation) and the left edge was given x-symmetry boundary conditions (x = 0, no y and z rotation). The right edge of each model was loaded with a 1 ksi horizontal uniformly distributed tensile stress.

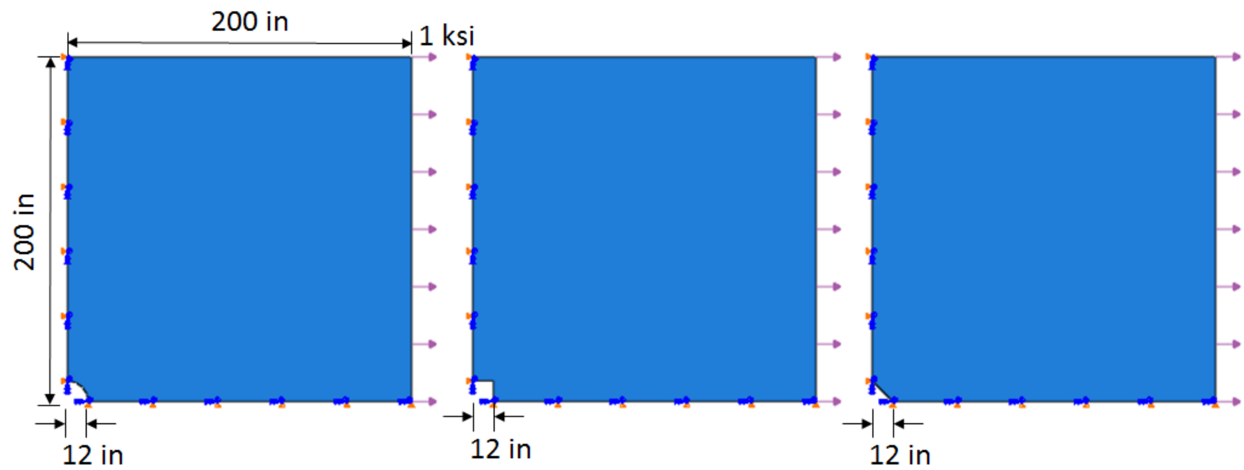

Figure 3.2: Boundary conditions, loading and dimensions for the circle, square and diamond pothole plate models

3.3.1 Circular Pothole

The circular pothole model was formed using a structured mesh consisting of approximately 2 inch quadratic quadrilaterals, shown in Figure 3.3. The horizontal tension stress (S_{xx}) contours and deformed shape after loading are shown in Figure 3.4. The stress reaches a maximum value of 3.03 ksi along the edge of the pothole on the y-axis of the model. The maximum stress is approximately three times the applied stress, which is consistent with the exact elasticity solution [11]. This suggests that the model is a good representation for the stresses that would occur surrounding a circular pothole. The normalized stresses along the vertical centerline of the circle (the left edge in the model) are plotted against the vertical distance from the edge of the hole in Figure 3.4. At the distance away from the hole increases, the stress decreases quickly, reaching within 125% of the applied stress twelve inches, or one radius, away from the hole and within 105% of the applied stress 36 inches, or three radii away from the hole. Such a behavior is well-expected according to St-Venant's principle.

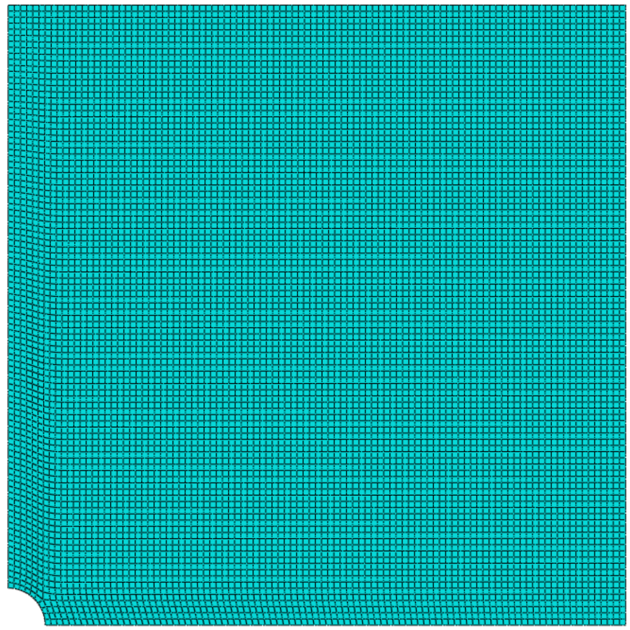

Figure 3.3: Circular pothole model mesh

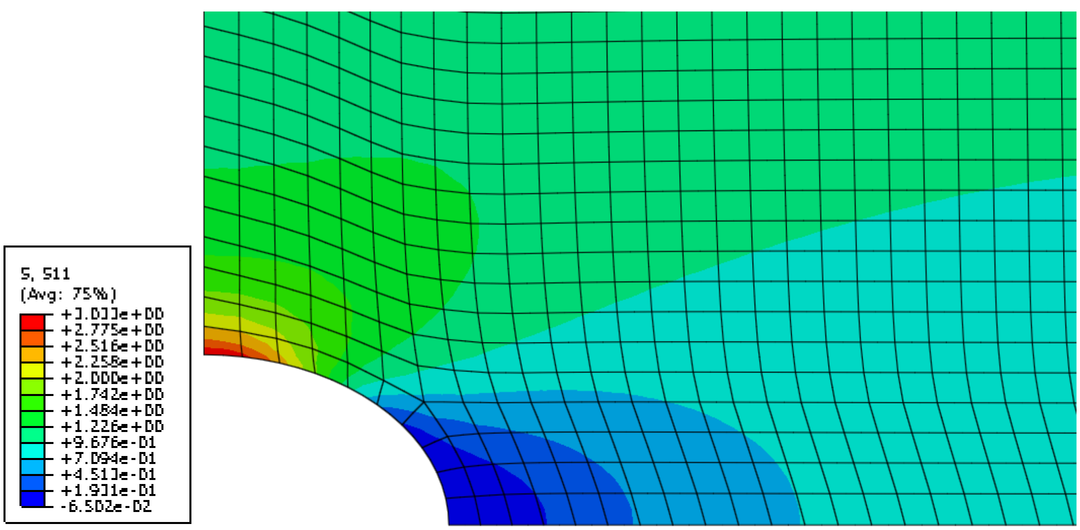

Figure 3.4: Horizontal stress contours and deformed shape of circular pothole model under 1 ksi horizontal loading

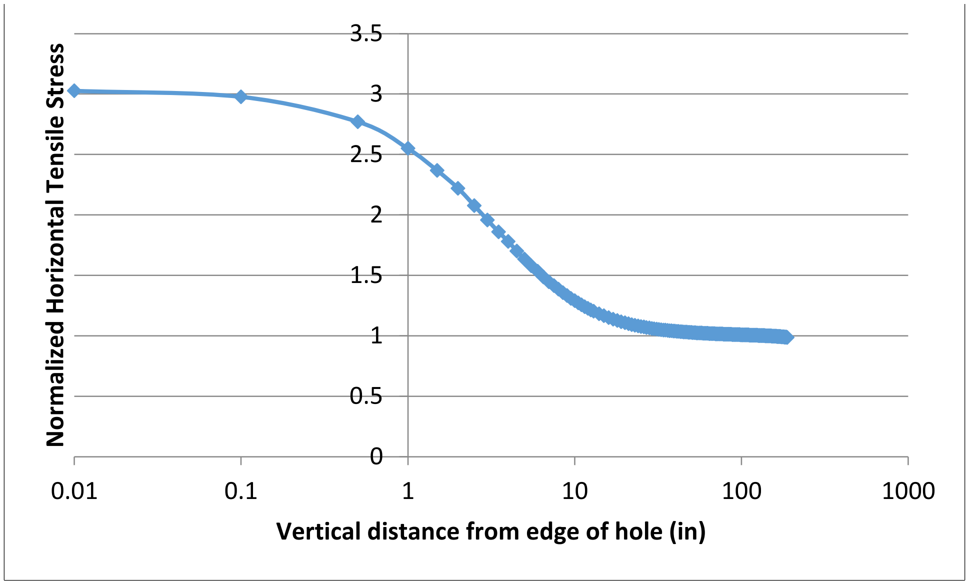

Figure 3.5: Plot of horizontal stress along the left edge of model for round pothole

3.3.2 Square Pothole

Unlike the round pothole, the square pothole has sharp corners, which lead to significant stress concentrations. To better capture the stress singularity at the corner, a special element was used in which the middle nodes were moved to the quarter points of the element (Figure 3.6). The circle and the rest of the model were each meshed separately using a mesh of linear quadrilateral elements without reduced integration. Both used a free mesh with 1" seeding. Figure 3.7 shows the mesh used for the square pothole model in the area near the hole and the crack tip.

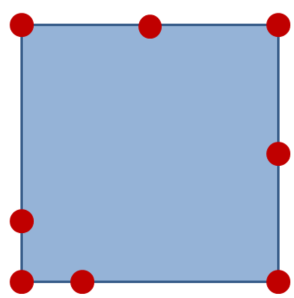

Figure 3.6: Special element used at corner

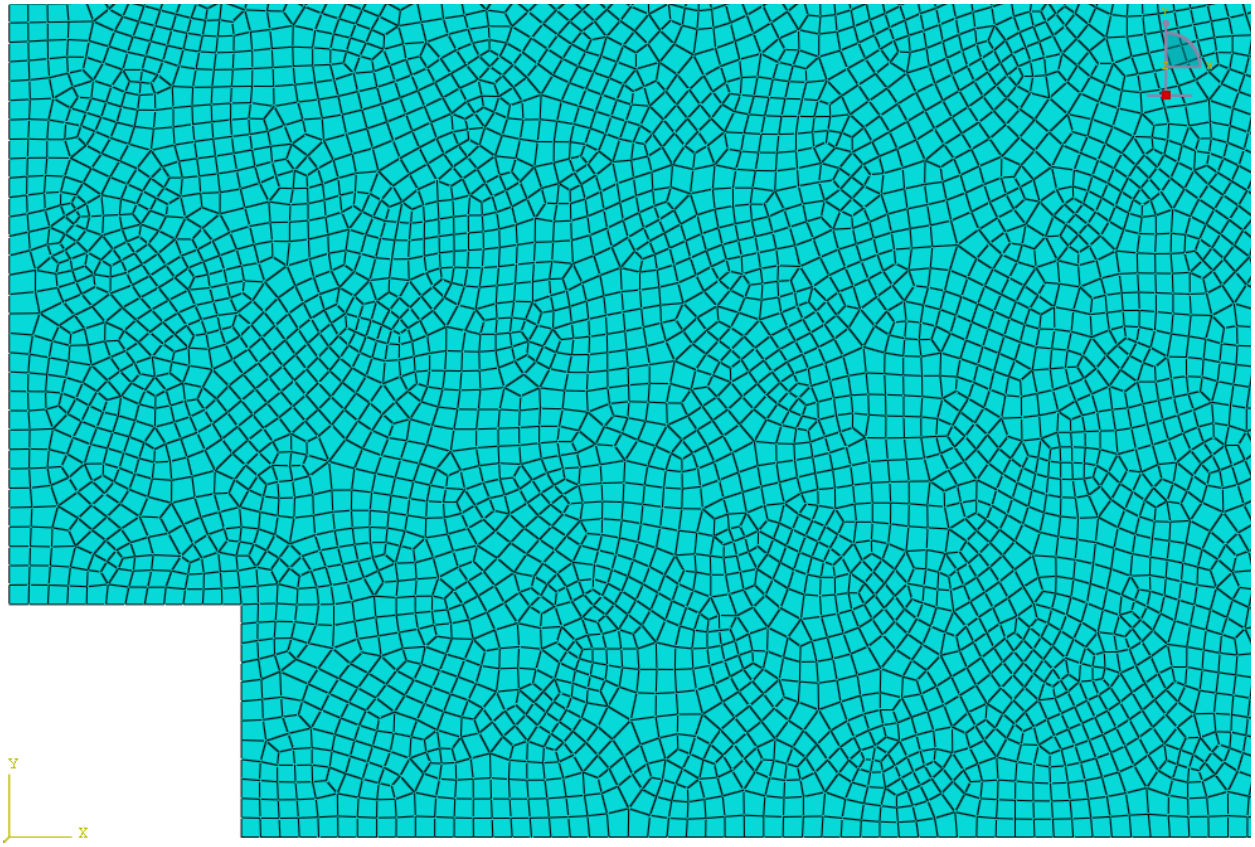

Figure 3.7: Square pothole mesh near pothole and crack tip

The maximum principal stresses were investigated for the square pothole model rather than the horizontal stresses because the crack is expected to propagate at a tilted angle from the corner of the pothole. Therefore, unlike in the case of the circular pothole, the maximum tensile stress would not be in the horizontal direction. The maximum principal stress contours plotted on the deformed shape in the area near the pothole are shown in Figure 3.8. To determine the line upon which the stresses were highest, the stresses were plotted on circles of various radii around the crack tip.

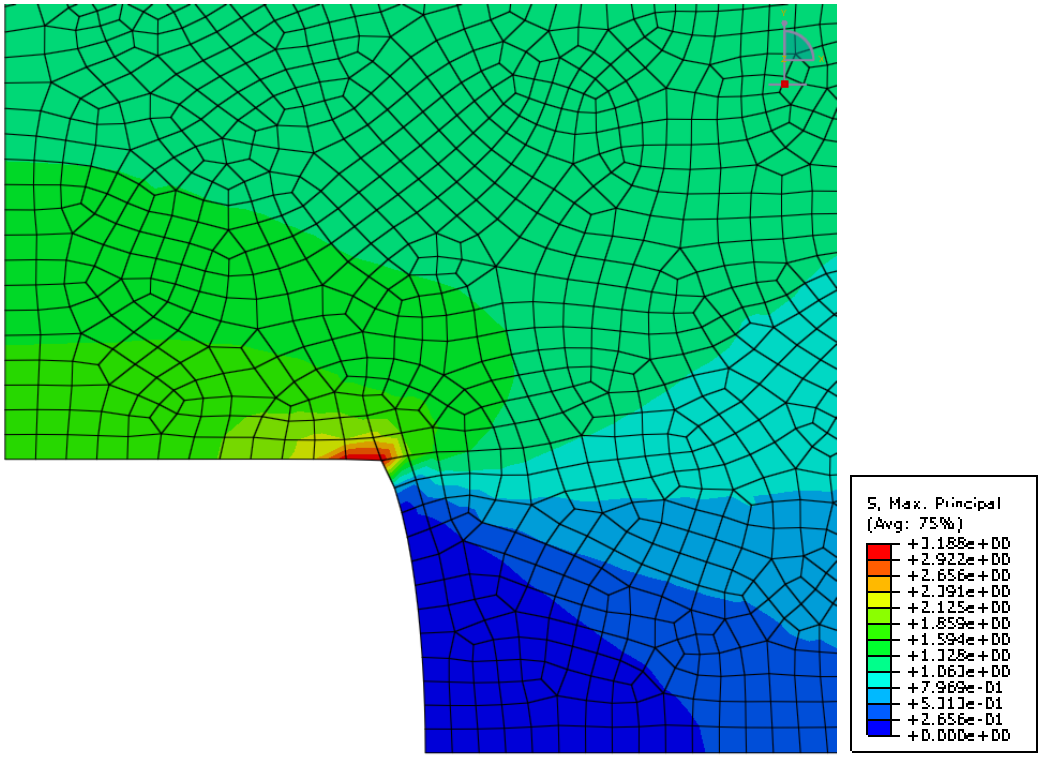

Figure 3.8: Maximum principal stress contours and deformed shape of the square pothole model under 1ksi loading in horizontal tension

The maximum principal stresses along the line from the corner of the hole left along the top edge of the hole are plotted against the distance from the corner in Figure 3.8. Finite element models are not able to accurately calculate the stresses in the region immediately adjacent to the corner of the hole (the stress approaches to infinity at the corner). However, the near-corner stress-field can be extrapolated from the stress plot. Away from the corner, the maximum principal stress is linear with the distance away from the hole on a log-log plot (shown in Figure B-1 in the Appendix B). The equation of the best-fit line for the linear portion of the graph is

$$\log(normalized\ max.principal\ stress) = -0.401\log(distance) + 0.504 \qquad (3.1)$$

The R^2 value for the best fit line is 0.993, meaning that the Eq. 1 fits the data set very well. Eq. 3.1 can be rearranged to give an equation for the normalized maximum principal stress:

$$\sigma = 3.19r^{-0.401} \qquad (3.2)$$

where σ is the maximum principal stress normalized by the far-field stress and r is the distance away from the vertex of the pothole along the top edge of the hole in inches. Eq. 3.2 can be used to extrapolate the stresses closer to the vertex, as shown in Figure 3.9. From interpolation, it can be found that the normalized maximum principal stress one inch away from the vertex of the hole is 3.19.

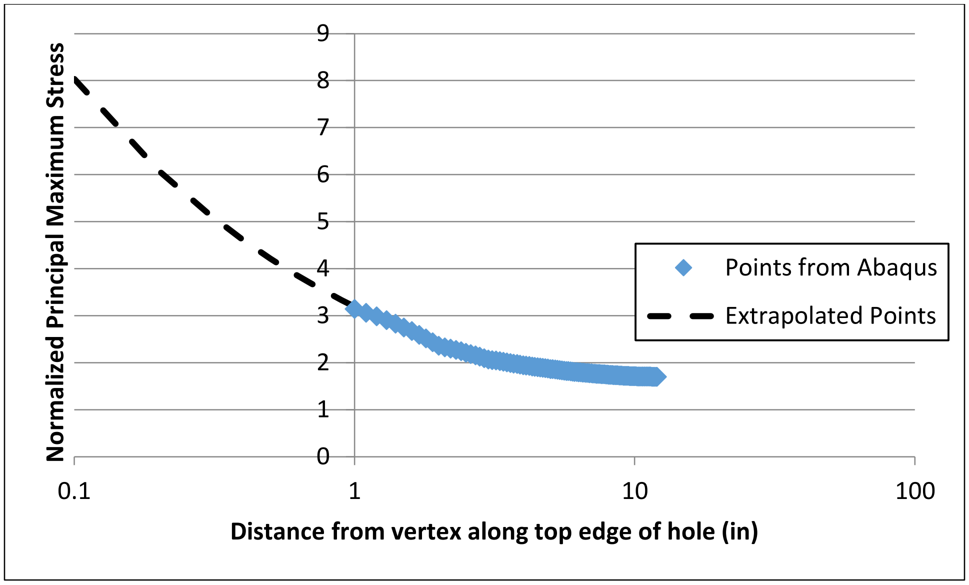

Figure 3.9: Maximum principal stresses in square pothole model

3.3.3 Diamond-shaped pothole

In addition to circular and square potholes, a diamond-shaped pothole was also investigated. The diamond shape used had 90° angles, which makes it a square, but the model is different from the square pothole model because of the direction of loading relative to the shape of the hole. The full diamond hole was modeled rather than a quarter section to avoid complications due to the crack direction being on the line of horizontal symmetry. Dimensions were as shown in Figure 3.2, but reflected over both lines of symmetry. The plate was loaded in horizontal tension with 1 ksi of loading. The symmetry of the model eliminated the need of the boundary conditions used to model the circular and square potholes and shown in Figure 3.2. The only boundary condition imposed was restraint in the y-direction on the bottom edge to prevent the rotation of the entire model. Similarly to the square model, circular partitions 4" in radius were drawn around the upper and lower corners of the hole, where the notches will create stress concentrations under horizontal tension. Similar to the analysis of the square hole, a special element was used to capture the singular stress field. The two circular regions and the rest of the model were each meshed individually with quadratic, quadrilateral elements without reduced integration using unstructured mesh, seeded to 1". However, due to the geometry of the diamond and the circular partitions around its vertices, many of the elements near the hole were larger than one inch. The mesh in the area near the hole is shown in Figure 3.10.

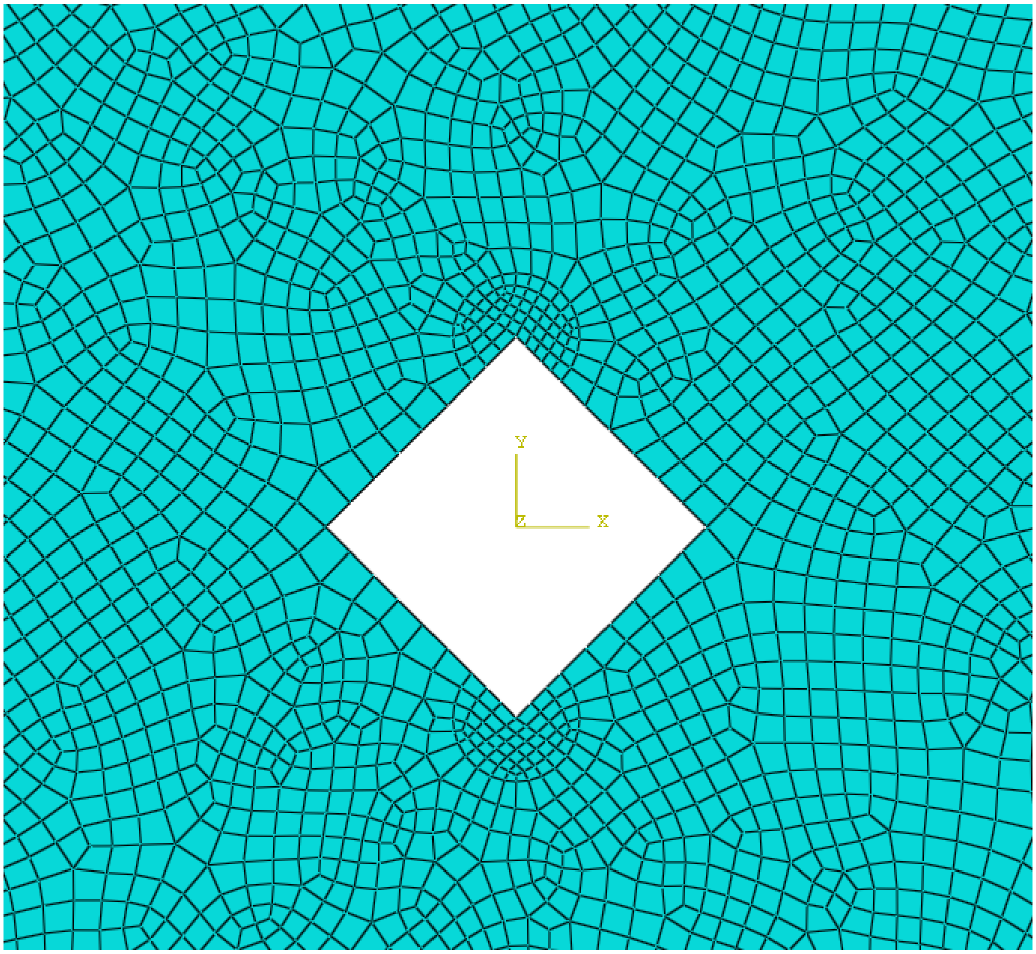

Figure 3.10: Mesh around diamond hole

The horizontal stress contours for the diamond pothole model in the area around the hole are shown in Figure 3.11 and Figure 3.12. Figure 3.11 shows that as expected, the stresses are approximately symmetrical in both the x-and y-directions.

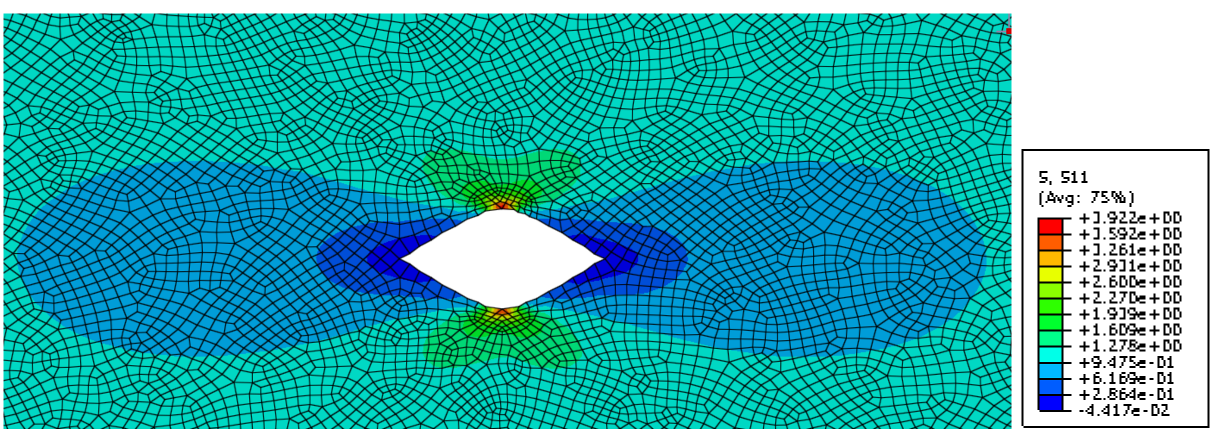

Figure 3.11: Horizontal stresses in diamond pothole model

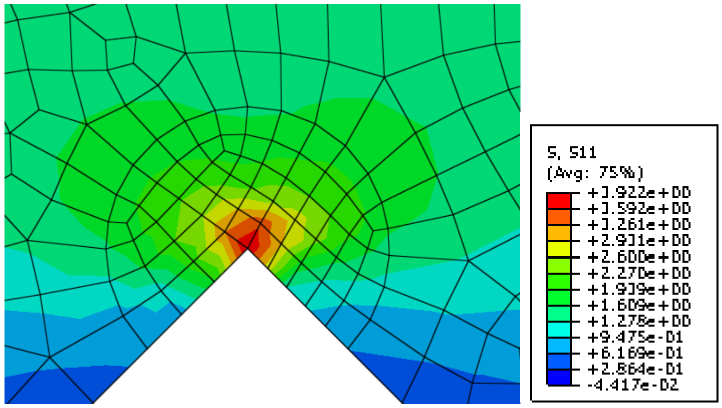

Figure 3.12: Close-up of stresses in diamond pothole model near crack tip region

The horizontal tensile stresses were examined along the line extending vertically from the top vertex of the diamond. The stresses along the path are shown in Figure 3.13. The log-log plot used to determine the relationship between normalized stress and distance is shown in Figure B-2 in the Appendix B. On the log-log plot, the linear relationship, which has an R^2 value of 0.985 is:

$$\log(normalized\ max.principal\ stress) = -0.458\log(distance) + 0.477 \qquad (3.3)$$

Then the exponential relationship between stress and distance from the vertex is:

$$\sigma = 3.00r^{-0.458} \qquad (3.4)$$

where σ is the horizontal stress along the vertical line starting at the top corner of the diamond and r is the vertical distance along from the vertex. Eq. 3.4 is used to extrapolate stresses back towards the vertex in Figure 3.12. The exact elasticity solution for the singular stress field in this case is given by the well-known Williams solution [12]:

$$\sigma \propto Kr^{-0.455} \qquad (3.5)$$

Eq. 3.4 approximately fits the relationship in Eq. 3.5. Using Eq. 3.4, the normalized horizontal tensile stress one inch from the corner of the pothole would be 3.00.

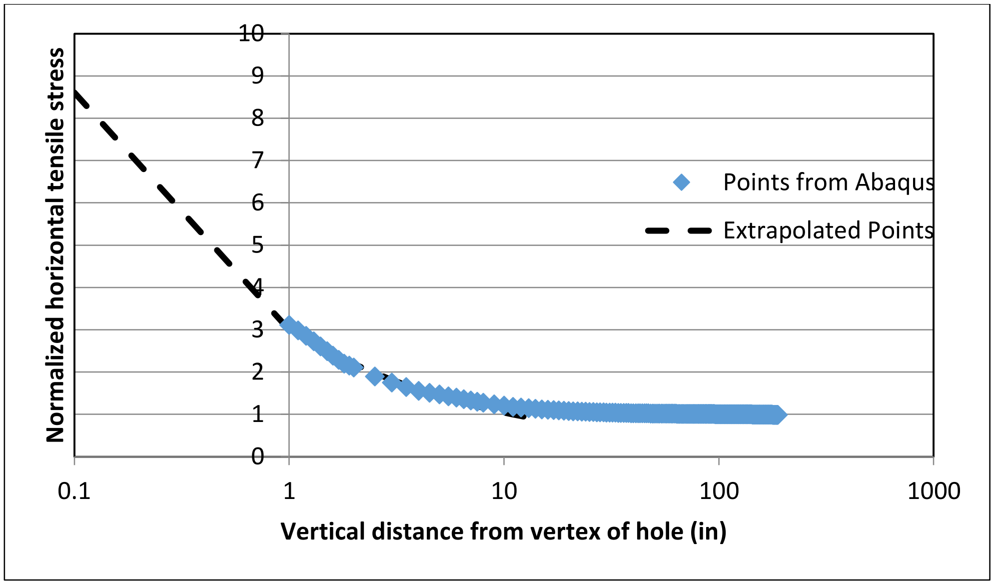

Figure 3.13: Horizontal stresses in diamond pothole model

3.3.4 Comparison between shapes

The stresses 1 in away from the location of maximum stress for the different shaped potholes are compared in Table 3.1. The square pothole model has the highest stress, followed by the diamond. The circle has the lowest stress. Therefore, it can be concluded that the best pothole shape to use to minimize stress concentrations is round.

Table 3.1: Comparison of normalized stresses between pothole shapes

Shape	Stress
Circle	2.55
Square	3.19
Diamond	3.00

3.4 FILLED CIRCULAR POTHOLE MODELS

The circular pothole was then modeled with the hole filled in to examine stresses in potholes after repair is completed. In each case the original piece was modeled identically to that in section 3.1. Four different scenarios were considered in this study:

- A hole with one fill piece of a weaker material attached to simulate a pothole repaired with a weaker fill material with perfect bonding.

- A hole with a weak thin interface between the main piece and a weak fill piece to simulate a pothole repaired with a weak fill material and poor bonding between the fill and the existing road.
- A hole with a weak thin interface between the main piece and a strong fill piece to simulate a pothole repaired with a strong fill material but with weak bonding between the fill and the existing road.
- A hole with an extremely weak interface between the main piece and a weak fill piece to simulate a pothole repaired with a weak fill material and with extremely poor bonding between the fill and the existing road.

3.4.1 Round Pothole Modeled without Interface Piece

The round pothole was first modeled with one fill piece. This model represents the situation where a perfect bond is formed between the existing asphalt and the fill material. The fill piece was modeled as a quarter section of a circle with a radius of twelve inches to perfectly fit into the existing asphalt model. The fill material was modeled as a second part with a Young's modulus of 500 ksi, half of the Young's modulus of the outer material. The geometries of the two parts were merged together while retaining the intersecting boundaries. The resulting merged model was meshed using a structured mesh of quadratic quadrilateral elements seeded for 2" elements, as shown in Figure 3.14.

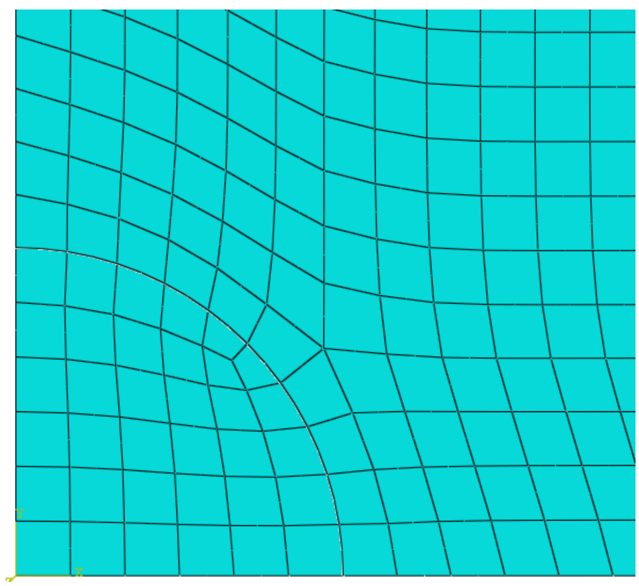

Figure 3.14: Filled round pothole mesh in the area of the hole

The horizontal tensile stresses are shown in Figure 3.15. The stress contours in the existing asphalt appear similarly shaped to those in the original unfilled model in section 3.1. However, the stresses are much lower. Along the direction of loading, the maximum stress in the existing pavement is 1.507 ksi, and the fill material has an approximately constant stress of about 0.753 ksi.

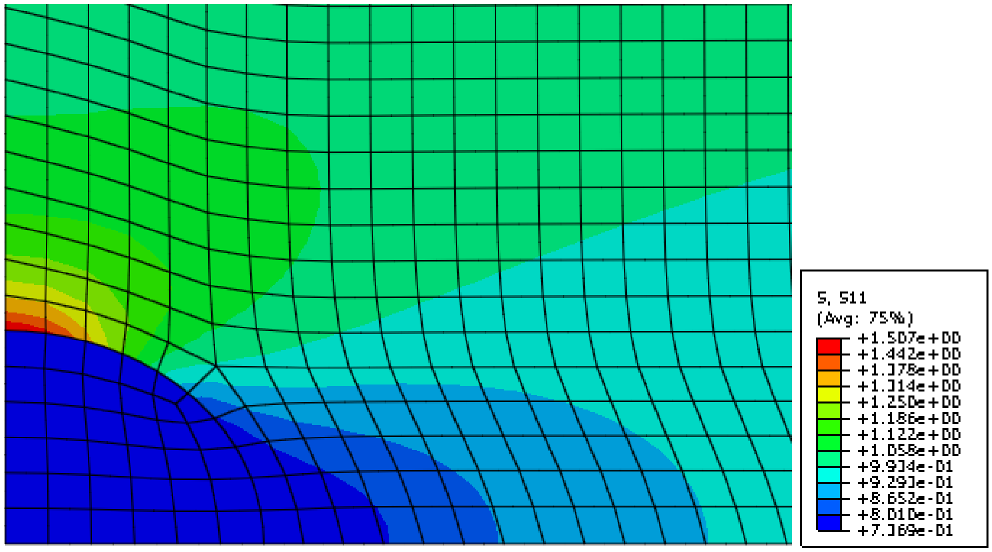

Figure 3.15: Horizontal tensile stresses plotted on deformed shape for filled round pothole modeled without interface piece

3.4.2 Filled Models with Interfaces

The filled potholes were also modeled with an interface piece between the existing asphalt piece and the fill piece to represent situations where the bond between the existing asphalt and the fill is imperfect. The interface was modeled as a thin quarter arc of a circle with a total thickness of 0.05”. The fill piece was remodeled with a radius of 11.95” so that the three pieces could fit together perfectly. Three combinations of interface and fill strengths were examined. In each case, the geometries of the fill, interface, and existing asphalt pieces were merged together to form one part, while maintaining the three separate material properties. The model was then meshed using 2” seeded quadratic quadrilateral elements in a structured mesh. The interface piece was meshed with just one row of elements due to its extreme thinness. Care was taken to ensure that the meshes matched where the parts met. The mesh used is shown in Figure 3.16. The same loading and boundary conditions were applied as had been used for the previous models.

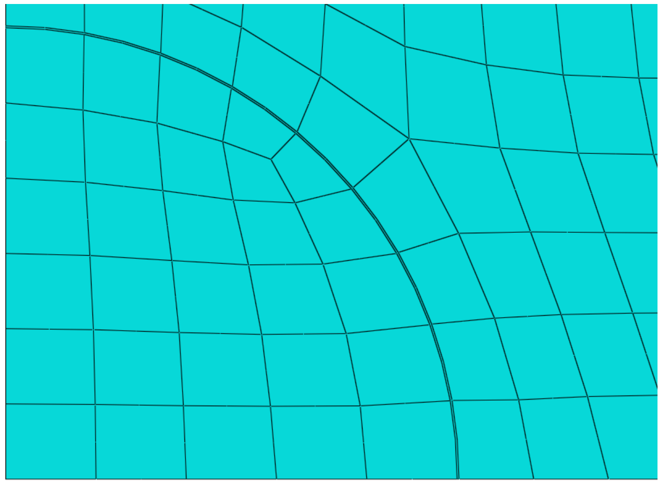

Figure 3.16: Mesh used in filled circular pothole with interface models in the area of the pothole

The interface model was first modeled with an elastic modulus of 1000 ksi for the existing asphalt, 100 ksi for the interface and 500 ksi for the fill. All three materials had a Poisson's ratio of 0.35. This model uses the same materials as were used in the previous model in section 3.4.1, with the addition of the interface. It represents the case where the same materials were used but a poor bond was formed between the existing asphalt and the fill material.

The horizontal stress contours for this situation are shown below in Figure 3.17. The maximum stress in the existing asphalt is 1.53 ksi. The stresses in the interface range from approximately 0.15 ksi to 0.76 ksi. The stresses in the fill are almost constant, ranging between approximately 0.73 ksi and 0.75 ksi.

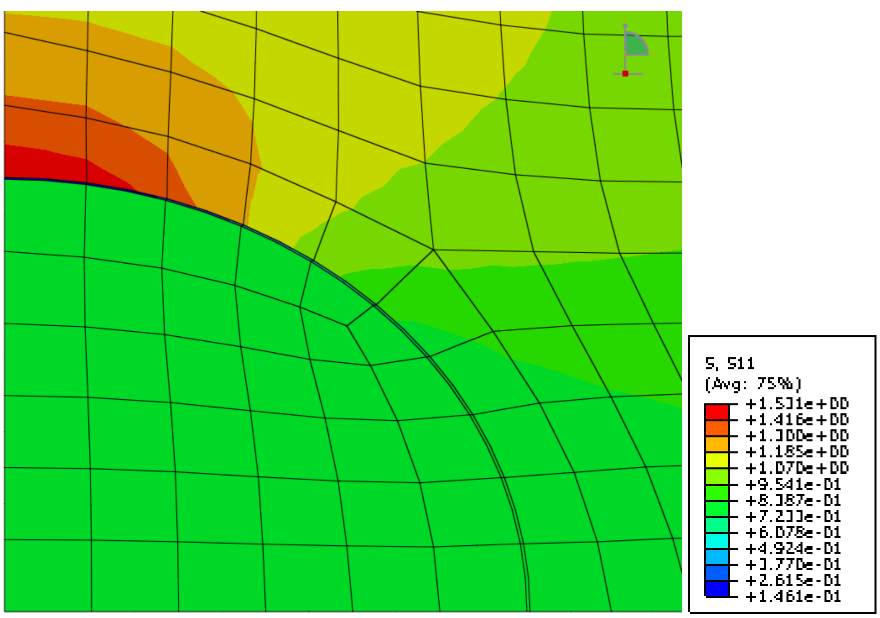

Figure 3.17: Stress contours plotted on deformed shape for circular pothole model with E=100 ksi in interface and E=500 ksi in fill

The round pothole was also modeled with fill with a Young's modulus of 1000 ksi (the same as the existing asphalt) while the interface Young's modulus was kept at 100 ksi. This model represents a situation where the pothole is filled with material equivalent to the existing asphalt but a poor bond is formed between the new and old materials. Other than the change in fill material elastic modulus, the model was identical to the previous model. The horizontal stress contours near the pothole for this model are shown in Figure 3.18. The stresses appear very uniform within the model. The existing asphalt has a maximum stress of 1.05 ksi at the boundary between the existing pavement and the interface. The interface has stresses ranging from 0.09 ksi to 1.00 ksi. The fill material has stresses ranging from 0.96 ksi to 1.00 ksi.

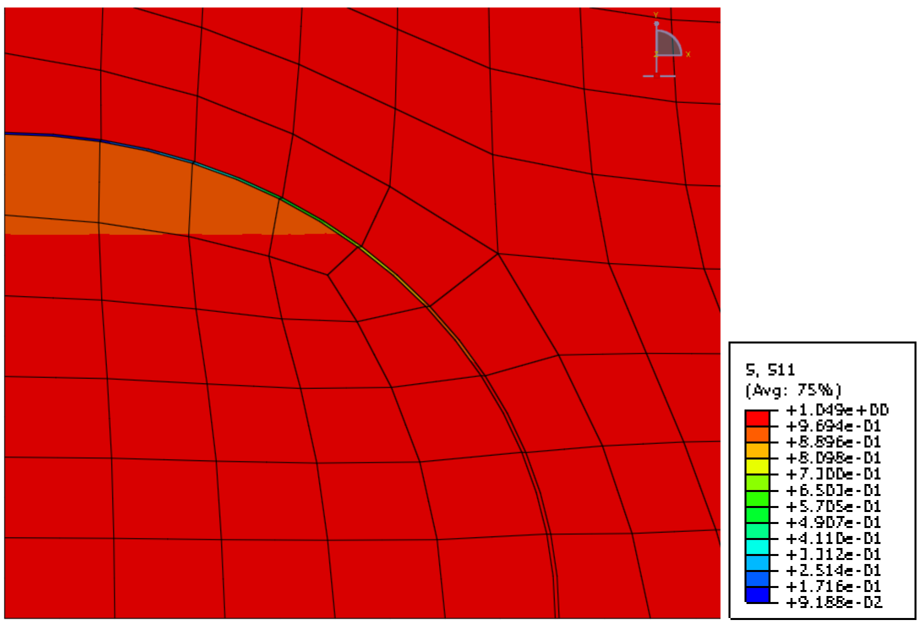

Figure 3.18: Stress contours on deformed shape for round pothole model with E=100 ksi interface and E=1000 ksi fill

Finally, the round pothole was modeled with an elastic modulus of 500 ksi for the fill material and 10 ksi for the interface. This model represents a situation where the pothole was filled with the same material as the first filled model, but an extremely poor interface was formed between the fill and the existing asphalt. The horizontal stress contours for this model are plotted on the deformed shape in Figure 3.19. The stresses in the existing asphalt are higher in this model than the other filled models, with a maximum horizontal tensile stress of 1.72 ksi. Stresses in the interface range from 0.00 ksi at the y-axis to 0.71 ksi at the x-axis. Stresses in the fill range from 0.54 ksi to 0.71 ksi. Deformation in the interface is also visible in Figure 3.19. No interface deformation was visible to the eye in the deformed shapes of the other models.

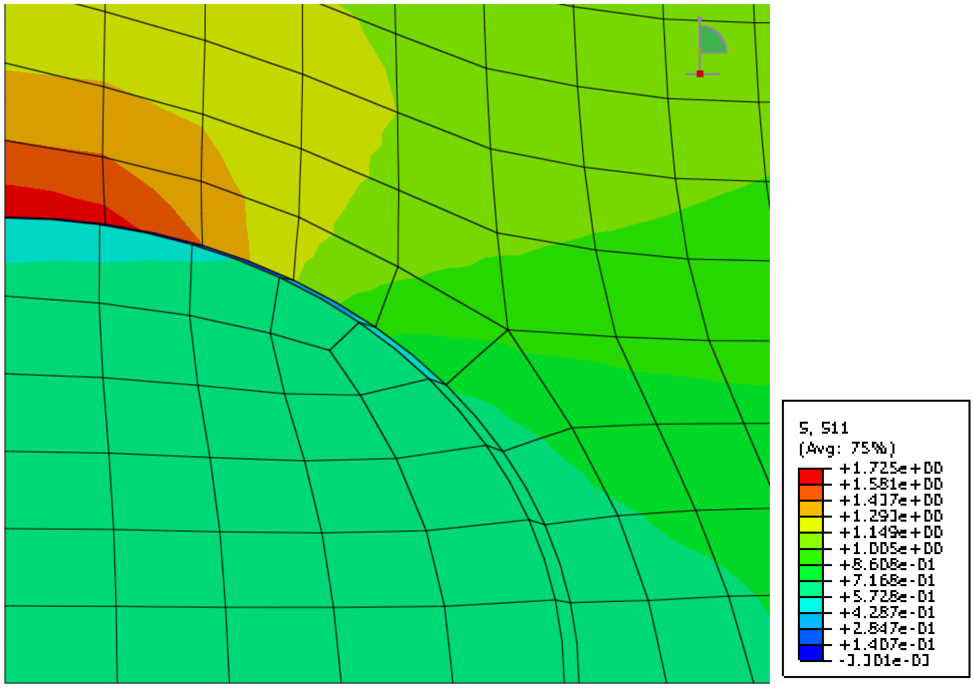

Figure 3.19: Stress contours plotted on deformed shape for round pothole model with interface E=10 ksi and fill E=500 ksi

3.4.3 Comparison Between Circular Models

The horizontal stresses along the *x*-axis in each circular pothole model are plotted together in Figure 3.20. As expected, all of the filled pothole models have significantly lower stresses in the existing asphalt than the unfilled pothole model. In addition to having lower peak stress values, the stresses in the filled models approach 1 much closer to the edge of the pothole than in the unfilled model. This suggests that in terms of stresses, any method of filling the pothole is better than leaving it unfilled. For the models with 500 ksi Young's modulus fill, the plot shows very little difference between no interface and the 100 ksi interface, but an increase in stress for the model with a 10 ksi interface. This suggests that a perfect bond is not necessary, but a poor bonding between the existing asphalt and the pothole fill material will result in increased stresses. Finally, Figure 3.20 shows that the model with 1000 ksi Young's modulus fill and 100 ksi Young's modulus interface had stresses that were significantly lower, as well as more uniform, than any of the other models. This suggests that using a patch material with the same stiffness as the original asphalt, as well as ensuring adequate bonding, is the most effective way to reduce stress concentrations in the existing pavement and in the pothole.

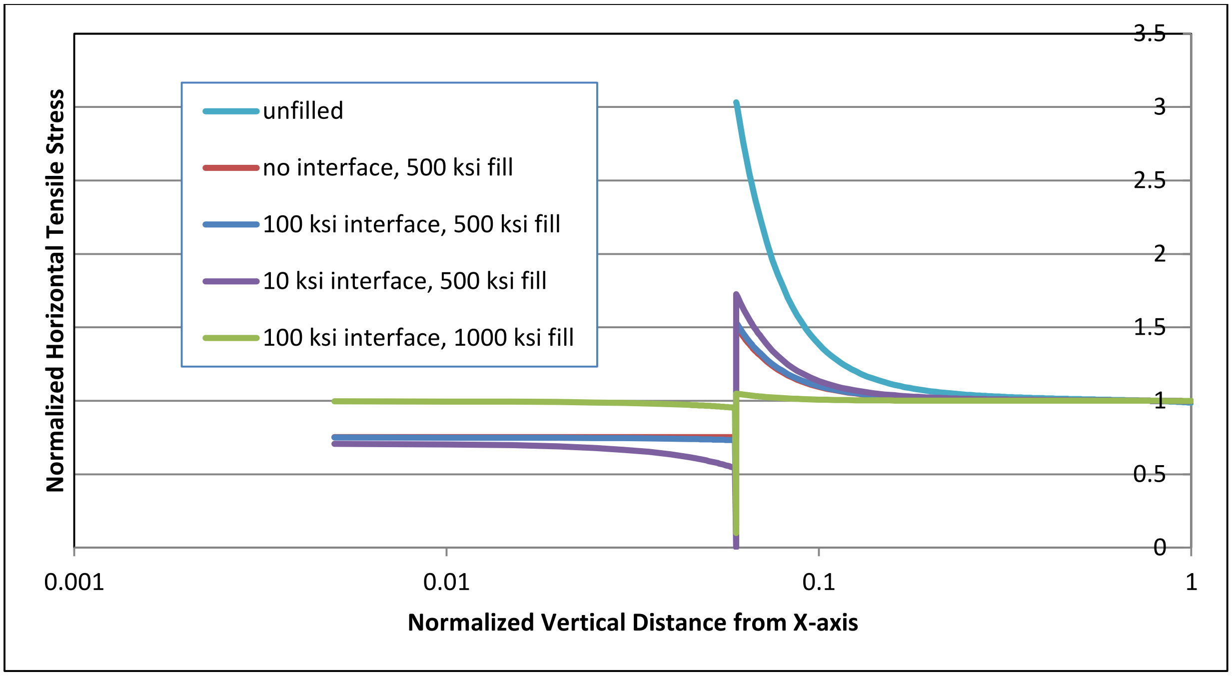

Figure 3.20: Plot of normalized horizontal stress versus vertical distance from the x-axis for the round pothole models.

In addition to stresses in the pavement and pothole materials, it is also important to examine the stresses in the interface, where debonding could occur. The stresses in the interface layers of the different models are compared in Table 3.2. The model with the 100 ksi interface and 1000 ksi fill had the highest normalized stress in the interface at 1.00. The model with the 10 ksi interface and 500 ksi fill had the lowest normalized stress in the interface at 0.71. It is clear that a more compliant interface and fill material will lead to a decrease in interfacial stress, however it will result in an increase in stresses in the pavement material. Therefore, the design should consider both aspects to reach optimum stiffnesses of the interface and the fill material.

Table 3.2: Stresses in interface

Model	Maximum Normalized Horizontal Stress in Interface
100 ksi interface, 500 ksi fill	0.76
100 ksi interface, 1000 ksi fill	1.00
10 ksi interface, 500 ksi fill	0.71

3.5 CONCLUSIONS AND RECOMMENDATIONS

Based on the numerical simulations performed, a number of conclusions can be drawn:

- When modeled as two-dimensional plates under horizontal loading using finite element software, unfilled circular-shaped holes showed lower stress concentrations than square or diamond-shaped holes. This suggests that circular-shaped potholes should be used to minimize stress concentrations near the boundary of the potholes.
- A filled pothole modeled with an interface with a Young's modulus one tenth the value of that of the existing asphalt showed almost identical stress profile to a similar pothole modeled with a direct bond between the existing asphalt and the fill. However, an identical pothole modeled with a Young's modulus for the interface one one-hundredth the value of the existing asphalt showed higher stresses. This suggests that perfect bonding is not necessary to minimize the stresses surrounding a patched pothole but the bond does need to be sufficiently strong to avoid an increase in stresses.
- The pothole patched with the same material as the surrounding asphalt showed significantly lower maximum stresses than any of the other scenarios modeled, as well as a more uniform stress profile. However, more compliant interface and fill materials would lead to a decrease in the stress in interface. Therefore, the design of pothole repair should consider the stresses in existing pavement, fill material, as well as the interface.

It should be noted that circular pothole repairs also represent the best construction option to completely fill the pothole with the repair material and compacting it. The repair material cannot flow into and fill pothole corners even when significant compaction is performed.

In a recent study [13], researchers concluded that infrared asphalt heater/reclaimer patching method can significantly improve the performance and longevity of pothole patches compared to throw and roll and spray injection methods, especially in winter conditions. This approach results in both better patching material properties as well as better bonding conditions, similar to the numerical results presented in this task.

CHAPTER 4: EXPERIMENTAL INVESTIGATION OF NEW MATERIALS FOR POTHOLE REPAIR

4.1 INTRODUCTION

The focus of this task was to perform experimental work to determine if relevant material properties can be obtained on pothole patching materials, and to investigate if the addition of graphene nano-platelets (GNP) to patching materials improve their properties.

Initially, four materials were tested: Perma-Patch, Summer Mix_UPM, Winter Mix_UPM, Winter Mix_St Paul. Several issues were encountered during sample preparation and several types of conditioning preparation methods were conducted on these patching materials before testing. Only Indirect Tensile Strength Test (IDT) was performed to investigate the material properties. A fifth material, GAP (mastic), was obtained later on and also tested using IDT strength.

At the end of the task, a sixth material, St. Paul Summer Mix, became available. For this material, samples were also prepared using two GNP additives: Micro 850 GNP and 4827 GNP. For each of these GNP materials, 6% by weight of the binder was added. For each type of GNP modification, 3 replicates were tested to measure air voids, IDT creep and strength, and SCB fracture energy and toughness at low and intermediate temperatures. Also, three control replicates were tested. Control replicates consisted of only St Paul Summer Mix, and contained no GNP additive.

4.2 INITIAL PATCHING MATERIALS

In the first round of testing, samples were prepared using four types of pothole patching materials, which are summarized in Table 4.1 and described in the next paragraphs.

Table 4.1: List of materials tested in the first round of testing

Patching Materials	Acronyms used in task report
Perma-Patch from MnDOT	PP
Winter **M**ix from **S**t. **P**aul Asphalt Plant	WM_SP
Winter **M**ix from **U**nique **P**aving **M**aterials (UPM)	WM_UPM
Summer **M**ix from **U**nique **P**aving **M**aterials (UPM)	SM_UPM

Perma-Patch is a proprietary formula composed of asphalt, special aggregate, and pressure-sensitive plastics. It sets up by compaction rather than by evaporation. Perma-Patch is a fast and easy permanent repair solution which can be used under any kind of weather condition (as claimed by the manufacturer). This is the most common and frequently used pothole patching materials on the market.

UPM is a cold-mix patch material for asphalt and concrete pavements manufactured by Unique Paving Materials Corporation. The binder is a proprietary blend of cutback asphalt cement and viscosity modifier, which is used to control its workability. UPM can be purchased with an open-graded aggregate mixture for cold weather applications or with dense-graded aggregate for warm weather applications. Two types of UPM mixes were investigated:

Winter Mix_UPM, a winter grade 2 material, specifically formulated to be used at temperatures below 40° F.

Summer Mix_UPM, a summer grade 4 material, specifically formulated to be used between 60° F– 80° F.

The winter mix from St. Paul Asphalt Plant is designated as 6C and uses ½" minus aggregates. The oil content is 5.5% of SC-800 (slow cure). The asphalt cement that is used is PG 64-22.

These patching materials do not need any mixing preparation or application of tack coat and can be poured directly into the hole. Minimal or no equipment is required for placing and compacting and can be opened to traffic immediately after application. A typical pothole-patching material is shown in Figure 4.1.

Figure 4.1: Pothole patching material.

To obtain information about the aggregates contained in the patching materials, the materials were burnt in the ignition oven and a sieve analysis was performed. The aggregate residue for the patching materials are shown in Figure 4.2. The gradation curves are shown in Figure 4.3.

Figure 4.2: Aggregate residue from patching materials. Upper Left: Perma-Patch. Upper Middle: Summer Mix_UPM. Upper Right: Winter Mix_UPM. Bottom: Winter Mix_St Paul.

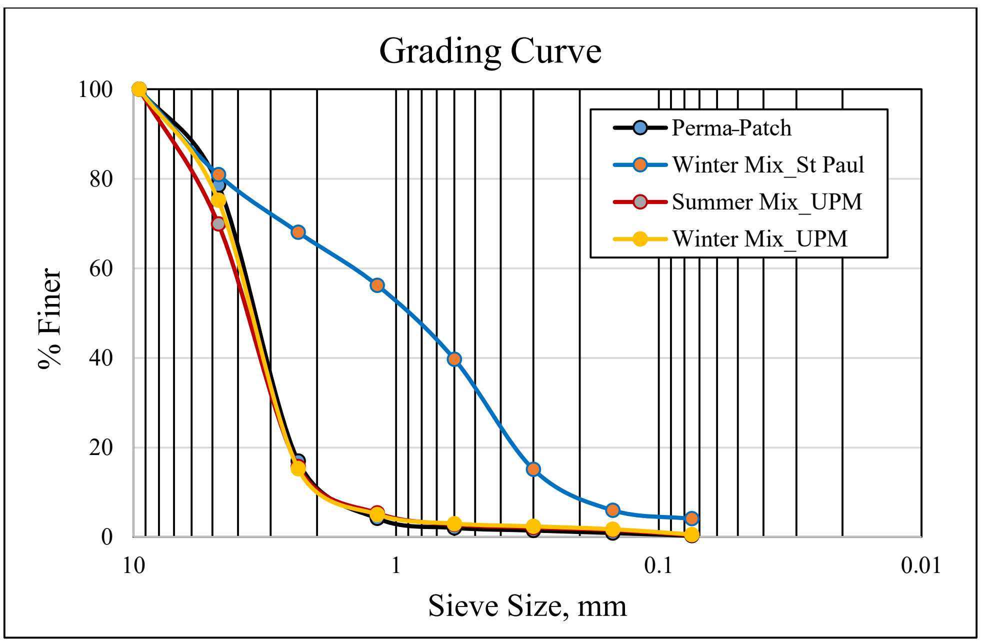

Figure 4.3: Gradation curves obtained for all four materials that were subjected to ignition oven test.

4.2.1 Sample Preparation and Testing of Initial Patching Materials

One of the biggest challenges of performing the proposed experimental investigation of the four patching materials was sample preparation that would result in specimens that could be tested using standard testing procedures developed for asphalt mixtures. Different compaction techniques and conditioning methods were used to accomplish this goal, as described below. Due to sample preparation issues, only one mechanical test was performed on these patching materials: IDT strength test conducted according to AASHTO T322-07. The procedure is described in detail in the experimental work for the St. Paul Summer Mix. The diameter of the specimen was 150 mm for plastic molds and 100 mm for steel molds.

4.2.2 Initial Compaction Methods of Test Specimens

First, gyratory compaction was used. However, it was impossible to compact the patching materials at room temperature. Only the winter mix from St. Paul asphalt plant (WM_SP) “survived” the compaction; the other three collapsed right after extraction. An example is shown in Figure 4.4, in which the middle sample is the winter mix from the St. Paul asphalt plant.

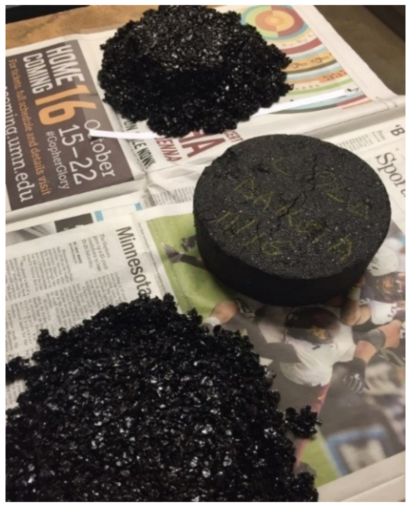

Figure 4.4: Sample preparation using gyratory compaction.

After gyratory compaction was not successful, manual compaction was used to prepare the IDT samples for PP, WM_UPM and SM_UPM. Cold conditioning was used after compaction to simulate winter patching and to provide some strength to the material. Samples were prepared as follows:

Cut plastic mold according to the IDT sample thickness

Pour a fixed amount of material in the mold

Use a steel cylinder to compact the material (the same person compacted all samples at room temperature)

Keep the compacted sample in the mold at -18°C for 5 days

Extract the sample from the mold after 5 days

Condition at test temperature (-24°C) for 1 hour before testing.

The sample preparation steps using plastic molds and manual compaction are shown in Figure 4.5.

Figure 4.5: Sample preparation using plastic mold and manual compaction.

Since this procedure is difficult and not repeatable, an MTS testing frame was used to simulate Marshall Compaction for repeatability (Figure 4.6). Several 100 compression cycles of a square wave between 0 and 20 kN at a frequency of 1 Hz were performed to each side of the mold. The setup is shown in Figure 4.6.

Figure 4.6: Sample preparation using plastic mold and MTS compaction.

Only the Perma-Patch was compacted using MTS and a plastic mold, and then tested for strength at -4ºC as a trial. The IDT strength results on the specimens compacted as part of these initial attempts are shown in Table 4.2 and plotted in Figure 4.7. As expected, MTS compaction produces specimens with higher strength than manual compaction. Among the samples tested using manual compaction, winter mix from UPM (WM_UPM) showed the highest IDT strength. The highest strength was obtained for the gyratory compaction.

Table 4.2: Preliminary IDT strength testing of specimens.

Sample No.	Patching Mix	Compaction	Compaction Mold	Before Compaction	After Compaction (before testing)	IDT Strength kPa
1	Winter Mix_St Paul (WM_SP)	Gyratory		Materials at Room Temperature	1.5 month at Room Temperature	709
2	Perma-Patch (PP)	Manual	Plastic		6 days in Freezer at -18C; 1hr at -24°C in the Chamber	82
3	Winter Mix_UPM (WM_UPM)	Manual	Plastic		6 days in Freezer at -18C; 1hr at -24°C in the Chamber	187
4	Summer Mix_UPM (SM_UPM)	Manual	Plastic		6 days in Freezer at -18C; 1hr at -24°C in the Chamber	115
5	Perma-Patch (PP)	MTS	Plastic		5 days in the oven at 40°C;1 day in the freezer at -18C; 1 hr at -24°C in the chamber	305

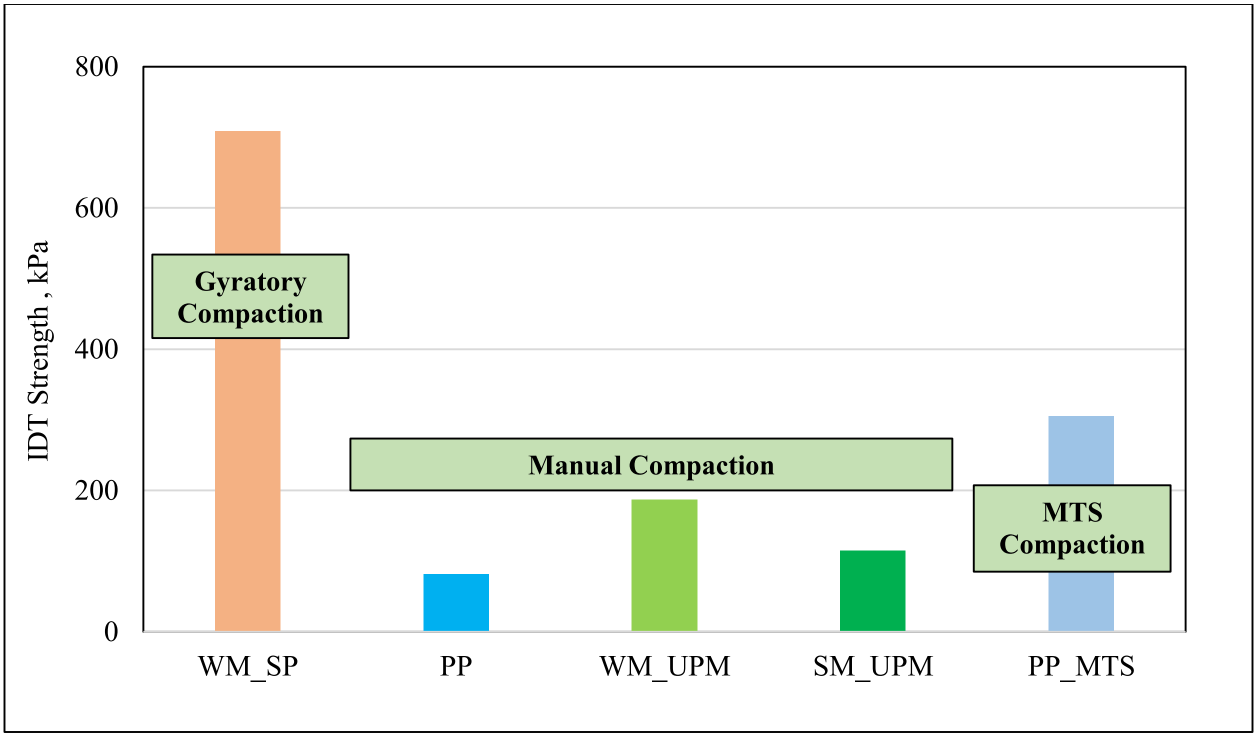

Figure 4.7: Preliminary IDT strength results at -24°C.

It was observed that the plastic mold bulged significantly during compaction and affected the geometry of specimen. To address this issue, steel molds were used to prepare samples using MTS compaction, as shown in Figure 4.8. This method was used for further testing, as described next.

Figure 4.8: Sample preparation using steel mold and MTS compaction.

4.2.3 Compaction Using MTS and Marshall Steel Molds

Cold conditioning before compaction was considered to better simulate winter patching at low temperature. Samples were prepared as follows:

A fixed amount of material was poured into steel molds

Molds were kept at 4°C for 20 hours in a refrigerator

Molds were taken out of refrigerator and compacted immediately

Specimens were extracted immediately

Specimens were conditioned for one hour at the test temperature (0°C and -24°C, respectively) in the MTS environmental chamber.

The strength results obtained following the procedure described above are shown in Table 4.3 and also in Figure 4.9. The winter mix from St. Paul has the highest IDT strength followed by winter mix from UPM. As expected, the test temperature has a huge effect on the strength value. All patching materials had very low strength values at 0°C. By comparison, a typical asphalt mixture has values in MPa rather than kPa.

Table 4.3: IDT strength results for compaction using steel molds

Sample No.	Patching Mix	Before Compaction	After Compaction (before testing)	Test Temperature	IDT Strength, kPa	Acronyms Used in Figure
1	Perma-Patch	All samples kept in refrigerator at 4°C for 18hrs	2 hrs at 0°C	0°C	3	PP_0°C
2	Perma-Patch		2 hrs at -24°C	-24°C	172	PP_-24°C
3	Summer Mix_UPM		2 hrs at 0°C	0°C	22	SM_UPM_0°C
4	Summer Mix_UPM		2 hrs at -24°C	-24°C	302	SM_UPM_-24°C
5	Winter Mix_UPM		2 hrs at 0°C	0°C	12	WM_UPM_0°C
6	Winter Mix_UPM		2 hrs at -24°C	-24°C	561	WM_UPM_-24°C
7	Winter Mix_St Paul		2 hrs at -0°C	0°C	36	WM_SP_-0°C
8	Winter Mix_St Paul		2 hrs at -24°C	-24°C	733	WM_SP_-24°C

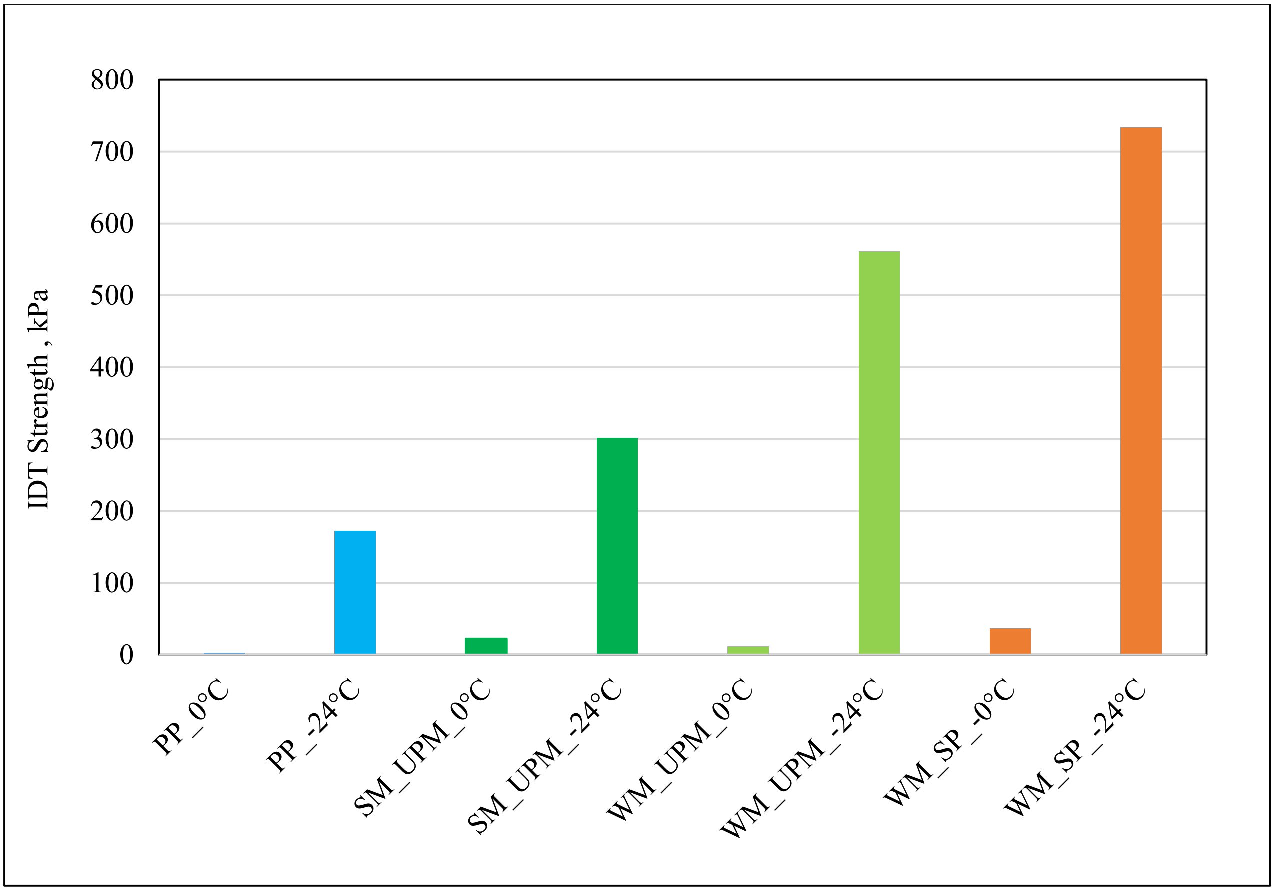

Figure 4.9: IDT strength of specimens compacted in steel molds at 0°C and -24°C.

4.2.4 Bonding experiment

Experiments were performed to determine if qualitative information can be obtained regarding the bonding strength between the patching material and the existing asphalt mixture in the pavement. In this part, only two patching materials were used; Perma-Patch (PP) and Winter Mix_UPM (WM_UPM). Samples were prepared using half HMA and half patching material (PP and WM_UPM) to simulate the actual field condition and check the bonding at the interface of existing pavement and patching materials. The diametric load was applied along the joint between the patching material and HMA and the crack propagation through the joint was observed. Patching materials were also tested individually to compare the test results with samples of half HMA and half patching materials. Sample preparation scheme is shown in Figure 4.10. Figure 4.11 and Figure 4.12 contain photos of sample preparation.

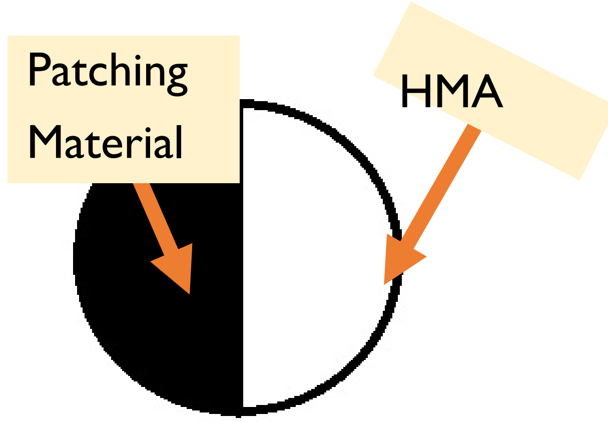

Figure 4.10: Sample preparation scheme. Samples were prepared using half HMA and half patching material.

Photos of various stages of sample preparation are shown in Figure 4.11 and Figure 4.12

Figure 4.11: Preparation of samples with half HMA and half patching material.

Figure 4.12: Additional photos of sample preparation and testing with half HMA and half patching material.

Since bonding between the cold patching mix and asphalt mix would not become effective until significant curing occurs, two accelerated methods of curing were used: in the first one the specimen was conditioned in the oven before compaction, and in the second method, the specimen was conditioned in the oven after compaction. Specimens conditioned before compaction were prepared as follows:

- Keep materials in the mold at 135°C in oven for 20 hours
- Compact the sample at room temperature
- Keep compacted specimen at room temperature for 5 days
- Extract specimen after 5 days and keep at test temperature (-24°C) for 1 hour before testing.

Specimens conditioned after compaction were prepared as follows:

- Compact specimen in the mold at room temperature
- Keep compacted specimen in the mold at 40°C for 5 days
- Extract specimen after 5 days and keep at test temperature (-24°C) for 1 hour before testing.

A flow chart of these steps is shown in Figure 4.13

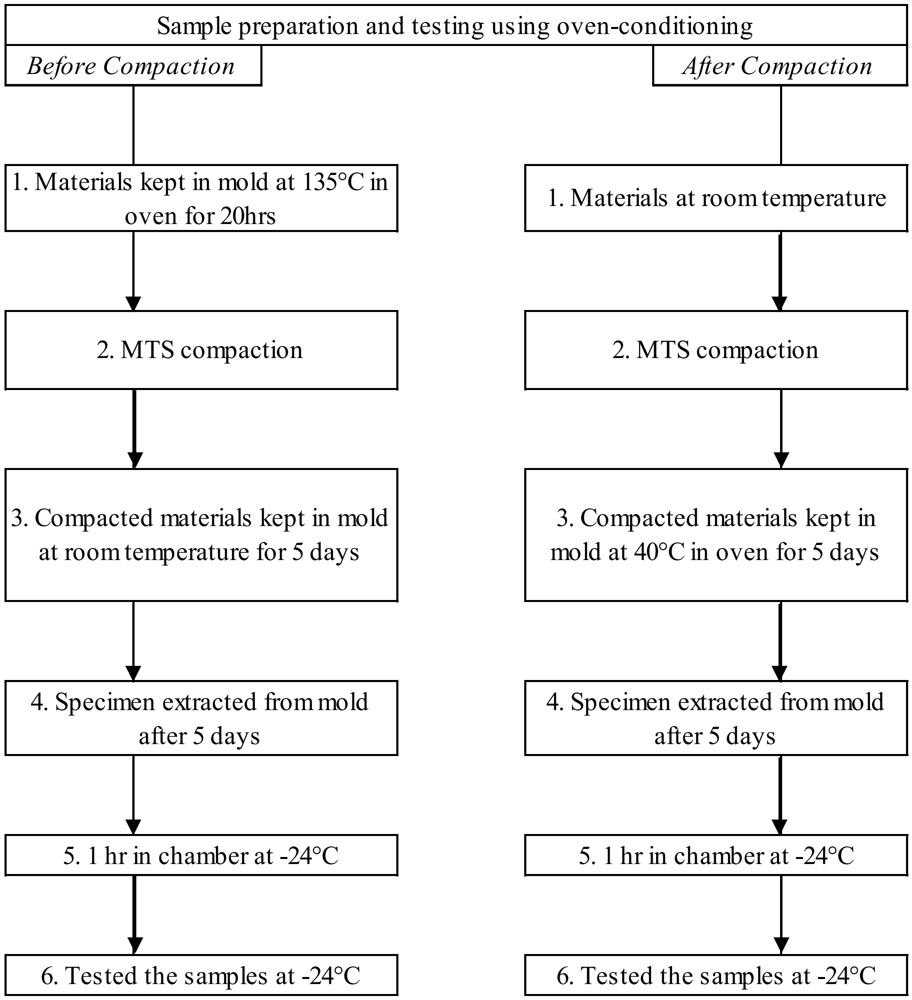

Figure 4.13: Flow Chart showing steps for oven-conditioning of the samples.

Table 4.4 and Figure 4.14 show the strength results. Table 4.4 also provides detailed information on the conditioning steps for each tested specimen.

As expected, the HMA specimen used in the bonding experiments has the highest IDT strength. Conditioning samples in the oven before or after compaction did not make a significant difference in strength results. However, bonded samples consisting of half patching materials and half HMA were observed to have higher strength than the samples of the patching materials itself. Winter Mix from UPM was observed to have a strong interface bond with HMA.

Table 4.4: Conditioning of specimens in bonding experiment

Sample No.	Samples	Before Compaction	After Compaction (before testing)	Conditioned in Oven	IDT Strength, kPa	Acronyms used in Figure
1	Hot Mix Asphalt loose Mix (HMA)	Hot HMA	5 days in the oven at 40°C; 1 hr at -24°C in the MTS Chamber	**After** Compaction	2311	HMA(after)
2	Perma-Patch (PP)	Room Temp PP	5 days in the oven at 40°C; 1 hr at -24°C in the MTS Chamber	**After** Compaction	479	PP(after)
3	Winter Mix_UPM (WM_UPM)	Room Temp WM_UPM	5 days in the oven at 40°C; 1 hr at -24°C in the MTS Chamber	**After** Compaction	398	WM_UPM (after)
5	Half Perma-Patch and Half HMA loose mix (PP-HMA)	Hot HMA and Room Temp PP	5 days in the oven at 40°C; 1 hr at -24°C in the MTS Chamber	**After** Compaction	1018	PP-HMA (after)
6	Half Perma-Patch and Half HMA loose mix (PP-HMA)	Hot HMA; Hot PP (in oven at 135C for 20Hrs)	5 days at Room Temperature	**After** Compaction	1050	PP-HMA (before)
7	Half Winter Mix_UPM and Half HMA loose mix (WM_UPM-HMA)	Hot HMA and Room temp UPM_winter	5 days in the oven at 40°C; 1 hr at -24°C in the MTS Chamber	**After** Compaction	1342	WM_UPM-HMA (after)
8	Half Winter Mix_UPM and Half HMA loose mix (WM_UPM-HMA)	Hot HMA; Hot UPM_winter (in oven at 135C for 20Hrs)	5 days at Room Temperature	**After** Compaction	1535	WM_UPM-HMA (before)

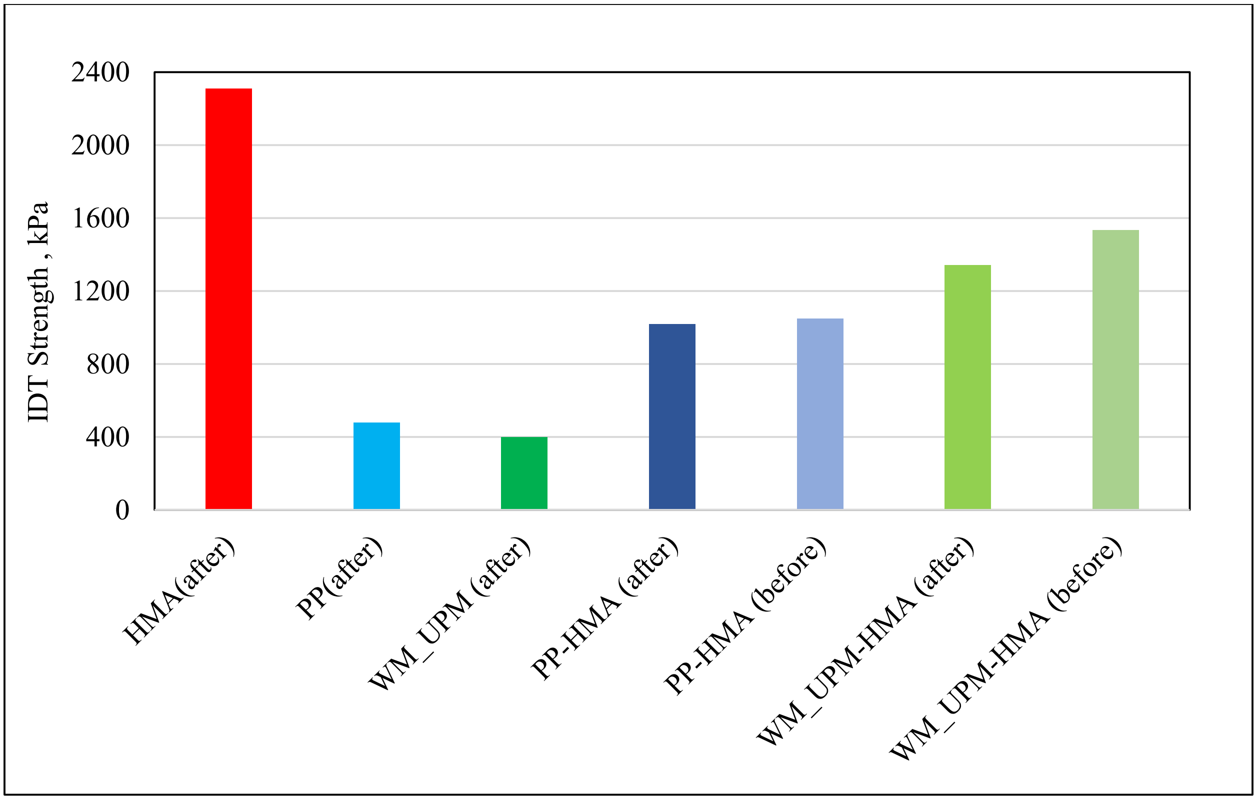

Figure 4.14: IDT Strength Results for Bonding Specimens at -24°C

4.3 GAP PATCHING MATERIALS

A fifth patching material was received (Figure 4.15) by the research team and a similar experimental investigation was performed. According to the manufacturer, GAP Mastic is a hot-applied, polymer modified asphalt mixed with engineered aggregates and modifiers designed to fill wide cracks and defects, to prevent water infiltration, and restore ride quality. It is formulated with a low viscosity for ease of installation and enhanced crack penetration. This material is extremely flexible, which enables it to perform exceptionally well in cold weather, yet also has a high softening point so it will not track or rut with traffic. GAP material is designed as a permanent repair solution for wide thermal cracks, fatigue cracking, rutting, and depressed, broken-up areas.

Figure 4.15: GAP Materials

Unlike the initial four patching materials, GAP is a more expensive product that has specific requirements. According to the manufacturer, this product must be heated using indirect heating methods, either a double boiler or hot oil circulating kettle and the equipment must be capable of maintaining constant agitation to the material to keep aggregate suspended evenly. The maximum safe heating temperature is 400°F (204°C), recommended application temperature is 340°F (171°C) and at the time of placing, the pavement temperature should be a minimum of 40°F (4°C). Application at lower temperatures may result in less adhesion due to the possible presence of excess moisture. If the surface temperature is less than 40°F, and the sealant must be applied, a heat lance or other appropriate means can be used to warm and dry the asphalt. Care should be taken to ensure that bonding surfaces are free of oil, dirt, dust, moisture, and any other contaminants that would inhibit good bonding of the sealant to the asphalt. To maximize adhesion, the repair area should be sprayed with a thin coating of GAP primer using a solvent resistant sprayer.

Compaction was not performed on GAP samples, since compaction of this material is not required in the field. The following steps were performed to prepare testing specimens using GAP materials:

The aggregates and the binder were kept in the bowl in the oven at 170°C for 6 hours

The heated aggregate and binder were mixed with the mixer for five minutes.

The mixture was poured into the mold right away. Initially, the mixture was poured in hot molds and molds at room-temperature. With the hot molds it was observed that, due to the large amount of binder and lower aggregate cooling rate, the binder started to accumulate at the bottom of the specimen, which made extracting the specimens difficult. Consequently, cold or room-temperature molds were used. The following steps were performed:

The molds were kept at 4°C for 18 hours

The samples were extracted after 18 hours

The extracted samples were kept in MTS chamber at 0°C and -24°C for 1 hour, to test them at 0°C and -24°C, respectively. Figure 4.16 shows an example of a GAP specimen and testing setup.

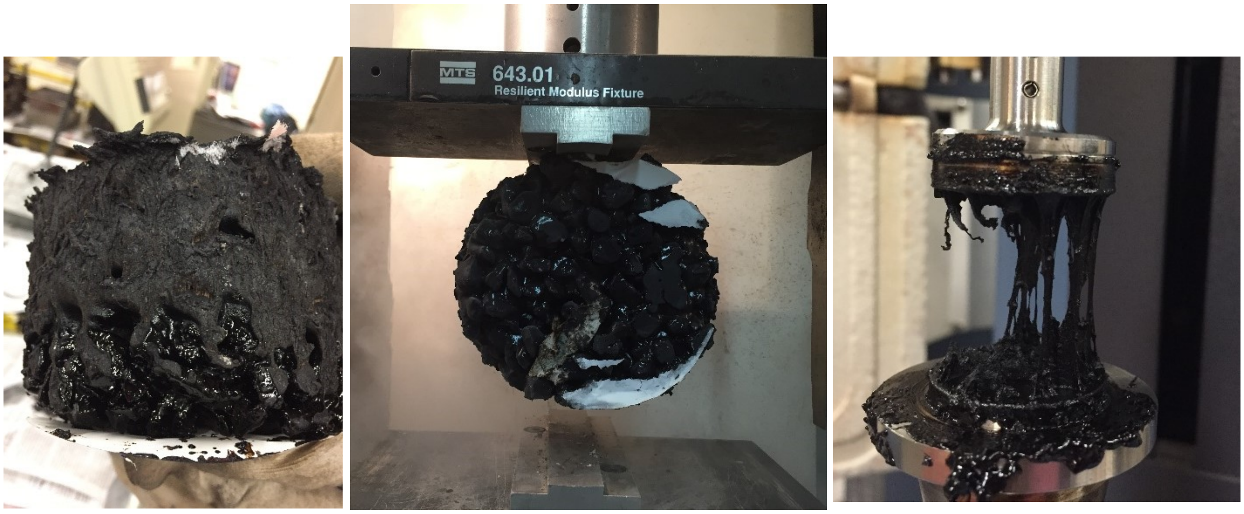

Figure 4.16: Sample and Testing of GAP Materials.

Table 4.**Error! Reference source not found.**5 and Figure 4.17 show IDT strength results. Table 4.7 also c ontains information regarding specimen preparation and conditioning.

Table 4.5: IDT strength testing of GAP

Sample No.	Compaction	Before Testing	Test Temperature	IDT Strength, kPa	Acronyms Used in Figure
1	No Compaction	2 hrs at 0°C	0°C	785	GAP_0°C
2			-24°C	2211	GAP_-24°C
3			0°C	515	GAP(hot mold)_0°C
4			-24°C	1894	GAP(hot mold)_-24°C

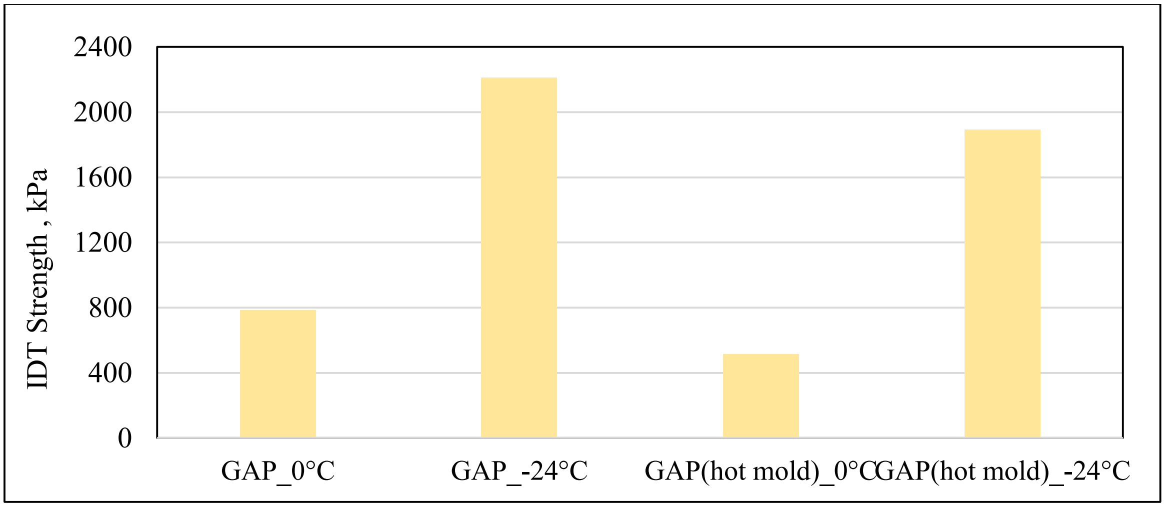

Figure 4.17: IDT Strength test Results for GAP material.

It was observed that using a hot mold reduced the tensile strength at both testing temperatures. It was found out that this was due to a much slower cooling rate of the material that allowed the binder to flow to the bottom of the testing specimen and making it weaker. The IDT strength of GAP at -24°C was similar to IDT strength of HMA, as reported in Figure 4.7.

Figure 4.18 below shows the strength results of all five different patching materials under cold-conditioning. The GAP was found to have the highest strength followed by winter mix from St Paul asphalt plant (WM_SP).

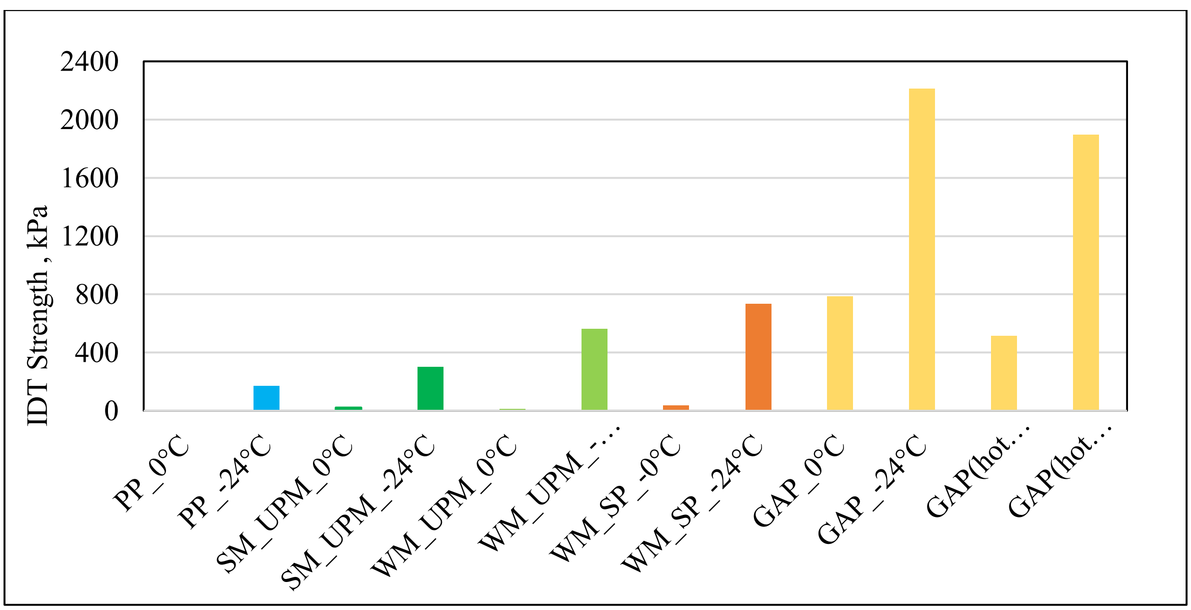

Figure 4.18: IDT Strength Test for Cold Conditioning of All Patching Materials.

4.4 WATER PENETRATION TESTING

A simple experiment was performed to get qualitative information about the water permeability of the patching materials specimens. Water penetration tests were performed by pouring water on IDT specimens of Perma-Patch and GAP. It was observed that water passed freely, as shown in Figure 4.19 below.

Figure 4.19: Test Setup for Water Penetration Tests.

This appears to indicate that during a rain event or snow melting, water accumulates at the bottom of the pothole, which significantly decreases the durability of the patching material unless special preparation techniques are used.

4.5 ST. PAUL SUMMER MIX

A sixth material was received after the above described testing was performed. The sixth material, St. Paul Summer Mix, was a summer asphalt mix received from St. Paul.

4.5.1 Sample Preparation and Testing of St Paul Summer Mix

Three mixtures were created using the St. Paul Summer Mix: a mixture containing 6% Micro 850 GNP, a mixture containing 6% 4827 GNP and a control mix, which contained no GNP additive.

Samples were prepared using the following steps:

- Place asphalt material in oven at 135°C for 6 hours
- Place heated asphalt material into mixer
- If additive was used, place additive in mixer with heated asphalt material
- Mix for 1 minute
- Place material back into oven to keep warm until compaction
- Once all mixtures were mixed, a portion of sample mixture was weighed
- Place 6.75 kg of mixture in the compaction mold
- Compact mixture using 100 gyrations in Superpave gyratory compactor
- Cure at room temperature for two days
- Cut each cylinder into two 38 mm thick samples for IDT testing and one 32 mm thick sample for SCB testing, that is further divided into two halves.

Three tests were performed on the St. Paul Summer Mix: IDT Creep Stiffness, IDT Strength, and SCB. Brief descriptions of the testing procedures are provided below.

4.5.2 IDT – Creep Stiffness and Strength

Creep stiffness and tensile strength tests followed procedures outlined in "Standard Test Method for Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device," AASHTO T322 -07 [14].

For creep, specimens were loaded diametrically using a vertical constant load of 0.8 kN/sec. Horizontal and vertical deformation were measured using extensometers fixed near the center of the sample. Deformation measurements were then used to calculate creep stiffness. Three replicates were tested for each material at three temperatures, -24°C, -12°C, and 0°C, for a total of 9 tests.

For creep stiffness, creep compliance is calculated first, using the following equations, taken from AASHTO Designation T322-07 [14]:

$$D(t) = \frac{\Delta X \times D \times b}{P \times GL} \times C \qquad (4.1)$$

Where:

D(t) = creep compliance at time t (kPa)

ΔX = horizontal deformation

P = average creep load applied to specimen

b = thickness of specimen (38 mm for all specimens)

D = diameter of specimen (150 mm for all specimens)

GL = gage length

Creep stiffness (S) is the inverse of creep compliance:

$$S = \frac{1}{D(t)} \tag{4.2}$$

At the end of each creep test, indirect tensile strength tests were performed. Specimens were loaded with a constant rate of vertical deformation until sample failure.

Tensile strength is calculated by the following equation, taken from AASHTO Designation T322-07 [14]:

$$S = (2P)/(\pi bD) \tag{4.3}$$

Where:

S = tensile stress of specimen

P = failure load for specimen

b = thickness of specimen (38 mm for all specimens)

D = diameter of specimen (150 mm for all specimens)

4.5.3 SCB Fracture Energy and Toughness

The SCB test procedure is outlined in "Standard Method of Test for Determining the Fracture Energy of Asphalt Mixtures Using the Semi Circular Bend Geometry (SCB)," AASHTO Designation: TP 105-13 [15].

For this test, semi-circular specimens were loaded into an MTS loading frame. The flat side of the samples were placed facing downward on two rollers. The rollers were covered with a friction reducing material. A vertical load was then applied diametrically. The load was applied at a constant CMOD of 0.0005 mm/s. Both load and load line displacement were measured.

Test results were then used to obtain fracture energy (G_f) and fracture toughness (K_{IC}).

Fracture Energy is given by the following equation, taken from AASHTO Designation: TP 105-13 [15]:

$$G_f = \frac{w_f}{A_{lig}} \tag{4.4}$$

Where:

$$W_f = \int P du \tag{4.5}$$

$$A_{lig} = (r - a) \times b \tag{4.6}$$

And:

G_f = fracture energy (J/m^2)
W_f = work of fracture (J)
P = applied load (N)

u = average load line displacement (m)
A_{lig} = ligament area (m^2)
r = radius of specimen (75 mm for all specimens)
a = notch length (m)

b = thickness of specimen (38 mm for all specimens)

Fracture Toughness (K_{IC}) is defined as the stress intensity factor (K_I) at the critical load (maximum load during testing). The stress intensity factor is given by the following equation, taken from AASHTO Designation: TP 105-13 [15]:

$$\frac{K_I}{\sigma_0\sqrt{(\pi a)}} = Y_{I(0.8)} \tag{4.7}$$

Where:

$$\sigma o = \frac{P}{2rb} \tag{4.8}$$

$$Y_{I(0.8)} = 4.782 + 1.219\left(\frac{a}{r}\right) + 0.063\exp(7.045\left(\frac{a}{r}\right)) \tag{4.9}$$

And:

P = applied load (MN)

r = radius of specimen (75 mm for all specimens)

b = thickness of specimen (38 mm for all specimens)

a = notch length (m)

Y_I = the normalized stress intensity factor (dimensionless).

4.5.4 Results for St Paul Summer Mix

Air void content, IDT strength, IDT creep stiffness, and SCB data for the samples tested are presented below.

Air Void Content

Figure 4.20 shows air void content of samples during compaction. Samples were compacted with 100 gyrations. However, the mixtures would not be compacted to 100 gyrations during placement in the field. Therefore, the figure shows the air void content up to 50 gyrations.

As shown, the samples with GNP compact more quickly (with fewer gyrations), and the samples with 4827 GNP additive compact 1% more than the control mixture.

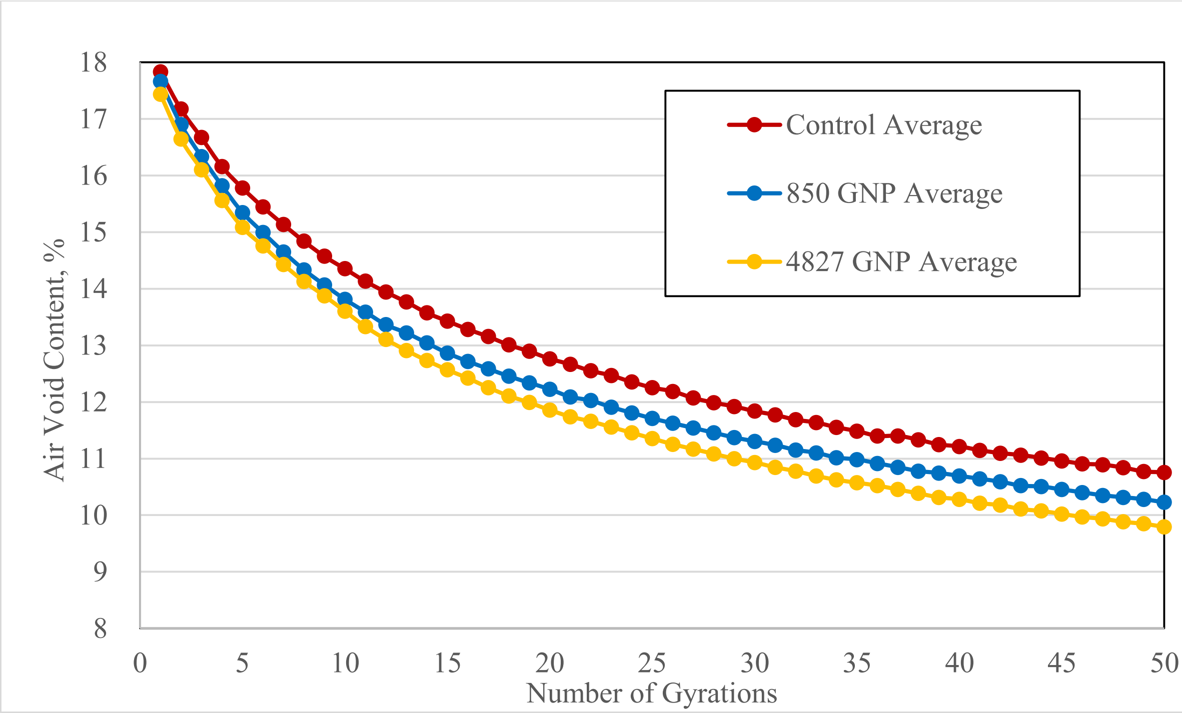

Figure 4.20: Air void content of samples during compaction of St. Paul Summer Mix

IDT Strength and Creep Stiffness

Values for tensile strength, calculated using equation (4.1), are presented in Table 4.6 and Figure 4.21. Each value is an average taken from three replicates. As shown, tensile strength increases in the samples containing GNP additive, and the 4827 GNP additive has a slightly higher increase in tensile strength than samples containing Micro 850 GNP additive.

Table 4.6: Tensile strength values for St. Paul Summer Mix.

	Tensile Strength (kPa)	
	0°C	-12°C
Control	2601	2688
Micro 850	2793	3263
4827	2915	3418

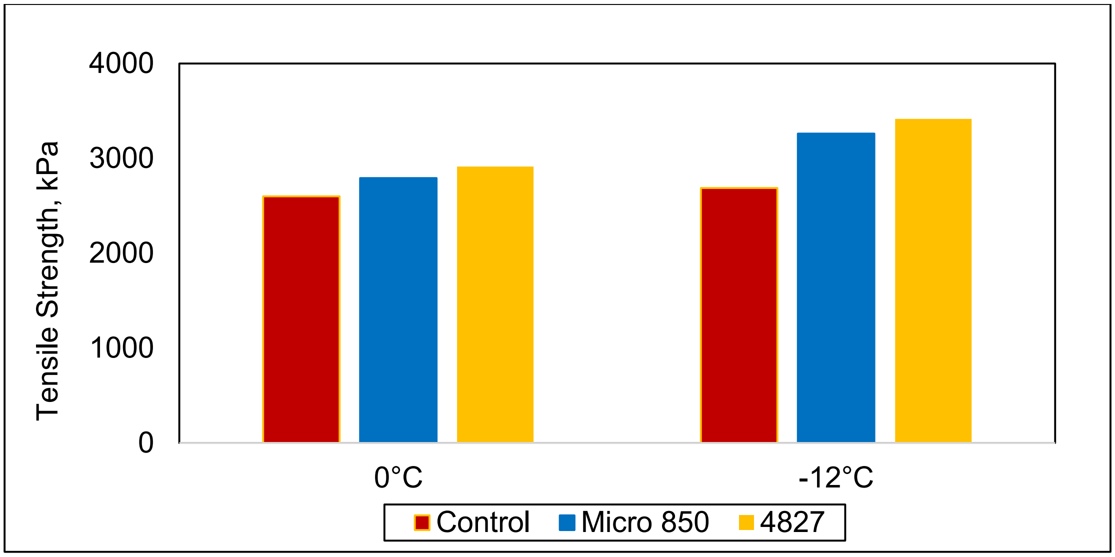

Figure 4.21: Tensile strength for St. Paul Summer Mix.

A summary of IDT strength values obtained at 0°C for all patching materials is shown in Figure 4.22. As shown, St Paul Summer Mix has much greater strength than any of the other materials. It is important to mention that the patching materials went through different sample preparation procedures. The St. Paul summer mix was conditioned in the oven at 135°C for 6 hours before gyratory compaction, whereas the initial patching materials were conditioned in refrigerator at 4°C for 18 hours before MTS compaction.

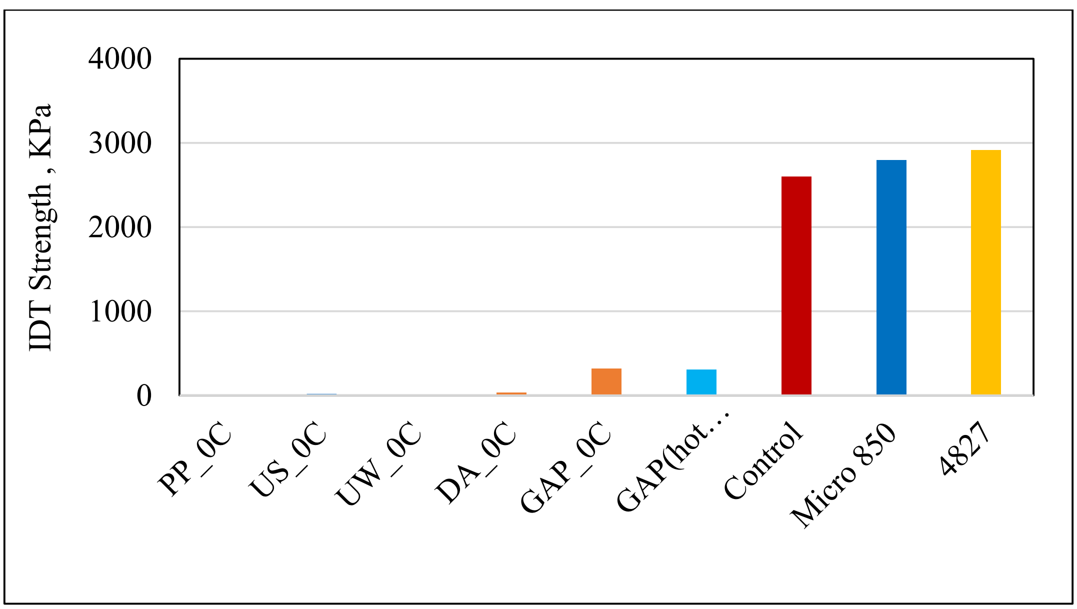

Figure 4.22: IDT Strength at 0°C for all materials.

Using equations (4.2) and (4.3), creep stiffness curves were constructed for all three materials at all three testing temperatures. Average values from three replicates per material were used to construct curves. Figure contains curves at -24°C,

Figure 4.24 presents curves at -12°C, and Figure 4.25 contains curves at 0°C.

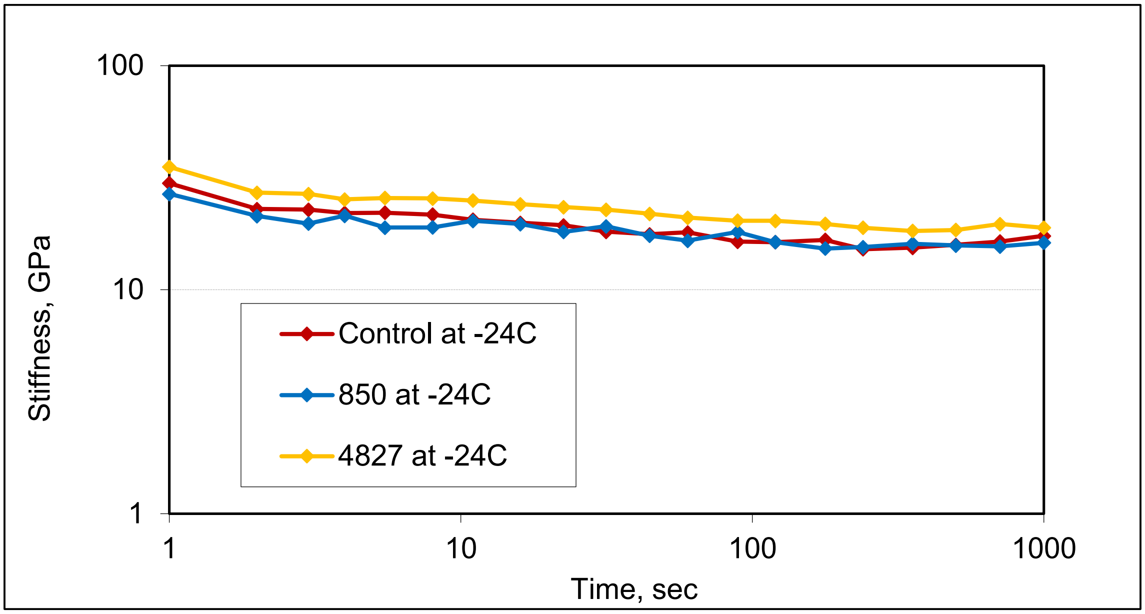

Figure 4.23: Creep stiffness curves of St. Paul Summer Mix at -24°C

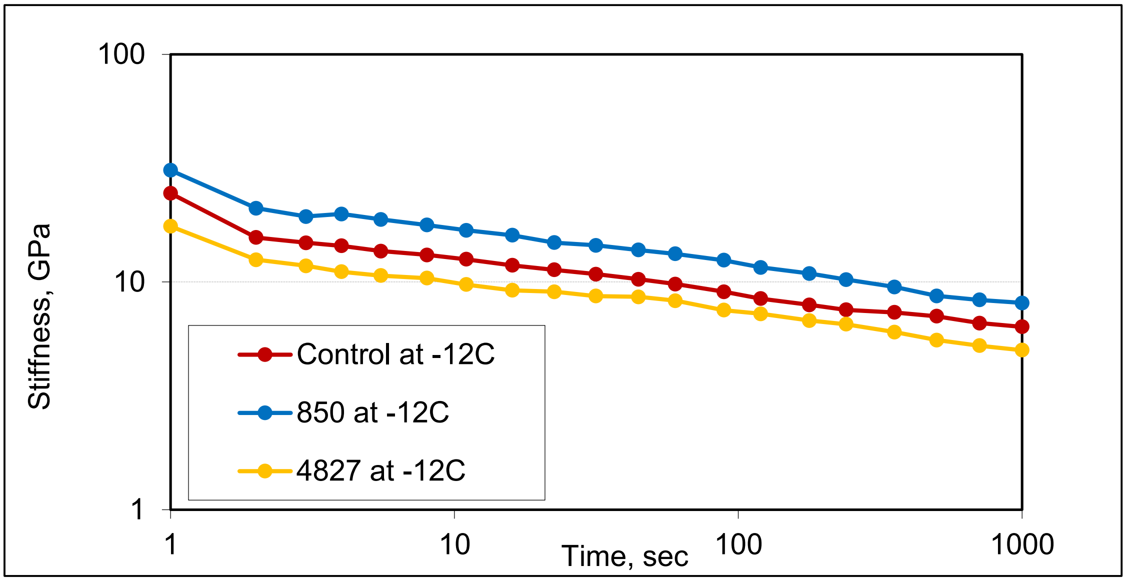

Figure 4.24: Creep stiffness curves of St. Paul Summer Mix at -12°C

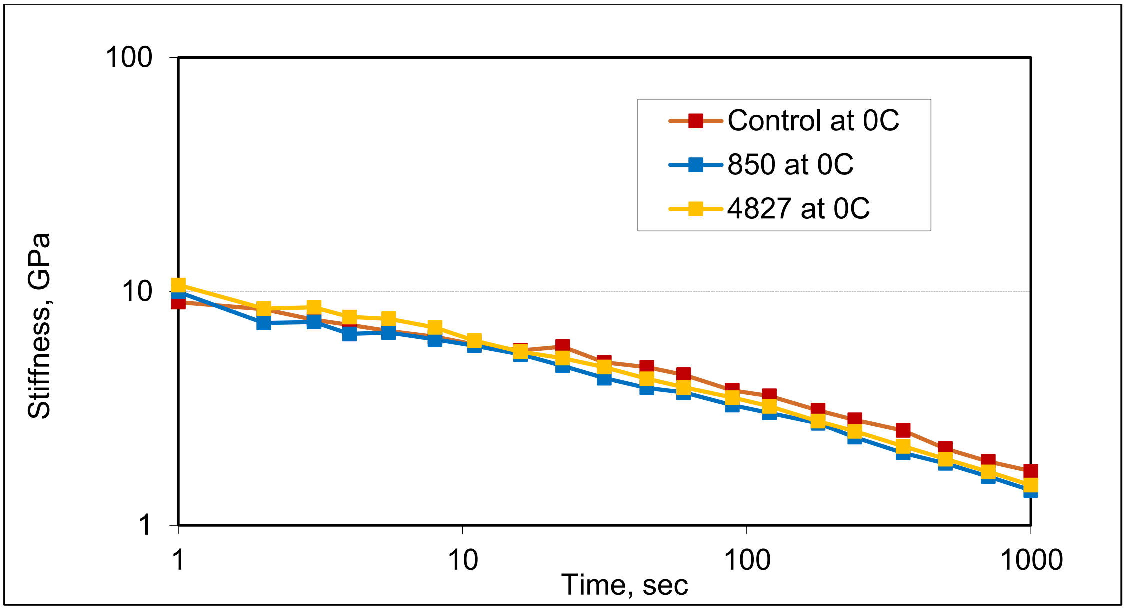

Figure 4.25: Creep stiffness curves of St. Paul Summer Mix at 0°C

SCB Fracture Energy and Toughness

Fracture energy was calculated using equations (4.4) to (4.6) and the results are shown in Figure 4.26.

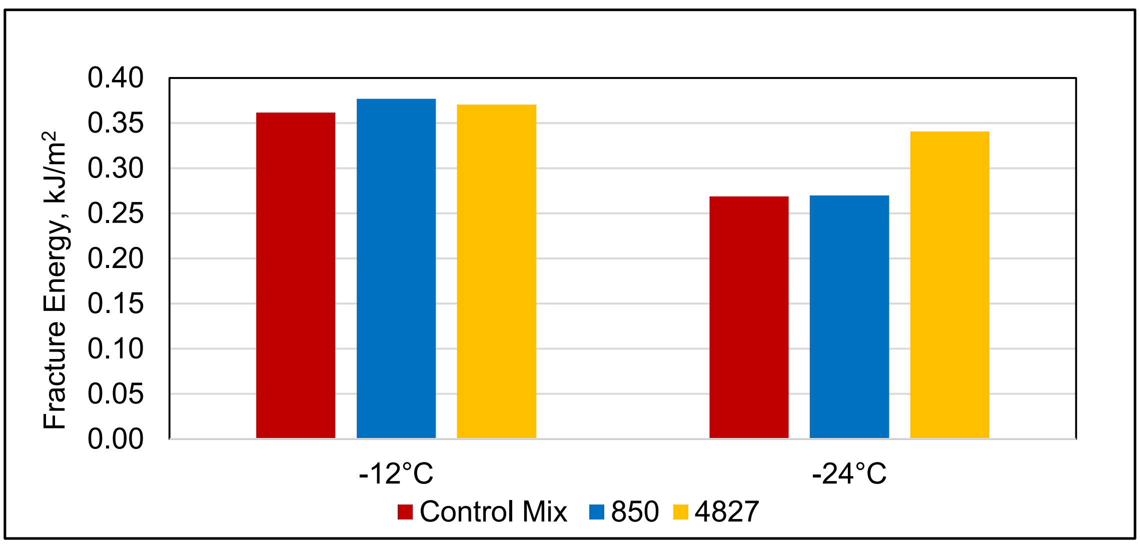

Figure 4.26: SCB fracture energy of St. Paul Summer Mix

Fracture toughness was calculated using equations (4.7) to (4.9) and the results are shown in Figure 4.27. As shown in Figure 4.27, fracture toughness increases in mixtures containing GNP additive, and the mixture containing the 4827 GNP additive has the highest increase in fracture toughness.

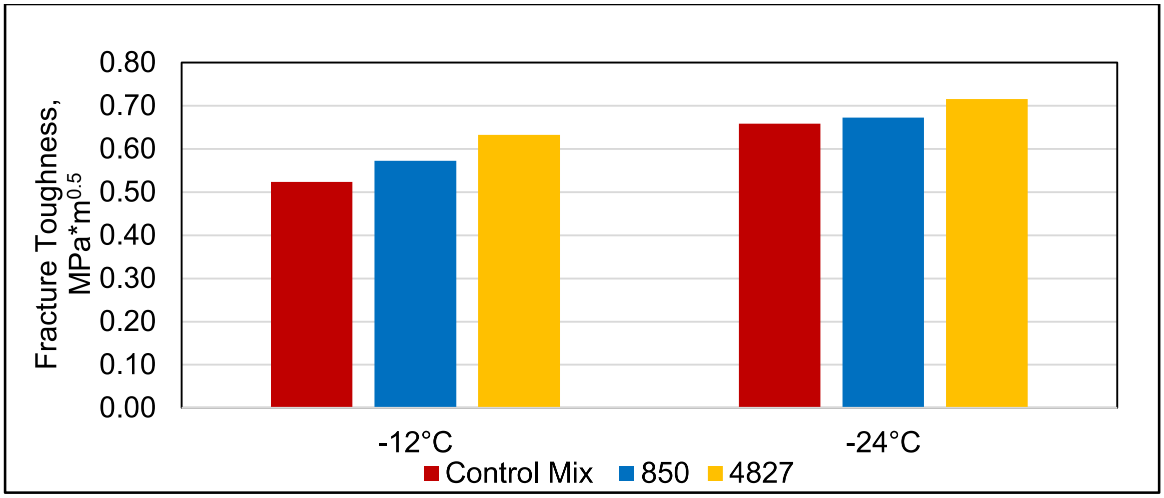

Figure 4.27: SCB fracture toughness of St. Paul Summer Mix

4.6 CONCLUSIONS

A number of challenges were encountered when trying to compact the initial four cold-patching materials, and various conditioning and compaction methods were investigated. Two types of conditioning were used to prepare samples before testing; cold conditioning and oven conditioning. Compaction using a method similar to Marshall compaction and steel molds appeared to work well for most materials.

An experimental investigation to determine bonding strength was also performed on specimens prepared using half HMA and half patching materials. The samples were conditioned in the oven either before or after compaction and tested at -24°C. A simple water penetration test was performed on two types of patching materials which provided qualitative information on water permeability of these materials. Some significant findings include:

- It was very difficult to prepare testing specimens due to the fact that the patching materials are cold mixtures that do not gain strength and stiffness unless significant curing of the binding component occurs. While cold mixtures can be poured and placed at typical winter temperatures, minimal curing occurs at these temperatures, which makes these materials very weak, with characteristics more like a filling material.
- Water can easily penetrate through the testing specimens, which further reduces the meager durability of these materials since water can accumulate at the bottom of the pothole after a rain event or snow melting.

The fifth patching material investigated, GAP, appears to be stronger than the intital materials at both 0°C and -24°C, when simulating winter patching through cold-conditioning. GAP can have strength values similar to regular hot mix asphalt at -24°C.

The sixth patching material tested was St Paul Summer Mix, with properties similar to regular hot mix asphalt. A number of conclusions were drawn from the experimental work investigating the addition of graphite nano-particles :

- The addition of GNP increases compaction level. After 50 gyrations, the mixture with Micro 850 had 0.4% less air voids than the control mixture, and the 4827 mixture had 1% less air voids than the control mixture.
- Tensile strength increased in the testing specimens prepared with GNP additive.
- Fracture energy and fracture toughness also increased for the specimens containing GNP additive.

These preliminary results indicate that the addition of GNP can positively influence the performance and durability of summer patching materials.

CHAPTER 5: PROACTIVE PAVEMENT PRESERVATION ACTIVITIES FOR POTHOLE PREVENTION

5.1 INTRODUCTION

In this chapter, an investigation was performed to summarize the main causes for premature failure of pothole repairs and to identify proactive pavement preservation techniques that can delay the initiation of potholes and reduce or eliminate the formation of significant pothole occurrence. The work plan included the evaluation of various scenarios, based on life cycle cost analysis, to identify optimal solutions. However, the authors were not able to find cost information for pothole repairs in Minnesota, and therefore, costs and analyses from several sources were identified and presented instead. This chapter contains summaries from 13 sources that were reviewed to:

- Identify proactive pavement preservation techniques that can delay the initiation of potholes and reduce or eliminate the formation of significant pothole occurrence
- Better understand the main causes of failure of pothole repairs
- Summarize cost information from available sources.

5.2 MNDOT PAVEMENT PRESERVATION MANUAL [16]

In the MnDOT Pavement Preservation Manual it is stated that selecting the proper treatment type and timing of treatment is necessary for successful pavement preservation. In order to achieve this, one must know: the existing pavement structure and condition, its expected performance, how it will be affected by different treatments, and any other factors that will affect treatment performance.

The Preservation Manual outlines treatment selection guidelines, which are based on both the current pavement condition and the types of distresses present. Pavement type, age and design life are also used to determine choice of treatment. Figure 5.1 contains treatment selection guidelines for flexible pavements.

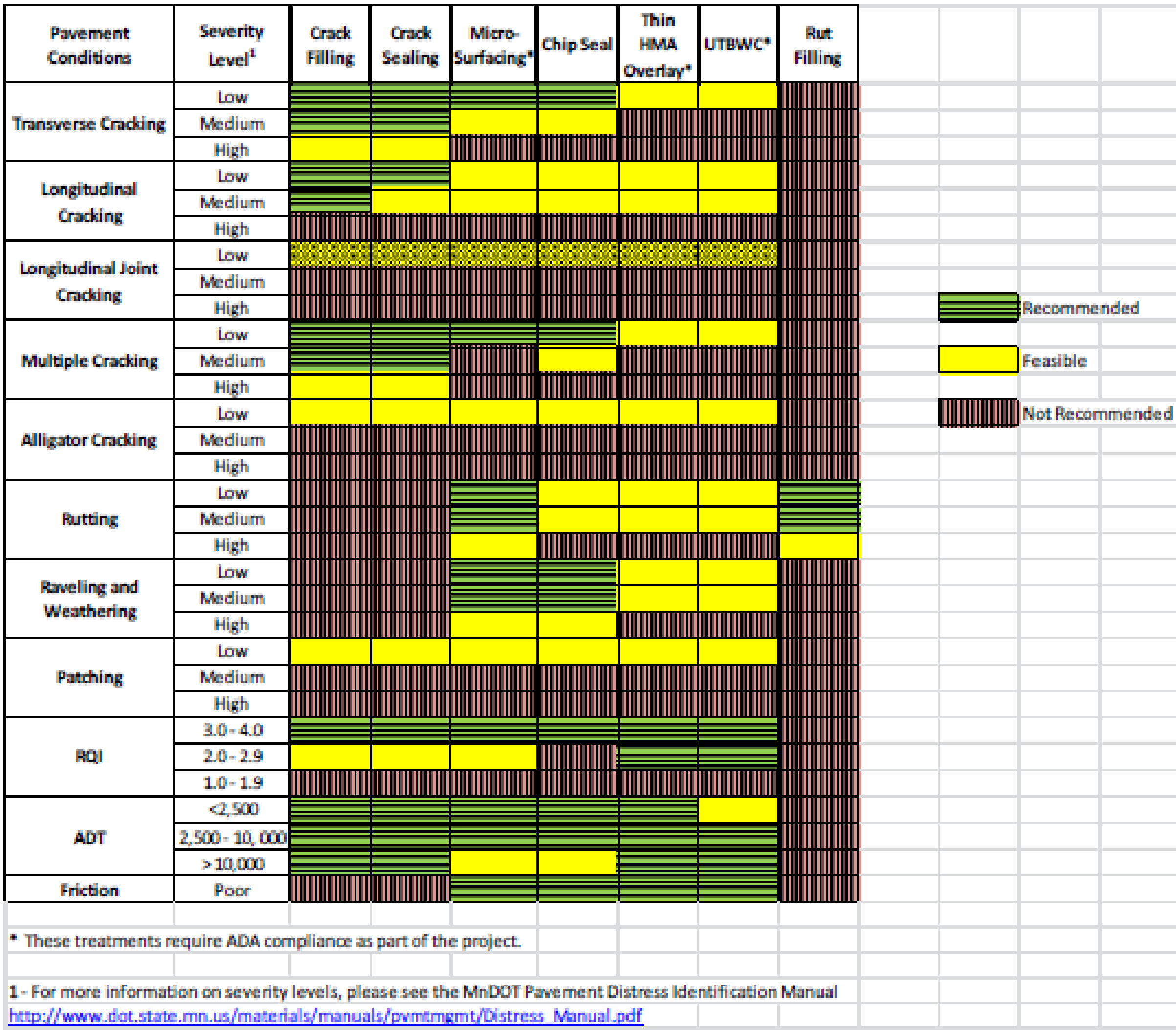

Figure 5.1: Treatment Selection Guidelines for Flexible Pavements [16]

Sometimes a combination of treatments is the best option. The selection process includes the following steps:

- "Gather pavement information.
- Assess pavement condition.
- Evaluate pavement data.
- Identify feasible preservation treatments."

MnDOT uses Highway Pavement Management Application (HPMA) to assess pavement and develop strategies. Field review, non-destructive testing and interviews with pavement personnel are also conducted. The Preservation Manual includes costs and lifespans for several preservation activities, which are presented in Table 5.1.

Table 5.1: Preservation activity costs and lifespans from the MnDOT Preservation Manual

Preservation Activity	Cost	Unit	Cost per lane mile	Life (years)
410 – Crack Filling	$115-125	per road station	$3200	6-8
420 – Rout and Seal Cracks	$125	per road station	$3300	6-8
430 – Micro Surfacing	$2.82	per square yard	$19,900	5-7
440 – Seal Coat	$1.85	per square yard	$13,000	5-7
451 – Thin Overlay or Thin Lift Mill and Overlay 1 to 1.5"	$0.75-1	per square yard	$6,125	8-10
452 – Thin Overlay or Thin Lift Mill and Overlay 1.5"	$5-6	per square yard	$30,000	8-10
460 – Ultra Thin Bonded Wear Course (UTBWC)	$5	per square yard	$35,200	7-12

5.3 WSDOT PAVEMENT ASSET MANAGEMENT [17]

Washington DOT (WSDOT) modified their pavement management approach in 1993 to include the asset management principle of Lowest Life Cycle Cost (LLCC). With this approach, the goal is to find “the most cost-effective way to provide a safe and reliable transportation system” [17]. If a road is renewed too early, the annual cost is high due to wasted service life. If the road is renewed too late, the agency and user costs are high, because the damage to the road has moved beyond just the surface, and the road will then be in much worse condition. Therefore, “the objective function of LLCC is to meet a minimum acceptable performance at the lowest possible annual cost.” Additionally, performing proper maintenance at the correct time will increase effective surface life and lower annual preservation costs.

Treatment costs are provided in Table 5.2. However, these costs are only accurate if the appropriate treatment is selected for the road. For instance, chip sealing is best used for low-volume roads. If used on a high-volume road, it may only add one year of life, which would then increase the typical annual cost.

Table 5.2: Pavement treatment costs

Treatment	Added Life (Years)	Typical Construction Cost (Per lane mile)	Typical Annual Cost (Per lane mile)
Maintenance	2-4	$5,000	$1,500
Chip Seal Rehab	6-7	$40,000	$7,000
Asphalt Rehab	10-17	$250,000	$18,000

WSDOT states that distress identification is the most important input into their pavement management system, since it is the basis for site specific evaluation, which leads to finding the most cost-effective preservation method. Once distress information is collected, WSDOT uses an 'equivalent cracking' method. Distress values are converted into an equivalent amount of fatigue cracking, and rehabilitation threshold is based on the equivalency. A 10% high severity cracking threshold is used.

WSDOT uses a rutting threshold of 0.5 inches, which is based on a safety justification—ruts filled with water can cause hydroplaning, and can also pull vehicles towards the rut path.

The International Roughness Index (IRI) threshold is 220 in/mile. This threshold is used as a trigger for resurfacing (however, roads are usually rehabilitated before this threshold is met, due to the LLCC management system used by WSDOT).

WSDOT also uses three pavement indexes that normalizes defects, allowing for a scoring scale of 0 to 100. Thresholds are set at a value of 50, at which rehabilitation methods are triggered. The three indexes are Pavement Structural Condition (PSC), Pavement Profile Condition (PPC) and Pavement Rutting Condition (PRC).

Curve fitting is used by WSDOT to predict road performance. "Historical Pavement Indexes are plotted and regression analysis is used to characterize and predict performance." An index value between 45 and 50 will trigger rehabilitation procedures.

Two main prioritization strategies have been utilized by WSDOT: Worst First (from 1969 to 1993) and LLCC (from 1993 to present). With the LLCC approach, treatments are applied when they are 'due,' instead of 'past due.' In this way, the overall road network conditions improved drastically. However, there is still an issue with lack of funding, and how to prioritize roads when there isn't money to treat them all. Therefore, a more sophisticated prioritization scheme was developed, which follows three steps:

1. “Project Categorization
2. Calculation of the Ranking Factor called Dollars per Lane Mile Truck ($/LMT)
3. Sort (rank) based on category and Ranking Factor”

The first step uses the following categories, with the lowest number having the highest priority:

- “Category 1 - Projects already programmed
- Category 2 - Projects where high risk of major expense is identified. If rehabilitation is delayed too long, then the risk of reconstruction, which is 2 to 5 times the cost of rehabilitation
- Category 4 - Asphalt to Chip Seal Conversion (asphalt with a new chip seal surface). This has a higher priority because life cycle costs of chip seal is one-third the cost of asphalt
- Category 5 - General category (no special considerations)
- Category 6 - Projects that can be deferred with maintenance
- Category 8 - Ramps “

The second step is based on:

- “Cost: The dollars per lane mile construction cost including PE and traffic control, divided by the total lane miles paved. For all other factors being equal, a higher cost per lane-mile will reduce priority.
- Lane-Mile Years (LMY) Gained: The lane miles paved multiplied by the expected years of life gained by the project. For all other factors being equal, a lower value of lane-mile years gained will reduce priority.
- Annual Number of Trucks: The higher number of trucks per year indicates an importance to commerce and a higher potential for rapid deterioration. For all other factors being equal, a lower number of trucks per year will reduce the priority.

These factors are combined into a single term called Dollars per Lane Mile Truck ($/LMT).”

WSDOT pavement preservation approach has allowed them to keep WA road network in a good state of repair, even with a decrease in funding. In part, this is due to using an aggressive program to use chip sealing when appropriate, use maintenance to extend service life, and by implementing new practices to extend cost efficiency, such as in-place recycling and crack and seal overlays.

5.4 PERFORMANCE EVALUATION OF ASPHALT PAVEMENT PRESERVATION ACTIVITIES [18]

Hajj et al evaluated Nevada DOT (NDOT) maintenance records from 1990 to 2005, which contained details on preservation treatment and costs for labor, equipment and materials. The records contained over 17,000 preservation activities performed on 847 road sections. All sections had at least 5 years of performance before application of another maintenance or rehabilitation treatment. Distress types recorded in the NDOT pavement management system included cracking, rutting, bleeding, raveling and surface roughness, and were recorded on an annual or biannual basis. At the end of the investigation, the following recommendations were made:

- The recommended preservation activities depend on the present serviceability index (PSI) value and the roughness of the road before treatment application. Of note is that PSI is highly influenced by the roughness of the road (IRI).
- The rut depths and the various cracking types reflect the structural condition of the pavement before the application of the maintenance activity.
- Even though crack filling was found to be effective only for a pretreatment PSI greater than 2.5, it is highly recommended and encouraged to apply crack filling when pavement cracks first develop, because timely treatment will help prevent further pavement deterioration.

5.5 LIFE EXPECTANCY OF REHABILITATION [5]

Van Rijn developed a manual for road maintenance planning in The Netherlands. The manual included life expectancy values for pavement repair methods, which are presented in Figure 5.2. The tables included in the figure clearly show that life expectancy varies as a function of road type, subgrade quality, type of distress, and repair method used.

Damage	Road type	Repair														
		overlay 50 mm			Surface treatment			Slurry seal & surface treatment			Slurry seal & overlay (70 mm)			Mill & Fill 40 mm		
	Sub grade	Sand	Clay	Peat	S	C	P	S	C	P	S	C	P	Sand	Clay	Peat
Rafeling	1	15	15	15	-	-	-	-	-	-	15	15	15	15	15	15
	2	16	16	16	7	7	7	7	7	7	16	16	16	16	16	16
	3	17	17	17	8	8	8	8	8	8	17	17	17	17	17	17
	4	17	17	17	10	10	10	10	10	10	17	17	17	17	17	20
	5	15	15	15	10	10	10	10	10	10	15	15	15	15	15	15
Fatigue cracks	1	9+	8+	7+	n/e	n/e	n/e	6+	5+	4+	13+	12+	11+	6+	5+	4+
	2	11+	10+	9+	n/e	n/e	n/e	6+	5+	4+	13+	12+	11+	6+	5+	4+
	3	14+	13+	12+	n/e	n/e	n/e	7+	6+	5+	14+	13+	12+	7+	6+	5+
	4	15+	14+	13+	n/e	n/e	n/e	8+	7+	6+	16+	15+	13+	8+	7+	6+
	5	16+	15+	14+	n/e	n/e	n/e	8+	7+	6+	16+	15+	14+	9+	8+	7+
Rutting/ roughness	1	12/15+	12/15+	12/15+	n/e	n/e	n/e	12	10	9	15	15	12	12/15+	12/15+	12/15+
	2	13/16+	9/13+	7/11+	n/e	n/e	n/e	13	9	8	16	13	11	13/16+	9/13+	7/11+
	3	15/20+	11/17+	10/13+	n/e	n/e	n/e	12	10	9	20	17	13	15/20+	11/17+	10/13+
	4	15/20+	11/17+	10/13+	n/e	n/e	n/e	13	11	10	20	17	13	15/20+	11/17+	10/13+
	5	25	20	17	n/e	n/e	n/e	15	13	12	20	18	15	-	-	-

Source: VBW ASFALT: Kosten van Wegverharding
Note: 25 means a new life value of 25 years; 15/20+ means additional life of 15 to 20 years on top of remaining residue life

Road type	Number equivalent standard axle loads (100 kN)	Maximum axle load (kN)	Percentage of trucks with higher axle loads than the standard of 100 kN
1	10^7	180	12.5
2	10^6	160	10
3	10^5	160	10
4	5×10^4	160	5
5	Bicycle lanes		

Source: VBW ASFALT: Kosten van Wegverharding

Figure 5.2: Life expectancy values from Van Rijn

5.6 PERFORMANCE OF ASPHALT PATCH REPAIRS [19]

In 2012, Rahman and Thom conducted a laboratory-based study on the performance of asphalt repairs in United Kingdom. The study was in response to the major problem of recurring failure within a few years of repair. The re-appearance of failures may be due to:

- Laying patching materials on failed areas, where underlying materials are likely in a poor state
- Extremely variable quality of service providers, ranging from poorly trained casual workers to professional contractors
- Variability of patch materials
- Inadequate compaction
- Poor surface preparation
- Overall inferior workmanship
- Improper materials.

In Task 1 of this study, two laboratory tests were conducted to understand the mechanism of pothole formation. Two-layer slabs of asphalt were subjected to repeat loading in each of the tests. Each test represented a possible technique of pothole simulation. For the first test, the asphalt had a 20mm upper layer compacted over a 50mm lower layer, either with or without a tack coat layer, and supported on a 30mm soft rubber layer. The main observations found were:

- “Cracks were top-down and many penetrated through the upper asphalt layer.
- The alligator pattern of cracking was considered simulative of that on a cracked road liable to subsequent development of potholes.
- Addition of water led to an acceleration of crack development.
- Increased load led to a moderate increase in cracking.
- Application of tack coat effectively prevented cracking.”

In the second test, asphalt layers were 20mm and 30mm, respectively, on a 40mm crushed stone sub-base and a 10mm soft rubber sheet, with no tack coat. Five specimens were tested: “two at 25°C, one dry and one wet (i.e. standing water on the surface), two at 10°C, one dry and one wet, and one which was subjected to repeated freeze-thaw cycles (thawing for about 30,000 load cycles and then being re-frozen) – but tested wet. In each case 100,000 load cycles were applied in total.” These two tests found that:

- The presence of water accelerates cracking, which increases permeability
    - Subbase becomes saturated which lowers strength, allowing for increased deformation, leading to potholes
- Tack coat application can improve crack resistance
- High temperature increased deformation
- Both tests are promising techniques for pothole simulation in a laboratory setting.

In Task 2 of this study, trial patching sections were built at the Nottingham Transportation Engineering Centre. Potholes with dimensions of 250 by 250 mm were created and four variables, listed in Table 5.3, were changed to simulate different repair scenarios.

Table 5.3: Variables changed during testing to simulate different conditions

Variable	Condition	
Material	Hot Mix	Cold Mix
Compaction	Standard	Poor
Surface Preparation	Clean and tack coat	Not cleaned and wet
Edge	Not sealed	Sealed
Pothole Depth	Shallow (25 mm deep)	Deep (40-50 mm deep)

A total of 23 simulations were run with different combinations of variables and the following observations were made:

- Rutting increased with increased loading. Highest values were in the standard cold mix repair rather than the hot mix repair.
- Standard repair performs slightly better in shallow potholes. Conversely, hot mix tends to perform marginally better in deep repairs.
- A well cleaned surface and application of tack coat performed slightly better than repairs on dirty and wet surfaces.
- Poor compaction accelerates rutting, which resulted in material flow at the edge and some edge cracking in the non-cleaned and wet cold mix repair.

5.7 DURABILITY ANALYSIS OF POTHOLE PATCHING MIXTURE IN SNOWY COLD REGION [20]

Kaito et. al performed an empirical analysis based on inspection records, observation data after repair and basic information on paved roads in southern Japan. They found that pothole generation was most dependent on ruts, structure, surface materials, and the device used to spray water for snow removal. These factors accounted for “over twofold differences in durability of patching mixtures.” Also, “repairing work conditions” had a greater impact on pothole lifespan than structural conditions, in particular whether water and dirt are removed before patch placement.

Lifespan of patches placed in September, January and February were found to be 10-25 days, which is significantly lower than those placed during other months (60-100 days). This difference was attributed to the presence of water. It was determined that current patching materials do not perform well under severe weather conditions in snowy cold regions, particularly when water is present.

5.8 ASPHALT CONCRETE PATCHING MATERIAL EVALUATION [21]

Berlin and Hunt conducted a study in Oregon to evaluate a range of patching materials, shown in table 5.4.

Table 5.4: Materials evaluated by Berlin and Hunt, with costs [28]

Product Name	Manufacturer	Mix Cost/ton	Binder Type	Binder Cost/ton
Bond-X	Seaboard Asphalt Products	$55	Cutback	$370
Elasti-Patch	Koch Materials		Cutback	$550
HFMS-2SP/HFE-300S (control)	Albina Asphalt	$55-68	Emulsion	$325
Instant Road Repair	Saftey Lights Company	$350 (in buckets)	N/A	
King Patch	Pacific Asphalt Marketing		Natural Tar Sands	
Optimix Cold Patch	Optimix	$55	Cutback	
Perma Patch	National Paving & Contracting	$75?	Cutback	
QPR 2000	Quality Pavement Repair	$38 (mixed at maintenance yard)	Cutback	
Tag 8000	Infratech Polymer	$152-186	Emulsion	
UPM High-Performance	United Paving Materials	$55-68	Cutback	

The authors performed laboratory testing and field verification to examine issues of uniformity, availability, handling, stockpiling, environmental impacts, compatibility with common roadway materials, and field performance. Potholes were monitored in the field for six months after treatment. Five material applications were performed:

- Laboratory testing (to correlate field performance with test results)
- Manufactured pothole in open-graded mix
- Manufactured pothole in dense-graded mix
- Natural pothole in open-graded mix
- Natural pothole in dense-graded mix

Due to the short amount of observation time (six months after installation), it was difficult for the authors to draw any major conclusions from the study. The authors, however, concluded that cold mix is advantageous because:

It can be stockpiled outside for several months at a time

It can be used in any type of weather

Has lower equipment and labor costs

They also recommended that ODOT maintenance should use proprietary patching materials for “potholes that are difficult to keep patched.” Proprietary mixes should be evaluated for (at minimum) gradation with allowable P#200 less than 5%, workability number less than 4, and minimum coating of 90%.

5.9 COMPREHENSIVE FIELD EVALUATION OF ASPHALT PATCHING METHODS AND DEVELOPMENT OF SIMPLE DECISION TREES AND A BEST PRACTICES MANUAL [22]

In an effort to develop decision trees and a best practices manual, Barman et al monitored and evaluated the performance of 20 different patches from five construction sites in Minnesota. Two types of potholes were patched: localized potholes and potholes along longitudinal joints. Four patch types were used: cold mix, recycled asphalt mix, mastic material, and mill and fill with virgin hot asphalt (HMA). The potholes were monitored for two years. The major findings were:

- Cold mix should only be used in potholes less than two inches deep, or else in two lifts. Dishing occurs if it is placed in potholes deeper than two inches. Alternatively, using a larger aggregate size may allow cold mix to be used for a larger pothole depth. During placement, pothole should be cleaned using compressed air
- Recycled asphalt mix is not suitable due to aged binder, which slows down the heating process, creating a patch that rapidly ages. Also, fine material in the mix can prevent bonding between binder and aggregate. Newly added binder does not appear to rejuvenate the old asphalt. (Note: these findings are based on observation of only two potholes. However, both potholes failed almost immediately)
- Mastic material (along with current installation practice) seemed to work well, but not for larger potholes along longitudinal cracks or along wheel path. The material does not support loads, so therefore is prone to dishing. Mastic material also creates a smooth surface, which may cause driving

hazards. Therefore, the material should only be used on centerline joints, or in longitudinal joints on the shoulder.

- Mill and fill with virgin HMA requires sufficient tack coat application, and attentiveness to ensure proper amounts of HMA is placed and well compacted. Trucks should not drive in the milled trench after tack coat has been applied. This patching method has a low service life, and significantly deteriorated around 100 days. This low service life may cause more damage to the road than the original distress, since the patch material is not always level with the existing roadway, leading to deterioration of rideability. Cracking or raveling of patches may also allow water infiltration, facilitating continued patch deterioration.

Decision trees were developed for localized potholes and potholes along longitudinal joints, as shown in Figure 5.3. They are intended to serve as guidelines for maintenance crews to use when deciding on proper pothole patching methods. A best practices manual was also developed to outlines patch selection, pothole preparation, placement, compaction, and moisture abatement.

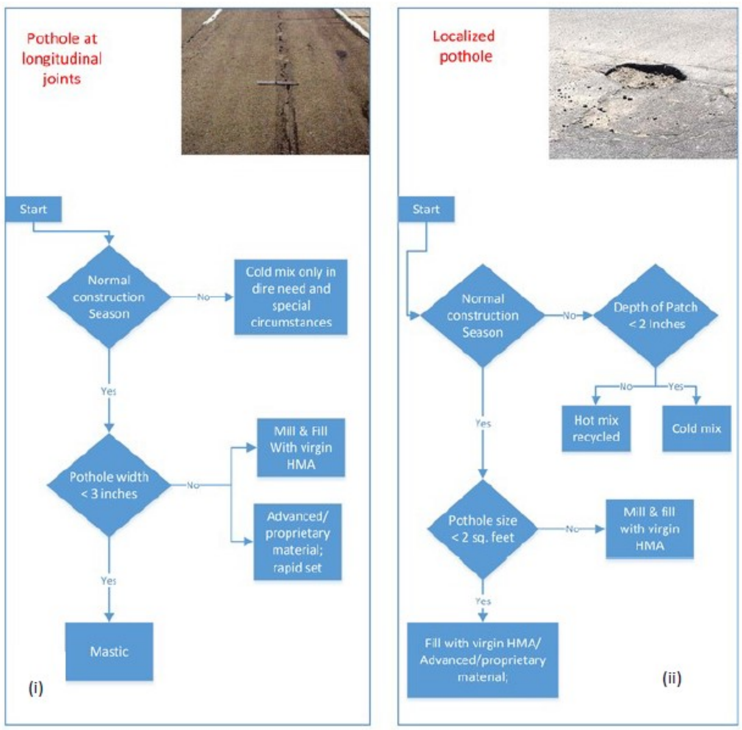

Figure 5.3: Decision trees for pothole repair [29]

5.10 A STUDY ON POTHOLE REPAIR IN CANADA [23]

In 2015, Biswas et al. conducted a study to investigate current pothole repair practices in Canada. The authors first distributed a questionnaire to Canadian transportation agencies, then performed laboratory testing to evaluate the performance of the cold mix patching materials that were most used by the transportation agencies.

Table 5.5 summarizes pothole repair information from six provinces. The table shows that most repairs are performed in the summer. When performed in the winter, the percentage of patching materials and patching methods used are shown. The four pothole patching materials commonly used in the winter are: conventional cold mix (CCM), hot mix asphalt (HMA), a proprietary mix (QPR), and Innovative Asphalt Repair (IAR).

Table 5.5: Pothole repair information from six Canadian provinces [30]

Province	Repair period (%)		Winter patching material (%)				Winter Patching Method (%)	
	Winter	Summer	CCM	HMA	QPR	IAR	Throw and go	Semi-permanent
AB	10	90	15	-	85	-	100	---
MB	10	90	-	-	50	50	100	---
ON	40	60	60	40	-	-	60	40
QB	43	57	75	25	-	-	80	20
SK	10	90	20	20	60	-	70	30
NB	10	90	-	5	95	-	95	5

Laboratory testing was performed on the four patching materials (CCM, QPR, HMA and IAR). The Marshall stability test, Indirect Tensile Strength (IDT), adhesiveness and cohesion tests were performed. Laboratory results indicate the following:

- QPR use in winter may lead to cracking, raveling, shoving and missing patch distresses, and a shorter survival period. QPR was found to have:
  - No Marshall stability (before or after curing)
  - Strength was much lower than HMA
  - Adhesiveness was acceptable
  - Cohesion was inadequate
  - Freeze thaw cycles have a significant effect
- CCM use in winter may lead to raveling and missing patch distresses. CCM was found to have:
  - Low Marshall stability before curing, but acceptable stability after curing

    - Acceptable adhesiveness
    - Cohesion is sufficient at higher temperatures, but not at lower temperatures
    - Susceptibility to moisture damage
- IAR use in winter may lead to cracking, raveling, shoving, edge disintegration and missing patch distresses. IAR was found to have:
    - No Marshall stability before curing, low strength after curing
    - The lowest IDT strength of all the materials tested
    - No cohesion at room temperature and lower
    - Moisture sensitivity
    - Greatly affected by freeze thaw cycles

The survey also collected information on repair survival periods per province. As expected, and shown in Table 5.6, repairs placed in summer have a much longer survival period in every province. Curing time and temperature had a significant effect on strength gain for all cold mixes. All cold mixes were sensitive to freeze-thaw damage. CCM showed higher stability and cohesion properties, while QPR showed better moisture resistance and adhesion properties.

Additionally, this study found:

The maximum survival period of winter patches is less than a year, while summer patches my last from one to more than two years.

Summer patch durability was higher with a combination of QPR and HMA

CCM has the best strength and cohesion, and Marshall stability was comparable to HMA after curing

QPR had the best resistance to moisture, but the freeze thaw cycle significantly increased its moisture sensitivity

The best results for winter maintenance for all locations except Manitoba were found by using HMA used with the semi-permanent method and CMA with the throw-and-go method

“Using a cold mix in the winter with less curing time, better cohesion properties and lower sensitivity to freeze thaw cycle may increase durability of pothole patches, especially in winter time”

Table 5.6: Survival periods of repairs placed in either winter or summer, in six provinces [30]

	Province	< 3 months	3 to 6 months	6 to 9 months	9 months	1 to 1.5 years	1.5 to 2 years	> 2 years
Winter	AB	x						
	MB				x			
	ON		x					
	QB			x				
	SK		x					
	NB	x						
Summer	AB							x
	MB							x
	ON					x		
	QB					x		
	SK						x	
	NB							x

5.11 MIX DESIGN AND PERFORMANCE-BASED SPECIFICATIONS FOR COLD PATCHING MIXTURES [24]

Rosales-Herrera et al. evaluated cold mixtures in an effort to establish design guidelines and performance based specifications for the Texas DOT. They first identified failure mechanisms for cold patching mixtures, then analyzed effects of several mixture characteristics (gradation, aggregate shape, binder content and viscosity, curing time, temperature, and admixtures on the mixture workability and stability).

The problem statement included the following problems to address:

- Lack of workability can lead to inadequate compaction and poor performance
- Stability is needed to resist deformation under load

- Workability and stability often conflict each other, so a balance between the two is essential to proper mix performance
- Stockpiled mixtures left unprotected, can develop a hard crust, which affects workability
- Lack of guidelines and specifications lead to overall inconsistent mixture behavior

The authors had the following objectives:

- "To identify failure mechanisms and review materials used, current homemade mix designs, field application procedures, and performance evaluation methods to establish design needs and criteria;
- To develop a cold-weather mix design procedure for homemade mixtures and establish performance-based mixture specifications for both homemade and containerized mixtures;
- To perform laboratory tests on homemade and containerized patching mixtures to evaluate their cold-weather workability and estimate their performance;
- To perform accelerated pavement tests (APT) on homemade and containerized patching mixtures to evaluate their performance;
- To evaluate the performance of homemade and containerized patching mixtures in the field; and
- To evaluate the effectiveness of various containers."

Six containerized mixtures were evaluated: Asphalt Patch, PermaPatch, Proline, QPR, Stayput, and UPM (Summer and Winter). Homemade mix designs from two Texas districts as well as mixtures designed in the laboratory were also evaluated. Field evaluations were also conducted in the two Texas districts: Lubbock, which represents cold and dry weather, and Lufkin District, which represents warm and wet weather. The Cost-Effectiveness analyses consisted in the following steps.

- Factors that influence costs or perceived costs were identified through discussions with TxDOT and vendors.
- A questionnaire was given to TxDOT personal in Lubbock District to determine different cost components associated with cold patch mixtures
- Interviews were conducted with TxDOT employees to understand purchasing procedures

The following cost components or criteria were considered in this analysis:

- Material cost, including shipping cost,
- Time to fill order,
- Specific storage requirements,
- Shelf life,
- Bag durability,
- Stability,
- Special handling requirements,
- Performance, and
- Other, specifically environmental impact.

5.12 LONG-TERM COST-EFFECTIVENESS OF ASPHALT PAVEMENT POTHOLE PATCHING METHODS [25]

In 2014, Dong et al. conducted a 14-month survey on field performance of patches on road sections in Tennessee with varying weather and traffic conditions. Performance of patches were rated according to overall distress conditions. Then, “the multiple linear regression method was used to analyze the influence of patching methods, materials, geometric features, climatic condition, and traffic factors on the performance of patches.”

According to a national survey, many highway agencies use the throw-and-roll procedure in winter for temporary repair and follow up with semi-permanent patching in summer as a more permanent repair. For this reason, in this study twelve semi-permanent patches were installed in summer, 6 months after throw-and-roll patches. Three procedures were investigated: cutting edges to remove old deteriorated pavement, heating the old pavement by an infrared heater, and spraying tack coat to strengthen the bonding. The procedures were identified as:

HMA,

HMA + cut squares,

HMA + tack coat,

HMA + infrared heater,

HMA + cut squares + tack coat, and

HMA + tack coat + infrared heater.

Geometric features of each patch were measured and annual average daily traffic (AADT) values and speed limits of the road section were collected. Accumulated freeze times were calculated using daily temperatures recorded by the local weather stations collected from the National Climatic Data Center. The authors performed field surveys after 0.25, 0.75, 1.5, 3, 6, 9, and 14 months from throw-and-roll patching. Since the semi-permanent patches were installed 6 months later, only an 8-month survey results were available for the semi-permanent patches.

The study found that throw and roll patches deteriorated very quickly, and 70% of them lasted less than 14 months. Throw and roll patches placed in winter usually only survived several weeks. The cutting procedure on semi-permanent patches removes pavement, so more material is needed to fill. This led to a dishing problem. Therefore, sufficient material amount and compaction is important. The field survey showed most common distresses were dishing, edge disintegration and missing patch, and sufficient compaction greatly improved stability.

A cost effectiveness analysis was performed using data provided by Tennessee DOT. The authors found that labor costs represented 50-60% of total costs, materials 20% for cold mixes and 5-6% for semi-permanent patches (Figure 5.4). The costs of semi-permanent patches were much higher than for the throw-and-roll patches due to increased equipment and labor costs. Since material cost accounts for a small part of the total, using more expensive but more durable materials could increase the cost-effectiveness significantly.

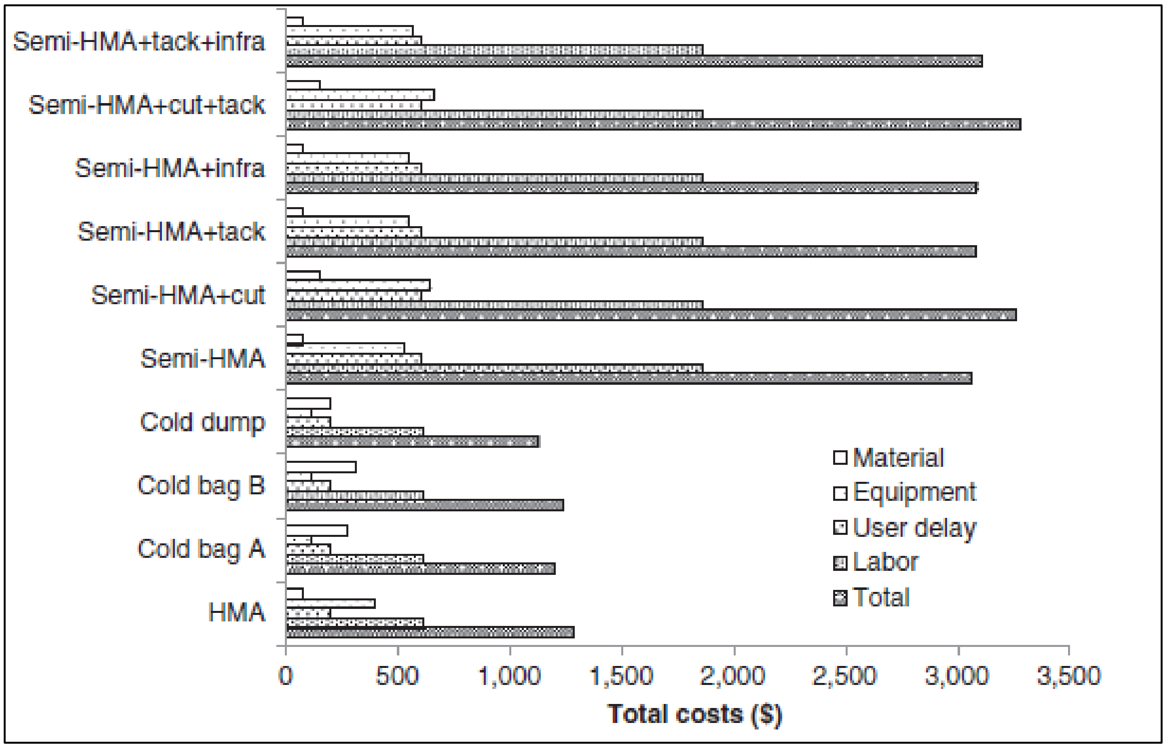

Figure 5.4: Costs per patching method [32]

The analysis showed that throw and roll were most cost effective in the short term, as shown in Figure 5.5. Semi-permanent were more cost effective in the long term.

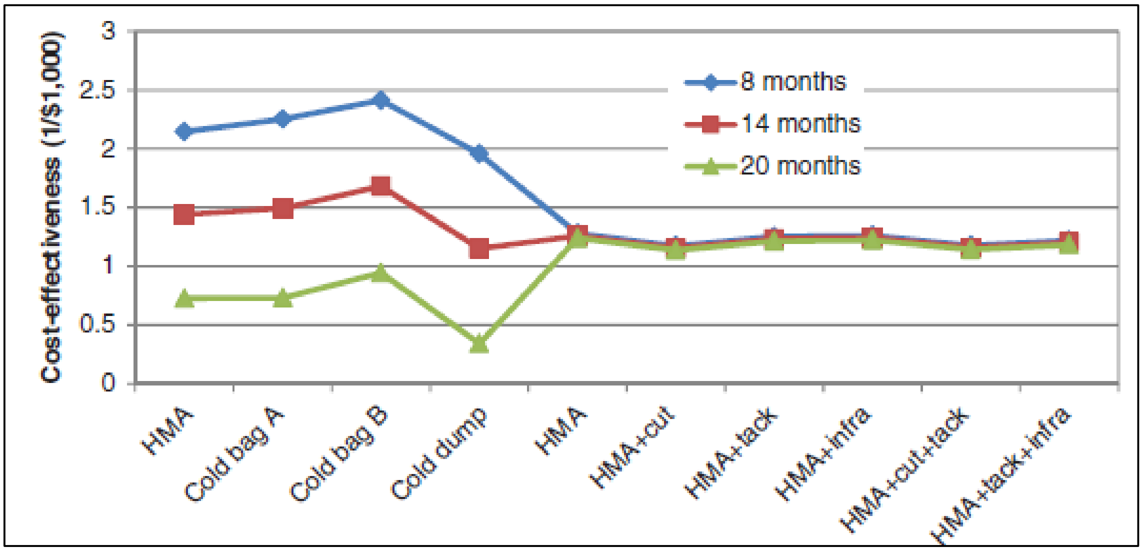

Figure 5.5: Cost benefit of patching methods, calculated as ratio of performance rating over cost [32]

5.13 EVALUATION OF WINTER POTHOLE PATCHING METHODS [26]

In 2014, Nazzal et al. evaluated the performance and cost-effectiveness of the tow-behind combination infrared asphalt heater/reclaimer patching method and compared it to the throw and roll and spray injection methods. Several sites in Ohio were studied, and both manmade potholes and field distresses were patched.

ODOT created manmade potholes along I-480 and patched them in January. Manmade potholes were used to ensure patches were evaluated under the same conditions. Patches were placed in and in between wheel path. Three patching methods were used to fill them: throw and roll, spray injection and infrared heater/reclaimer. The authors noted that the artificially created potholes were very clean compared to real potholes, no water was present, and the aggregates were not coated (normally would be coated) with asphalt, which could cause the control potholes to perform more poorly. Several additional sites were studied, including:

- Site 2: US 422--Pavement had significant cracking. Five patches were installed in February using the infrared heater.
- Site 3: State Route 168—Spot patches using throw and roll and infrared were used to repair grinding and skidding from Amish horses. Installation was in June. Three different methods were used with infrared.

Field inspections were performed up to 188 days after installation. Two types of data were collected: survival (number of patches still in service) and distress (types of distresses on patches). The results found that potholes repaired using the infrared heater had higher rating than other two methods, as shown in figure 5.6.

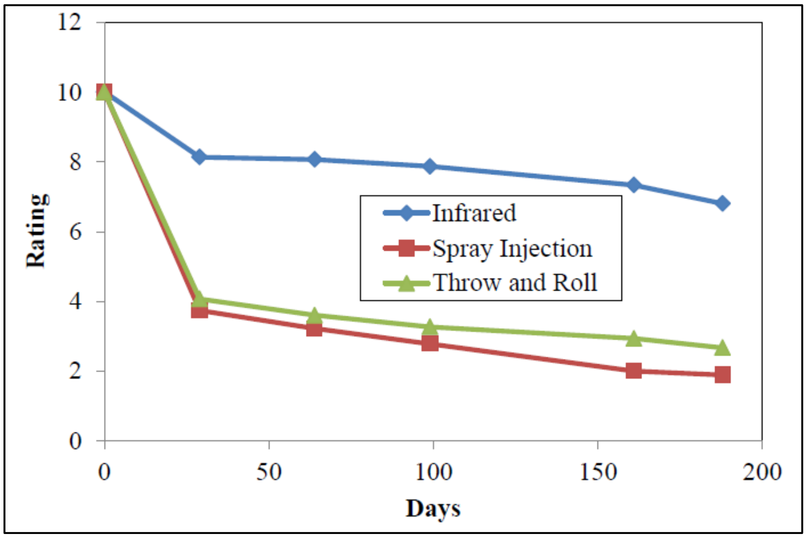

Figure 5.6: Rating given to each patching method [33]

The cost analysis found that the throw and roll method was more cost effective for a period of less than 12 months. For longer durations (such as permanent repairs), the infrared method was found to be the most cost effective (as shown in Tables 5.7 and 5.8).

Table 5.7: Labor costs for different methods [26]

Patching Method	Number of Workers in Maintenance Crew*	Labor for Labor Crew ($/day)	Material	Total Cost ($/ton)
Infrared	4 workers	$1079.64	HMA	$68
Spray Injection	5 workers	$890.55	Emulsion and Aggregate	$203.30
Throw and Roll	6 workers	$701.46	Cold Mix	$101.80

**Each crew also has one supervisor in addition to the number of workers*

Table 5.8: Equipment Costs for Patching Methods [26]

Patching Method	Total Cost	Equipment	Cost ($/day)
Infrared	$335.27	Small vibratory roller	$147.30
		One-ton dump truck	$24.63
		Minuteman daily equivalent cost	$9.97
		Minuteman maintenance cost	$1.37
		Minuteman operating cost	$152.00
Throw and Roll	$39.01	One ton dump truck	$24.63
		DODGE 4W Truck	$14.38
Spray Injection	$498.99	Small vibratory roller	$147.30
		One ton dump truck	$24.63
		Durapatch daily equivalent cost	$6.69
		Durapatch maintenance cost	$1.37
		Durapatch operating cost	$319.00

Cost Analyses were performed using values shown in Table 5.9 and the equation below:

Table 5.9: Summary of inputs used in cost analysis [26]

Input	Infrared Method	Spray Injection Method	Throw and Roll Method
Material Cost ($/ton)	99.52	203.3	101.78
Initial Need (tons)	321.04	321.04	321.04
Repair Crew Wages ($/day)	1079.64	890.55	701.46
Traffic Control Wages ($/day)	319.92	319.92	319.92

Repair Equipment Cost ($/day)	335.27	498.99	147.3
Traffic Control Equipment Cost ($/day)	26	26	26
Productivity (tons/day)	0.89	2.24	3.68
User Delay Costs ($/day)	0	0	0
Estimated Average Repair Life (months)	Analysis period	2.14	3.52

CT = [(TTOT/LEXP)] x [(N/Po) x (CL - CE - CTC) + (N × CM)]

Where:
CT = Total cost of patching operation for the given time frame, dollars
TTOT = Time for analysis, years
LEXP= Life expectancy for material-procedure combination, years
N = Material needed for patching initial potholes, tons
Po = Productivity of the operation, tons per day
CL = Cost of labor needed for patching operation, dollars per day
CE = Cost of equipment needed for patching operation, dollars per day
CTC = Cost of traffic control for patching operation, dollars per day

CM= Cost of material delivered to yard, dollars per ton

The cost analysis shows that while the infrared method is initially the most expensive, over time, the cost becomes the least expensive (Figure 5.7).

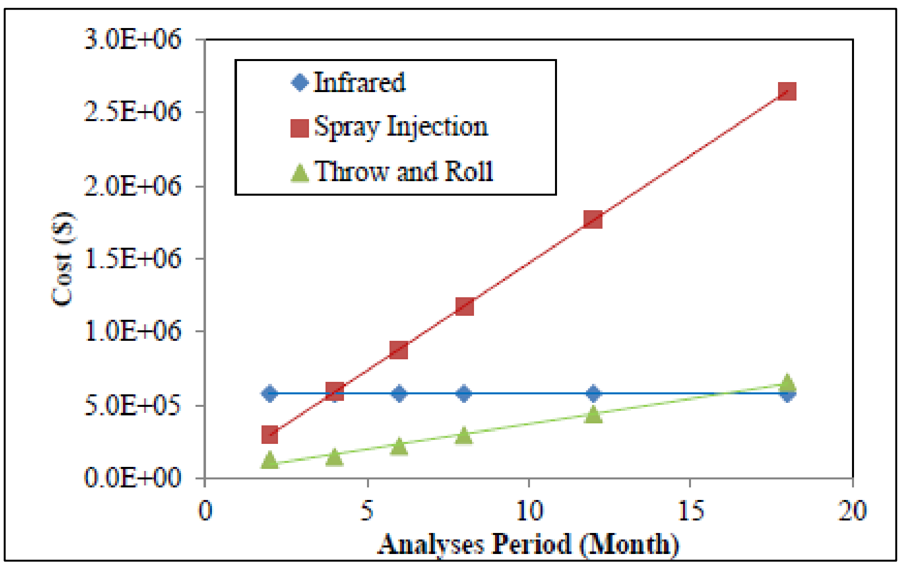

Figure 5.7: Cost of potholes over time [26]

The authors concluded that

- "The infrared is more cost-effective than the spray injection method when used for winter potholes patching.
- For short-term repairs, the throw-and roll method will cost less than the infrared method if the users' costs were not considered.
- For permanent repairs, the infrared method will be more cost effective than throw and roll method.
- If the cost of damage to vehicles of traveling public was considered, the infrared might be more cost effective than throw and roll method especially for medium size (2 ft. to 3 ft. in dimensions) and large size potholes (more than 3 ft. in dimensions)."

5.14 POTHOLE EUROPEAN PROJECT [27]

A very comprehensive research effort on potholes was recently completed as part of a two-year European study called POTHOLE that involved seven countries. The main objective of the project was to address "the road agencies' need for durable construction and maintenance methods for the repair of damage occurring after hard winters due to repeated frost-thaw cycles." The authors emphasized that the current methods and techniques used need to be improved, due to the significant economic loss from the damage, the increasing number of crashes, injuries and deaths caused by potholes, as well as the repair of potholes with materials that are only suitable on a short-term basis.

The study contains a very detailed section on Life-Cycle Cost-Benefit Analysis (LCCBA), which, unlike other studies, includes both agency and users costs associated with pothole repairs.

Two time periods, 3 and 6 years, were used in the analysis. Both periods represent the remaining service life of the asphalt section and were regarded as two reasonable ends of a spectrum which are expected to require different repair strategies. The repair strategies investigated are shown in Table 5.10.

Table 5.10: Repair alternatives [34]

Repair alternative	Repair material	Repair technique
1a	Cold-mix asphalt	Unprepared fill-and-roll
1b	Cold-mix asphalt	Prepared fill-and-roll
2a	Synthetic binder	Prepared fill-and-roll
3a	Hot-mix asphalt	Unprepared fill-and-roll
3b	Hot-mix asphalt	Prepared fill-and-compaction
3c	Hot-mix asphalt	Milling and resurfacing section

In order to schedule pothole repair, an agency needs to know when and how many potholes are likely to occur within the remaining life time of the asphalt section. A pothole progression model, suggested by the Highway Development & Management Tool (HDM-4), was used in this study. In terms of repair timing, it was assumed that the period until potholes are repaired can vary between 3 and 9 month and this variation was accounted for in the LCCBA by using a minimum, middle, and maximum value, as shown in Table 5.11.

Table 5.11: Response time [34]

Type	Response time (months)		
	min	[illegible]	max
Immediate repair (IR)	0		
Deferred repair (DR)	3	6	9

Based on the detailed LCCBA performed in this study, the authors concluded the following:

(1) Immediate pothole repair strategies are preferable compared to deferred pothole repair strategies. Although deferred repair strategies have lower agency costs, the user costs increase drastically and, thus, the total costs increase.

(2) The unprepared patching of potholes with cold-mix asphalt incurs the highest costs compared to other patching strategies. The low patching survival of this strategy increases the total number of potholes to be repaired.

(3) Patching strategies have very similar costs. Although these strategies have different patching survival rates and repair costs, the longer patching survival and higher costs of one strategy is outweighed by the shorter patching survival and lower costs of another strategy.

(4) In situations with high traffic intensity, a deferred resurfacing of the road section is more cost-effective than a deferred patching of potholes.

(5) In situations with low traffic intensity, deferred pothole patching is more cost-effective than a deferred resurfacing of the road section.

5.15 CONCLUSIONS AND RECOMMENDATIONS

A number of conclusions and recommendations can be made from the investigation performed in this chapter.

<u>Identify proactive pavement preservation techniques that can delay the initiation of potholes and reduce or eliminate the formation of significant pothole occurrence.</u>

Both references evaluated, Minnesota Pavement Preservation Manual and Washington DOT asset management program, provide proactive pavement preservation techniques that can delay or prevent the formation of potholes. Among them, using a very good data tracking system, and applying the right treatment for the right situation at the right time are key components. Maybe the most important is taking a proactive budgeting strategy to ensure money is available on a consistent basis in the short run, to significantly reduce the much higher long-term costs.

Better understand the main causes of failure of pothole repairs

All references summarized in this task identified similar causes for the failure of pothole repairs: using patching materials of inferior quality, poor construction practice, harsher than normal winters and large number of freeze thaw cycles. These refer in particular to winter patching, since late spring and summer pothole repairs are of higher quality and can be applied and compacted similarly to typical hot mix asphalt. As shown in chapter 4 and also reported by others, most cold mixtures used for winter are used just to fill the potholes temporarily; they have very poor mechanical properties that make them prone to immediate failure that requires multiple repairs of the same pothole over the season. This is not surprising since workability at low temperature for these materials is achieved using asphalt emulsions that require higher temperatures for curing which is not possible in winter conditions.

The work performed in chapter 4, and references summarized in this chapter, identified a number of more expensive but longer lasting methods that can significantly improve the durability of winter pothole repairs. Among them, using GAP Mastic, which is a hot-applied, polymer modified asphalt mixed with engineered aggregates and modifiers, and using infrared technology to compact and cure pothole repair materials. In Minnesota, work performed at the Natural Resources Research Institute demonstrated the potential use of micro wave technologies for pothole materials containing taconite aggregates.

Based on these findings, it would be beneficial to perform field studies similar to the work in references [25] and [26] to determine the best technology for Minnesota conditions. MnDOT could choose several locations that require repair, and choose a handful of repair options. The repairs could be monitored over a 2 to 5 year period, and lifespan data could be collected. Artificial potholes, created by core extraction at MnROAD, can also be used for similar purposes.

Summarize cost information from available sources

Researchers have contacted staff from MnDOT, Hennepin and Dakota County to obtain information related to pothole repairs required to perform cost comparisons for various scenarios. Since this information was not available, summaries of cost comparisons detailed in three references [25, 26, and 27] were summarized and presented as examples. It is therefore recommend that a rigorous tracking system of pothole repair activities should be developed to determine which materials/techniques are the most effective for various pavement conditions in Minnesota. In particular, the following information should be collected to perform cost effectiveness evaluation:

- Pothole size, location, and date of repair
- Repair type, amount of material (with material costs) and labor records (how many workers or man hours)
- Records on survival rates of pothole repairs and how often the same potholes are repaired.

The analyses on cost effectiveness [25, 26] and Life-Cycle Cost-Benefit Analysis (LCCBA) indicate that while the cheaper materials and methods are more cost effective in the short run, the more expensive and durable repair methods provide substantially higher effectiveness in the long run. The benefits are even higher if user costs are considered in the analysis [27].

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

A summary of the work performed in this investigation and relevant conclusions and recommendations are provided below.

6.1 SUMMARY

In Chapter 2, a literature review was performed to summarize recent national and international efforts on providing solutions to preventing the initiation and development of potholes and, once developed, repairing them. There is general agreement that pothole formation is mainly caused by the delayed response to fixing common pavement distresses in the initial phase of their development. The most common distress related to pothole formation is cracking, which can be the result of different failure mechanisms. Once cracks form, and are not repaired, water infiltrates into the pavement surface layer and accelerates the damage process through various mechanisms, ranging from stripping to freeze-thaw cycles. A proactive pavement preservation approach represents a viable solution that can significantly reduce the presence of potholes.

An excellent summary of current pavement patching practices in the US and other countries is provided in a recently published NCHRP Synthesis [4]. In general, similar repair methods were found in many countries. The throw-and-go method was found to be one the most commonly used methods due to its high production rate. This method results in low-quality repairs and should be replaced by the throw-and-roll technique, which also has a high production rate but produces superior results. Semi-permanent, spray-injection, and edge-seal methods are also used by agencies, and more and more agencies have started to use automated equipment. These methods produce higherh quality repairs however, their costs are higher. It was found that agencies in the US do not always follow specifications, plans or guidelines for patching compared to agencies in other countries. It was also found that most agencies in other countries monitor the performance of patch repair after installation, a critical component in quantifying the benefits of various patching methods.

A survey was distributed to MnDOT maintenance superintendents and local engineers to obtain current pothole repair practices. Similar to national and international practice, it was found that throw-and-roll is the number-one repair method used and that hot mix asphalt is the number one material used. The main factors responsible for pothole formation were found to be the weather and the wearing course condition, and public complaints were the number-one trigger for repair activities, while pavement condition parameters that are part of a management program were second. It was also found that crack sealing and patching were the most common preservation activities, followed by chip seals.

In Chapter 3, numerical simulations were performed to determine if certain geometric configurations (round vs. square, etc.) were more favorable in reducing the stresses that develop in pothole materials and at the interface with the old pavement and to determine a set of desirable material properties for long-lasting pothole repairs.

Pavement sections containing three different shaped potholes, round, square and diamond, were modeled using finite element analysis. Based on the numerical simulations performed, it was concluded that circular-shaped potholes minimize stress concentrations near the boundary of the potholes and can increase the durability of pothole repairs. Circular pothole repairs also represent the best construction option to uniformly fill the pothole with the repair material and compact it; the repair material cannot easily flow into and fill pothole corners.

The simulations also indicated that perfect bonding is not necessary to minimize stresses surrounding a patched pothole; however, the bond does need to be sufficiently strong to avoid an increase in stresses. It was also found that potholes patched with the same material as the asphalt being repaired showed significantly lower maximum stresses than any of the other scenarios modeled, as well as a more uniform stress profile.

It is important to mention that a literature search found no published reports on stress analysis of pothole repairs. This is in agreement to the findings presented in the final report of the comprehensive POTHOLE European project [27], in which the authors mention that the geometry of repaired potholes has not been investigated. They also mention that potholes are generally repaired as square areas, with joints in the direction of traffic, and hypothesize that a diamond shape could increase durability and also reduce noise.

In Chapter 4, extensive experimental work was performed to determine whether relevant material properties can be obtained on pothole patching materials. Currently, there are no required specifications for patching materials in the US. A similar situation is reported throughout Europe, where there are no requirements for material properties, making it very difficult for stakeholders to choose between materials on the market. There is also no mandatory materials information that needs to be made available by manufacturers.

Initially, four materials were tested: Perma-Patch, Summer Mix_UPM, Winter Mix_UPM, Winter Mix_St Paul. A fifth material, GAP (mastic), was obtained later on, followed by a sixth material obtained at the end of the task, St. Paul Summer Mix. For this last material, an investigation was performed to determine if the addition of graphene nano-platelets (GNP) results in any significant improvements in mechanical properties.

Difficulties were encountered in preparing cylindrical specimens for mechanical testing for the first four materials. First, gyratory compaction was used to compact the patching materials at room temperature. Only the winter mix from St. Paul asphalt plant (WM_SP) “survived” the compaction; the other three collapsed right after extraction from the mold. Different methods of manual compaction and of conditioning after compaction were investigated. It was determined that cold conditioning before compaction followed by compaction using steel molds and MTS compaction load simulated winter patching at low temperature the best. Due to difficulties with specimen preparation, only IDT strength test was performed at 0°C and -24°C. As expected, the winter mix from St. Paul had the highest IDT strength followed by winter mix from UPM. It should be noted that the results for the summer mix from

UPM are not representative of its performance, since the material was compacted and used at temperatures much lower than the recommended temperature values.

Two patching materials, Perma-Patch and Winter Mix_UPM, were used in experiments to investigate the bonding strength between the patching material and the existing asphalt mixture in the pavement. Samples were prepared using half HMA and half patching material to simulate actual field condition and a diametral compression load was applied along the joint between the patching material and HMA. The two patching materials as well as the hot mix asphalt were also tested individually for comparison purposes. As expected, the all HMA specimen had the highest IDT strength. The bonded samples consisting of half patching materials and half HMA were observed to have higher strengths than the individual samples of patching materials. The Winter Mix from UPM had the highest interface bond strength with HMA.

The fifth tested material, GAP Mastic, is a hot-applied, polymer modified asphalt mixed with engineered aggregates and modifiers designed to fill wide cracks and defects to prevent water infiltration and restore ride quality. Unlike the first four patching materials, GAP is a more expensive product that has specific preparation requirements, including heating using indirect heating methods. The testing specimens were simply poured into the molds, with no compaction, since compaction of this material is not required in the field. It was found that the IDT strength of GAP at -24°C was similar to IDT strength of regular HMA, and significantly higher than the strength of the other patching material investigated.

A simple experiment was performed by pouring water on IDT specimens of Perma-Patch and GAP to get qualitative information about the water permeability of the patching materials specimens. It was observed that water passed freely, which appears to indicate that during a rain or snow melting event, water can accumulate and refreeze at the bottom of the pothole, and this significantly decreases the durability of the patching repair. This is in agreement with multiple observations of poor performance of pothole repairs during seasons with multiple freeze-thaw cycles.

The sixth material tested was a summer asphalt mix received from St. Paul asphalt plant. Three mixtures were prepared using the St Paul Summer Mix: a mixture containing 6% Micro 850 GNP, a mixture containing 6% 4827 GNP, and a control mix, which contained no GNP additive. Since testing specimens could be prepared without any problems using a gyratory compactor, additional testing was performed on these materials: IDT creep stiffness and strength, and SCB fracture energy and toughness. The results indicated that fracture energy and fracture toughness increased for the specimens containing GNP additive. Also, the addition of GNP increased the tensile strength, particularly at the lower test temperature of -12°C. It was also found that the three mixtures had significantly higher IDT strength values at 0°C, compared to all other patching materials tested. It is important to note that while at - 24°C the GAP mastic had similar strength values to HMA, at 0°C the GAP strength was significantly lower than the strength of HMA.

The work performed in Chapter 4 showed that for summer patching materials, sample preparation and testing can follow the same procedures used for hot mix asphalt. However, for cold mixtures used for winter patching, both sample preparation and testing can be challenging and require additional work to develop a common evaluation method based on mechanical properties. The experiments performed in this task indicate that winter cold mixtures do not gain strength and stiffness unless significant curing occurs. Cold mixtures can be poured and placed at typical winter temperatures, but minimal curing occurs at these temperatures, which makes these materials very weak, with characteristics more like filling materials. An external source of heat needs to be provided to accelerate curing and provide reasonable mechanical properties to these materials. For summer mixtures, which have similar properties to regular HMA and last much longer, earlier failures can be more related to poor construction practice and bond failure of the interface with the existing pavement.

In Chapter 5, an investigation was performed to summarize the main causes for premature failure of pothole repairs and to identify proactive pavement preservation techniques that can delay the initiation of potholes and reduce or eliminate the formation of significant pothole occurrence.

It was found that lead states, such as Washington and Minnesota, use proactive pavement preservation activities that can delay or prevent the formation of potholes. Among them using a very good data tracking system and applying the right treatment for the right situation at the right time are key components. Maybe the most important is taking a proactive budgeting strategy to ensure money is available on a consistent basis in the short run to significantly reduce the much higher long-term costs.

All references identified similar causes for the failure of pothole repairs: using patching materials of inferior quality, poor construction practice, harsher than normal winters, and a large number of freeze-thaw cycles. These refer in particular to winter patching, since late spring and summer pothole repairs are of higher quality and can be applied and compacted similar to typical hot mix asphalt. As shown in Chapter 4 and also reported by others, most cold mixtures used for winter repairs are used just to fill the potholes temporarily; they have very poor mechanical properties, making them prone to immediate failure that requires multiple repairs of the same pothole over the season. A few more expensive but longer lasting methods are available, such as using GAP mastic, using an infrared asphalt heater/reclaimer patching method [13], and using micro-wave technologies for pothole materials containing taconite aggregates [1]. The addition of GNP improved the compaction and mechanical properties of the summer patching materials.

Since information related to pothole repairs required to perform cost comparisons for various scenarios was not available from the local sources identified, summaries of cost comparisons detailed elsewhere were summarized and presented in Chapter 5. The analyses on cost effectiveness and Life-Cycle Cost-Benefit Analysis (LCCBA) all show that while the cheaper materials and methods are more cost-effective in the short run, the more expensive and durable repair methods provide substantially higher effectiveness in the long run. The benefits are even higher if user costs are considered in the analysis.

6.2 CONCLUSIONS AND RECOMMENDATIONS

Based on the work performed in this investigation, the following conclusions can be drawn and the following recommendations can be made.

There is general agreement that pothole formation is mainly caused by the delayed response to fixing common pavement distresses in the initial phase of their development. Minnesota has a number of preservation strategies that are available and which have been successfully used in a number of projects. However, there are still a number of misconceptions on the timing of application of pavement preservation, construction practice, and the long-term benefits of a pavement preservation program.

Recently, the Federal Highway Administration launched the fourth round of Every Day Counts (EDC-4), which supports moving the preservation concept to a higher level and focuses on sustaining the infrastructure through investments over the "whole-life" and through quantifying the risks. The EDC-4 has three components: the When and Where, which address preserving highway investments by managing transportation pavements proactively based on the 3Rs: right treatment, right pavement, and right time; and the new How component, which promotes quality construction and materials practices, including treatment options that apply to both flexible and rigid pavements [16]. For flexible pavements, these include using improved specifications for thin asphalt surfacing such as chip seals, scrub seals, slurry seals, microsurfacing, and ultrathin bonded wearing courses. Rigid pavement strategies include rapid retrofitting of dowel bars; the use of new, fast-setting partial- and full-depth patching materials; advanced pavement removal techniques to accelerate patching construction times; and advancements in diamond grinding. [16, 28, 29].

It is therefore recommended that the current MnDOT Pavement Preservation Manual [30] and the documents made available as part of EDC-4 [16, 28, 29] are used to determine best preservation strategies. The EDC-4 has also produced an informational video promoting the benefits of pavement preservation, which is available on line [31].

A number of conclusions can be drawn from the limited experimental work that can help in the decision process of selecting pothole repair materials:

Cold mixtures used for winter patching that do not require heating for placing and compaction have poor mechanical properties and are expected to require frequent re-repairs, especially in winters with many freeze-thaw cycles. The UPM repair materials appear to have better mechanical and bonding properties compared to Perma-Patch.

Winter patching materials that require an external source of heat for placing and compaction have significantly better mechanical properties and are expected to last longer. However, they are more expensive and require specialized equipment and training.

Pothole repairs performed in late spring and summer with hot mix asphalt are the most durable and may last for more than one winter season.

In situations with high traffic, resurfacing of the road section might be more cost-effective than patching of potholes in summer. The opposite might be true for low-volume roads.

Currently, there are no required specifications for patching materials. One step forward would be to select patching materials based on the estimated durability of the pothole repair [27]:

Category I: Short-term durability (less than 1 year), used for emergency repairs of potholes that could last until weather conditions allow using more durable repair materials

Category II: Medium-term durability (1 to 3 years), used for pothole repairs on roads for which the surface layer will be replaced in a few years

Category III: Long-term durability (more than 3 years), intended for repair of potholes in relatively new pavement surfaces that are expected to last for more than 3 years.

All life-cycle analyses demonstrated that cheaper materials and methods are more cost-effective in the short run however, the more expensive and durable repair methods provide substantially higher effectiveness in the long run. The benefits are even higher if user costs are considered in the analysis.

A number of new materials and innovative technologies are available to provide more durable solutions for winter pothole repairs, which represent the most challenging situation; the repair materials need to be placed at cold and very cold temperatures at which curing and compaction is not possible unless additional heating is provided. All three techniques and materials documented in this investigation, GAP, infrared heating, taconite mixture and microwave heating, require an external energy source to obtain the final product. The use of GNP additives show promising benefits for summer patching since they increase the compaction level. The addition of GNP may provide benefits for winter pothole repair since they can be heated significantly by application of microwave energy, similar to the effect observed in taconite aggregates.

The research team, however, is not able to make long-term recommendations for better patching strategies, materials and methods, since cost and performance information was not available for current pothole repairs in Minnesota. In order to perform cost analyses to determine which materials/techniques are the most effective for various pavement conditions in Minnesota, it is recommend that a simple tracking system of pothole repair activities be developed and implemented. In particular, the following information should be collected to perform a cost-effectiveness evaluation:

- Pothole size, location, and date of repair
- Repair type, amount of material (with material costs) and labor records (how many workers or man hours)
- Records on survival rates of pothole repairs and how often the same potholes are repaired.

REFERENCES

1. Zanko, L. M. (2015) Evaluate and Develop Innovative Pavement Repair and Patching: Taconite-Based Repair Options Contract No. 99008, Work Order 51 Draft Final Report. Natural Resources Research Institute, University of Minnesota Duluth, MN.

2. Lofton, A. (2013). Automated Pothole Patching Equipment. Caltrans Division of Research, Innovation and System Innovation, CA.

3. Materials and Procedures for Repair of Potholes in Asphalt-Surfaced Pavements Manual of Practice Report No. FHWA-RD-99-168 (1999). U.S Department of Transportation Federal Highway Administration, Washington, DC.

4. Behnood, A., Olek, J., Magee, B, McDaniel, R. S.,Pollock, R. (2014). NCHRP Synthesis 463 Pavement Patching Practices A Synthesis of Highway Practice. Transportation Research Board, Washington, DC.

5. Van Rijn, J. (2010) Road Maintenance Planning. In Development.

6. Komba, J., Maharaj, A., Paige-Green, P. (2010). Potholes: Technical Guide to their Causes, Identification, and Repair. CSIR Built Environment, Stellenbosch, South Africa.

7. ERES Consultants, Inc. (1991). Pothole Repair. TechBrief based on Report No FWHA-RD-98-073, Champaign, IL

8. Tighe, S. , Wei C. (2004). Development of Preventive Maintenance Decision Trees Based on Cost-Effectiveness Analysis An Ontario Case Study. *Transportation Research Record*: 1866. 9–19.

9. Fujiwara, E., Kaito, K., Kobayashi, K., Okizuka, R. (2009).Durability Analysis of Pothole Patching Mixture in Snowy Cold Region. Osaka University, Kyoto University, Obayashi Road Corp, Kyoto, Japan.

10. D. Yang, J. Xie, K. Zhang, Z. Liu, A. Wang, W. Wang. (2009). Numerical Simulation of Stress Field in Inclusions of Large Rudder Arm Steel Castings, *China Foundry*, 6, (3), 219 - 225.

11. T. L. Anderson, (2005). *Fracture Mechanics, Fundamentals and Applications*, Boca Raton, FL: CRC Press.

12. M. L. Williams. (1952). Stress Singularities Resulting from Various Boundary Conditions in Angular Corners of Plates in Extension, *Journal of Applied Mechanics*, 19, (4), 526-528.

13. M. D. Nazzal, S. Kim, A. R. Abbas. (2014). Evaluation of Winter Pothole Patching Methods, Ohio Department of Transportation Report FHWA/OH-2014/2, Cincinnati, OH.

14. AASHTO. (2007). Standard Method of Test for Determining the Creep Compliance and Strength of Hot-Mix Asphalt (HMA) Using the Indirect Tension Test Device: T322-07., AASHTO, Washington, DC.

15. AASHTO. (2013). Standard Method of Test for Determining the Fracture Energy of Asphalt Mixtures Using the Semicircular Bend Geometry (SCB): TP 105-13, AASHTO, Washington, DC.

16. Turgeon, C. (2016). *MNDOT Pavement Preservation Manual,* St. Paul, MN, MNDOT

17. Uhlmeyer, J., Luhr, D.,Rydhom, T. (2016). Pavement Asset Management, Prepared for Washington Department of Transportation, Seattle, WA.

18. Hajj, E., Loria, L.,Sebaaly, P.E. (2010). Performance Evaluation of Asphalt Pavement Preservation Activities. Transportation Research Record: 2150, 36–46. DOI: 10.3141/2150-05

19. Rahman, M. & Thom, N. (2012). Performance of Asphalt Patch Repairs. The Nottingham Trent University and The University of Nottingham, Nottingham, UK

20. Kaito, K., Kobayashi, K., Fujiwara, E.,Okizuka, R., Durability Analysis of Pothole Patching Mixture in Snowy Cold Region. Osaka University, Kyoto University, Obayashi Road Corp, Kyoto, Japan.

21. Berlin, M., Hunt, E. (2001). Asphalt Concrete Patching Materials Evaluation, Interim Report SR 548. Prepared for Oregon Department of Transportation Research Group, Salem, OR

22. Dailey, J., Dave., E., Barman, M.,Kostick, R.D. (2017). Comprehensive Field Evaluation of Asphalt Patching Methods and Development of Simple Decision Trees and a Best Practices Manual, Research Report, Final Report 2017-23, Prepared for Minnesota Department of Transportation, St. Paul, MN.

23. Biswas, S., Hashemian, L.,Hasanuzzaman, M., Bayat, A. (2015). A Study on Pothole Repair in Canada through Questionnaire Survey 1 and Laboratory Evaluation of Patching Materials *Canadian Journal of Civil Engineering,* 43(5):443-450

24. Rosales-Herrera, V., Prozzi, J.,Prozzi, J.A. (2007). Mixture Design and Performance-Based Specifications for Cold Patching Mixtures. Texas Department of Transportation CTR Technical Report: 0-4872-2, Austin, TX.

25. Dong, Q., Huang, B.,Jia, X. (2014). Long-Term Cost-Effectiveness of Asphalt Pavement Pothole Patching Methods. *Transportation Research Record*: 2431, 49–56. DOI: 10.3141/2431-07

26. Nazzal, M., Kim, S., Abbas, A. (2014) Evaluation of Winter Pothole Patching Methods. Prepared for: The Ohio Department of Transportation, Office of Statewide Planning & Research., Cincinnati, OH

27. Durable Pothole Repairs, (2013). POTHOLE, Project No. 832700, Milestone No. 9 – Life-Cycle Cost-Benefit Analysis, Andreas Hartmann, University of Twente, The Netherlands.

28. Every Day Counts, Pavement Preservation: Implementation Plan, March 2017. U.S Department of Transportation, Federal Highway Administration, Washington, DC.

29. Every Day Counts, Pavement Preservation: When, Where, and How, FHWA-16-CAI-018. U.S Department of Transportation Federal, Highway Administration, Washington, DC.

30. Every Day Counts, Pavement Preservation: How Workbook, FHWA -16 -CAI -012. U.S Department of Transportation, Federal Highway Administration, Washington, DC.–

31. USDOT FHWA, Innovation Spotlight: Pavement Preservation (When, Where, and How). Retrieved from https://www.youtube.com/watch?v=qNXFD6LSoxo&feature=youtu.be, Aug 24, 2017.

APPENDIX A: SURVEY RESULTS OF CURRENT POTHOLE REPAIR PRACTICES IN MINNESOTA

1. Please provide your name, position and email address in the text box below.

Text Response
Steven Lillehaug, City Engineer/Director of Public Works slillehaug@ci.brooklyn-center.mn.us
Dave Halbersma, Pipestone/Lincoln County Engineer, david.halbersma@co.pipestone.mn.us
Dietrich Flesch, Wabasha County Engineer, dflesch@co.wabsaha.mn.us
Barry Underdahl, Street Superintendent bunderdahl@invergroveheights.org
City of Plymouth
Glenn Olson Public Works Director/City Engineer glenn.olson@ci.marshall.mn.us
Adam Edwards aedwards@ci.orono.mn.us Director of Public Works and City Engineer Orono MN
James Kosluchar Public Works Director / City Engineer jim.kosluchar@fridleymn.gov
Joe Triplett Public Works Director | County Engineer Chisago County Public Works
Mike Burns, Infrastructure Maintenance Manager, mburns@rochestermn.gov
Mike Legg, Operations Manager; mlegg@co.carver.mn.us
TJ. Heinricy Street & Park Supervisor City of Northfield
Sam Muntean, Lac Qui Parle County Highway Engineer, sam.muntean@lqpco.com
Chris Link Operations Superintendent clink@cityofrichfield.org
Stephen P. Schneider Nobles County Public Works Director sschnieder@co.nobles.mn.us
John Olson, Public Works Manager, jolson@ci.hutchinson.mn.us

John Brunkhorst, County Engineer john.brunkhorst@co.mcleod.mn.us
Cory Farver Maintenance Supervisor cory.farver@co.washington.mn.us
Wayne Stevens County Engineer wayne.stevens@co.brown.mn.us
Dan Curley Public Works Superintendent dcurley@shoreviewmn.gov
Jona Jacobson, Becker County Highway Maintenance Superintendent jwjacob@co.becker.mn.us
John Schelonka   Maintenance Superintendent johns@co.morrison.mn.us
Michael Flaagan Pennington County Engineer mlflaagan@co.pennington.mn.us
Andrew Sander, Swift County Engineer, andy.sander@co.swift.mn.us
Trudy Elsner, Operations - Road & Bridge Engineer, Trudy.Elsner@hennepin.us
Jeff Stevens - Operations Manager Public Works Division jstevens@stlouispark.org
Rick Hoium Ottertail County Highway Dept - Maint Supv rhoium@co.ottertail.mn.us
Mark Daly, PE Faribault County Engineer/Director of Public Works mark.daly@co.faribault.mn.us

Statistic	Value
Total Responses	28

2. In your area, what are the main mechanisms of pothole formation (check all that apply)?

#	Answer		Response	%

1	Traffic Intensity		16	43%
2	Wearing course condition		26	70%
3	Weather		32	86%
4	Backlog of repairs		14	38%

Statistic	Value
Min Value	1
Max Value	4
Total Responses	37

3. What type of preservation activities do you perform in your area to reduce pothole occurrence (check all that apply)?

#	Answer		Response	%
1	Crack sealing		35	95%
2	Patching		35	95%
3	Fog seals		8	22%

4	Rejuvenation		3	8%
5	Slurry seals		1	3%
6	Microsurfacing		2	5%
7	Cape seals		0	0%
8	Thin or ultrathin hot asphalt overlays		14	38%
9	Chip seals		29	78%
10	Other (please specify)		6	16%

Other (please specify)
spray patching
2" Mill and Overlay
Replay ag. oil seal
Mill and Fill Holes
spray injection patching
spray patching

Statistic	Value

Min Value	1
Max Value	10
Total Responses	37

4. What triggers pothole repair activities? Please briefly describe how you monitor roads to determine repair needs.

#	Answer		Response	%
1	Pavement conditions as part of pavement management program		24	65%
2	Public complaints		29	78%
3	Other		14	38%
4			12	32%

Other	
	We proactively repair roads on an annual basis at different levels throughout 100% of the City as part of our pavement management program. We have different levels of repair that we perform based on the categorization of the roadway (e.g. next planned programmed improvement, overlay, chip seal, etc.).
	reports, operator route monitoring, superintendent review, engineer review, tech review of overall system

patch continuously as duties allow	A pavement management plan was not put into effect soon enough and the budget is a third of what is necessary to just keep up with the current number of miles of pavement.
	What we have noticed is that the wear course we put down in the early 2000's seems to be a dryer mix with less oil, and now is separating forming holes.
	Regular inspections of the roadways
road patrols	Our maintenance staff does routine road patrols. Occasional public complaint.
	We have our "hot" known areas from pavement conditions and do pothole repairs on an ongoing basis on those streets, other areas are identified by public complaints
	We sweep all the streets 5 - 8 times throughout the summer months. At that time we take notes on what needs patching. We also cover the whole City spot patching in the Spring and then again in the fall.
	We know where are trouble spots are located
	We patch them as they occur. We don't have a constant patching crew.
	We are in constant review of our system be it pavement, signage, downed trees, drainage, authorized or unauthorized work in our R/W. We also get calls if anything new shows up including the public, sheriff's department or any other departments.
Field inspection	We have roving crews patch once in the spring and fall check the streets as a yearly maintenance task to stay on top of pavement.
review by staff	

staff observations	
Observation by PW	
Inspection	
Staff observation	
Part of normal maintenance activity is to have crews mill and patch potholes	
Normal Maintenance	
Periodic inspection	
visual inspection	
Foreman's review	

Statistic	Value
Min Value	1
Max Value	4
Total Responses	37

5. What is the main pothole repair method used in your area?

#	Answer		Response	%
1	Throw and go		7	19%
2	Throw and roll		20	54%

3	Spray injection		1	3%
4	Semi-permanent		3	8%
5	Edge seal		0	0%
6	Permanent		2	5%
7	Other (please specify)		4	11%
	Total		37	100%

Other (please specify)
We perform both throw and roll and permanent, dependent on road
We do 70%, dura patch 10%, 20% mill and patch
Variety depending on conditions, weather & crack.
We Do More Mill/Fill of Holes Now

Statistic	Value
Min Value	1
Max Value	7
Mean	2.76
Variance	3.63

Standard Deviation	1.91
Total Responses	37

6. What materials have you found to be the most successful in pothole repair?

Text Response
see above
Hot mix
hot mix when available
Much of our problems are not potholes but spalling due to age of the asphalt. We use hot sandmix or spray patch using angular trap rock.
hot asphalt mix
Hot Asphalt
Hot mix, polymer blended cold mix
Tack and patch with hot mix and with longitudinal joints dura patching
Hot mix asphalt with a properly prepared hole and good RC tack applied. We have also used high quality cold mix in the winter season, but demoed out the "microwaved" asphalt from Leap last year with positive results.
Hot mix material rolled in compacted.
Hot asphalt mix
Reconstruction with Concrete, no seriously each pothole has its own challenge. If the time permits to clean the pothole and remove any loose material, tack well and patch with hot mix asphalt then the repair holds up fairly well.

Hot asphalt mix
Polymer added hot mix
High oil-content fine mix, UPM fall mix
Hot mix asphalt is best but UPM mix works good for contained holes.
Asphalt, and the Spray Patch
bagged cold mix for small holes, permanent patches for large areas
When we do it right, mill/fill holes and surrounding area with hot mix is the best.
Hot asphalt mix
We throw and go mostly if hot mix sometimes throw and roll, known pothole extensive areas are permanently patched with hot mix or semi-permanently patched with hot mix over the summer based on known planned rehab work in the area.
Hot asphalt mix
The best has been a mix that is produced in the fall made by Harddrives in Isle MN. Keep it stored out of the elements.
We have a pile of cold mix that we heat up during the patching process.
The Cold Patch or 1/2 inch hot mix I like to use the crushed granite.
Hot mix
tack oil applied before using a 1/2" or less mix. Roller a must
Hot Mix
Hot mix

Statistic	Value
Total Responses	29

7. What is the main pothole repair material used in your area?

#	Answer		Response	%
1	Hot asphalt mix		23	64%
2	Generic stockpile mix		6	17%
3	Spray patcher		1	3%
4	Proprietary asphalt mix (please specify)		5	14%
5	Polymeric materials		0	0%
6	Crumb rubber mastic		0	0%
7	Other (please specify)		1	3%
	Total		36	100%

Proprietary asphalt mix (please specify)	Other (please specify)
mesabi bituminous cold mix	Cold mix

Team Lab cold mix	
UPM	
cold patch	
Winter Grade Cold Patch	

Statistic	Value
Min Value	1
Max Value	7
Mean	1.81
Variance	1.93
Standard Deviation	1.39
Total Responses	36

8. Please number the following in order of importance when choosing patching materials, with number 1 being most important and number 5 being the least important.

#	Answer						Total Responses
1	Cost	1	11	14	9	1	36
2	Ease of construction	5	5	10	14	1	35

3	Life span	11	10	6	7	1	35
4	Availability	18	6	7	3	2	36
5	Other (please specify)	2	1	0	0	3	6
	Total	37	33	37	33	8	-

Other (please specify)
Effectiveness
how well it works
Temp and Weather

Statistic	Cost	Ease of construction	Life span	Availability	Other (please specify)
Min Value	1	1	1	1	1
Max Value	5	5	5	5	5
Mean	2.94	3.03	2.34	2.03	3.17
Variance	0.80	1.26	1.47	1.57	4.17
Standard Deviation	0.89	1.12	1.21	1.25	2.04

Total Responses	36	35	35	36	6

9. What is the main mechanism of pothole repair failure in your area?

#	Answer		Response	%
1	Pothole material failure		4	11%
2	Construction issues		4	11%
3	Recurrence of original failure mechanism		21	57%
4	Other (please specify)		8	22%
	Total		37	100%

Other (please specify)
We are not sure of the cause of the failure but something pertaining to a chip seal coat and original pavement incompatibility
Age of asphalt cannot hold itself together
failure of pavement around the repair
we see very little failure

Wear Course Condition
end of life pavement life
Moisture
Improper patching procedures

Statistic	Value
Min Value	1
Max Value	4
Mean	2.89
Variance	0.77
Standard Deviation	0.88
Total Responses	37

10. What is the average life span of a pothole repair in your area?

Text Response
ranges from 1 year to 7 years
3 years
varies

6 mo.
5 years
3-5 years
1-2 years
2-5 years
not sure
1 year
Unknown, really do not track the life span of pothole repairs but we do not have "redevelopment" issues that come to mind.
1-3 years
2
1 to 3 years
3 year
permanent
1 year
Several months
3 years
guessing 4-5 years
Depends on Weather

unknown
UPM-1 YR; MILL/FILL-5+ YR
10 years
it depends upon which technique used to repair the, throw and go in March could be a week, permanent patched hopefully last until rehab or recon
2-5 years
1-5 years
1 to 5 years
10 years
1 to 5 years
3 years with ideal repair conditions
2-5 years
3 months
1-2 years

Statistic	Value
Total Responses	34

11. What is the average cost of patches in your area?

Text Response
unknown
annually? by size of patch?
$248,000 per year
150
$10,000
total ~$10K / yr
$100,000/year, $150/ton placed including labor and equipment
not sure
Depending on the material, Cold mix is costing us $110/ ton, Leap material cost us $150/ ton.
$7k annually
$10 to $20
don't know
Varies
unknown
hard to quantify
varies due to season
$20,000
UNKNOWN

depends on the size of the pothole
we don't track costs on a per pothole or per patch basis
$2.50 s.f.
100,000
100 per ton
varies (winter, spring and summer)
varies
We don't track cost per hole....

Statistic	Value
Total Responses	26

12. If more money were available, in what areas would you like to spend it?

#	Answer		Response	%
1	Research		1	3%
2	Staffing		14	38%
3	Equipment		13	35%
4	Materials		15	41%

5	Other (please specify)		8	22%

Other (please specify)
Need to determine the cause of the premature failure of the pavement and chip seal incompatibility
preventative maintenance
pavement management
Rehabilitation or reconstruction
financing rehabs every 20 years which is the design life for the original bituminous
mill and overlay $$
recondition sooner
Pavement rehabilitation

Statistic	Value
Min Value	1
Max Value	5
Total Responses	37

13. What is your biggest concern regarding potholes in your area, and how would you like to see it addressed?

Text Response
Investment of preventive maintenance strategy (chip seal coat) that seemingly has been detrimental to the life and durability of the pavement.
Deterioration of wear course to the point of not being able to keep up with potholes. More construction funding.
avoidance....reconstruct surfaces more timely
Compounding pavement condition issues due to age. Pavement must be replaced at the end of its lifecycle.
More money for materials for patching.
Other road authorities responses to pothole complaints and hazards can be slow.
Larger budget to do better preventative maintenance would reduce pot holes.
Need more funding to do the preventive maintenance such as crack sealing, chip sealing, fog sealing, ect.... This greatly reduces the formation of potholes.
Public Safety
Having to overlay a road sooner than expected due to surfacing failure from multiple potholes
no issues
Pavement age leads to deterioration at joints that leads to pot holes. Adequate funding to keep up pavement surface would keep potholes from forming.
The need to match available staff, equipment & materials resources with work needs. Too much dependence upon contracted repairs.
Pothole repair is typically labor intensive and expensive. Figure out something to help with that.

Winter season Cold mix is not the best. Would like to be able to access Hot Mix in the winter season. If more plants would be open in the winter patching would last longer and be more cost effective.
More funding for construction so wear course condition would not get in such poor condition.
As in above, if rehabs were financed and completed at the design life of the original pavement we wouldn't have such a hard time with potholes
not potholes per say, but sealcoat delamination
Mastic is the future because it last the longest however very expensive. I see a lot of failures at the seams of the wear course.
Having the proper equipment is the biggest issue for us. We feel that cold mix (plant generated) is the best material to use.
I would do a short term fix and go out and overlay the area for a longer term fix.
Many roads are beyond the expected life; more reconstruction projects rather than short term fixes.
a better product that works in the winter but last through the spring. Current products deteriorate due to spring thaw - water - and break down the patch before hot mix is available.
We have a lot of highways that are over 25 years old. These roads are worn out. Rather than repair them, pavement should be replaced. Additional funds are needed to meet our current needs.

Statistic	Value
Total Responses	24

APPENDIX B: STRESS PLOTS FOR SQUARE AND DIAMOND POTHOLE MODELS USED TO FIND INTERPOLATION EQUATION

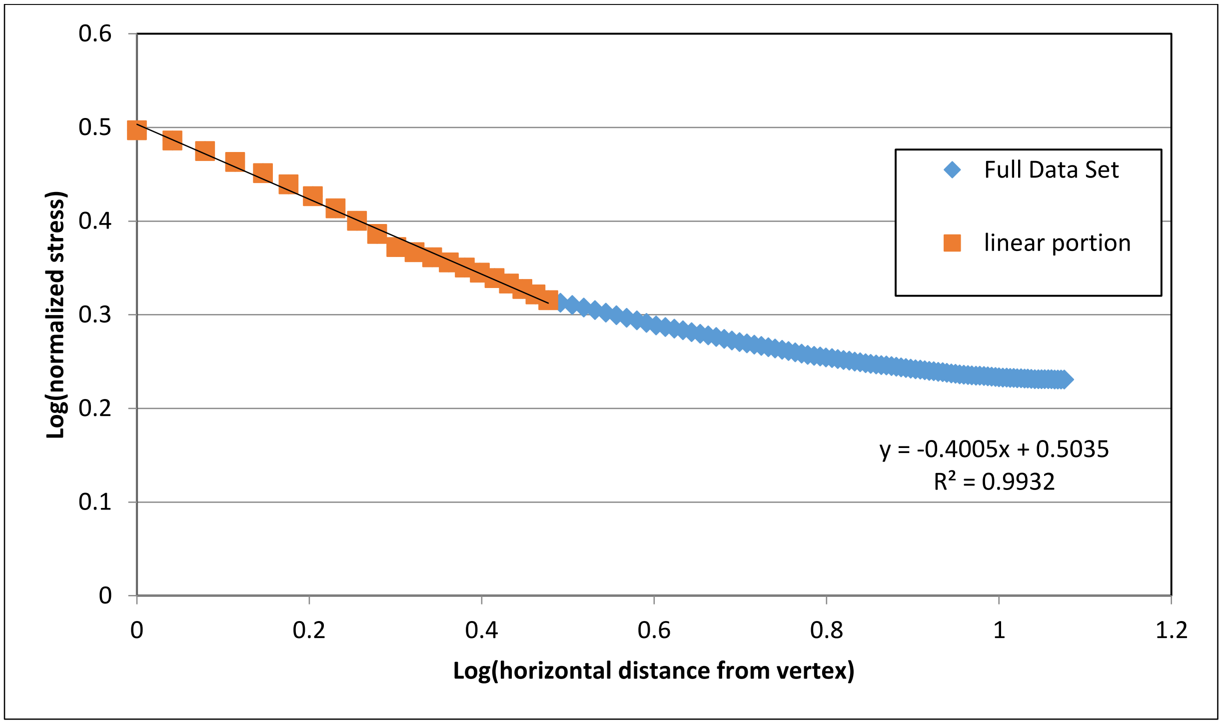

Figure B.1: Log-log stress plot for square pothole model used to find interpolation equation

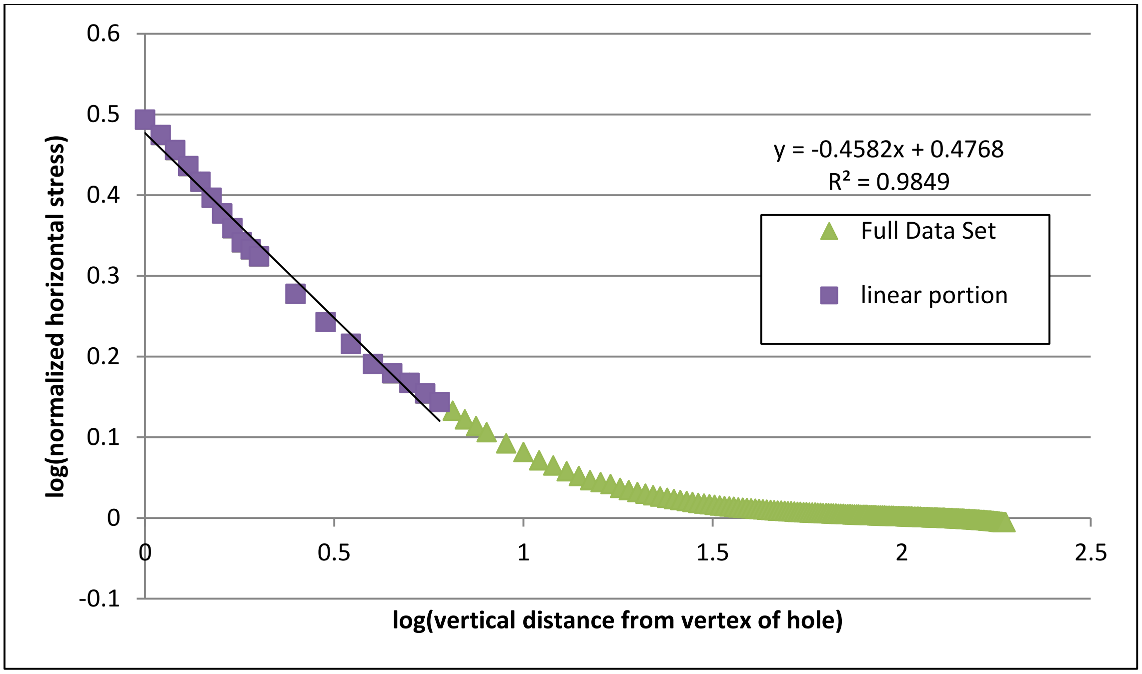

Figure B.2: Log-log stress plot for diamond pothole model used to find interpolation equation