



Evaluate and Develop Innovative Pavement Repair and Patching: Taconite-based Repair Options

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Final Report

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Executive Summary

This project represents one component of a broader effort by MnDOT to evaluate current practices, materials, and policies for pavement patching and repair, for both asphalt and concrete pavements, including evaluation of pothole patching practices, basic pavement maintenance, utility repair methods, and rapid repair materials. In support of this effort—and with the support and cooperation of MnDOT and MnDOT District 1–Natural Resources Research Institute (NRRI) conducted additional evaluation, refinement, field testing, and performance monitoring of two taconite-related approaches to pavement repair that rely on mixes/techniques that contain (or are enhanced by) taconite mining byproducts and co-products.

The first taconite-related approach to pavement repair uses a rigid pavement/pothole repair compound formulation developed and patented by NRRI that is fast-setting, taconite-based, and contains no petroleum or Portland cement. Depending on the formulation, the repair compound can be water-activated or activated by a chemical solution. A water-activated formulation referred to as Rapid Patch utilized by the then-licensee of NRRI's patent—was the focus of the investigation.

The second taconite-related approach to pavement repair employs a high-power (50kW), vehicle-based (truck-mounted) microwave system for in-place pothole/pavement repair/recycling, in which magnetite and/or magnetite-containing aggregate (taconite rock) can enhance microwave absorption and therefore the system's performance.

To evaluate both approaches, the project was divided into three tasks, which are presented chronologically following this extended Executive Summary. Tasks 1 and 2 focused on field installations and testing—conducted in October and November 2012 and March 2013—and follow-up performance monitoring and documentation of the installations through June 30, 2013. Task 3 continued these and other project activities through August 2015, concurrent with the preparation of this final report.

Task 1 output also included an updated and expanded literature and a summary of material acquisition, formula/equipment optimization, laboratory testing, and preliminary field testing. Task 2 activities included: field- and demonstration-ready deployment testing; comparative evaluation of repair materials and methods/heating products, including microwave vs HeatWurx; interim data compilation and analysis; post-repair performance monitoring and documentation; preparation of informational sheets about the two products and their repair procedures; a summary of media coverage; and presentation of preliminary and interim results at two venues: 1) the Transportation Research Board (TRB) Mineral Aggregates Committee (AFP70) meeting on January 15, 2013, at the TRB's 92nd Annual Meeting in Washington, D.C.; and 2) the Center for Transportation Studies Research Conference on May 22, 2013.

While completing Tasks 1 and 2, NRRI also compared the performance of both taconite-based methods to more traditional patching and repair approaches, including newer repair technologies such as the Stepp asphalt recycling machine and the infrared HeatWurx asphalt pavement heating and recycling device. The microwave and HeatWurx comparison showed the microwave system to be much more effective than the HeatWurx unit at heating asphalt pavement to higher

temperatures at a significantly greater depth and in much less time; this differential widens as the starting ambient asphalt pavement temperature decreases. The larger footprint of the HeatWurx unit appears to make it a better-suited device for situations where larger-scale pavement heating is needed, as opposed to doing pothole-sized repairs. Field observations showed that its top-down (infrared) heating is more effective when the starting ambient pavement temperature is well above freezing. Cold temperature (wintertime) applications for the HeatWurx device appear to be more limited, unless sufficiently long heating times are available.

Task 1 and 2 field tests showed that microwave-based pothole repairs could be completed in less than 10 minutes using an asphalt pavement and repair mixture comprised of recycled asphalt pavement (RAP), recycled asphalt shingles (RAS), and a small quantity of magnetite (referred to as the RAP-RAS-Mag mix), with the mixture heated uniformly to $>200^{\circ}\text{F}$ ($\sim 100^{\circ}\text{C}$) to a depth of 3 inches ($\sim 7.5\text{ cm}$) in about 6 to 8 minutes.

Task 1 and 2 testing showed that the Rapid Patch field-mixed compounds could achieve a set time of less than 15 minutes and be drivable in 30 minutes. The compound's formulation can be adjusted to achieve set times that match summer and winter temperature conditions.

From July 1, 2013, through August, 2015, Task 3 project work revisited and built upon Task 1 and Task 2 findings and focused on: 1) continued performance monitoring and documentation of field repairs; 2) updating the literature review; 3) additional microwave technology testing and heating modeling; 4) investigating how the Rapid Patch formulation could be modified to impart "flexibility" (resilience) to the repair; and 5) additional meeting and conference presentations.

Rapid Patch repair compound summary

The rapid repair compound appears to be better suited for rigid and relatively deep repairs, where the surrounding or underlying pavement is Portland cement concrete (PCC). Two installations stand out, performance-wise: 1) The Highway 169 bridge deck near Keewatin, MN. This deep saw-cut repair performed very well for over three years following its November 2010 installation (before the start of this project); and 2) a utility repair made around a steel manhole cover at 64th Avenue West and Grand Avenue (Highway 23) in Duluth, during the project's October 31, 2012, field trial. While cracked, the repair was still largely intact as of August 26, 2015. The compound has also shown fair to moderately good performance in transverse joint repairs made in a PCC segment of TH 61 northeast of Duluth, relative to repairs made with the Stepp Asphalt Recycler in 2012 and 2014 repairs made with the taconite compound and UPM.

Because of its demonstrated positive performance in a variety of applications (current and previous), this compound will be further refined and developed by NRRI. For example, in addition to further evaluating the potential of imparting resilience (flexural) properties to the compound through the addition of fibers and/or other additives, NRRI is working to simplify the formulation (making it a two-part system instead of three-part), adjust its component gradation, and to automate (mechanize) its deployment to minimize or avoid entirely hand-mixing and hand installation by maintenance crews. The investigator also sees its potential as a higher-volume "foundation filler," to be placed before installing thinner overlying applications of more

expensive flexible repair materials such as mastic, thereby reducing the quantity and cost of using such materials.

Microwave-based repair summary

The project's sub-freezing field trials showed microwave-based repair to be the least temperature-dependent of the two taconite-based repair options, and of most pavement repair options in general. Whereas the Rapid Patch compound appears best-suited for rigid repairs in PCC pavements under cool to moderate ambient temperature conditions, the microwave repair approach is best-suited for repairing potholes in hot mix asphalt (HMA) pavements at all ambient temperatures, including very cold. Modeling indicates that microwave repair of asphalt pavement at a temperature of 0° F (-17.7° C) would take only about 25% (about 2 minutes) longer than microwave repairs made when the asphalt pavement temperature is 40° F (4.4° C). The modeling results are in good agreement with what was measured during project field trials, where individual repairs took about 10 minutes to complete.

Because the microwave equipment heats the existing pavement to the point that the pavement itself becomes part of the repair, an excellent bond is achieved. In the investigator's opinion, it is this microwave-induced thermal bond between the repair and the surrounding pavement **that** makes the technology superior to most other methods for repairing potholes in HMA pavements, especially wintertime repairs. Importantly, the project also demonstrated that an effective microwave pothole repair compound can be made almost entirely from inexpensive and abundant recycled materials such as recycled asphalt pavement (RAP) and shingles (RAS), as opposed to cold and hot mix repair compounds that rely on specialized asphalt formulations, virgin asphalt, and/or binders.

Conclusions

The two repair alternatives evaluated during this project merit further development and consideration, as the field performance of both suggests they have long-term potential for more widespread use. Based on feedback from maintenance personnel who used and/or observed both repair alternatives during the project, both alternatives would benefit from operational modifications that would reduce the deployment time required to complete a repair and increase the number of repairs that can be accomplished during a single shift. Doing so would lead to greater acceptance and more widespread use of both.

Maintenance crews and engineers continue to stress the need for more effective and more efficient (mechanized/automated) pavement repair and maintenance solutions. The ideal repair would be a repair that lasts at least a year, can be performed in all seasons, and can be installed easily and relatively quickly—all while keeping traffic delays to a minimum. At this point in time, no single repair method achieves this ideal. However, the two alternatives studied during this project represent potentially important steps in that direction, and at a minimum represent additions to the "tool-kit" of maintenance and repair options that can be applied to pothole and other pavement failures and distresses.

Chapter 1

Introduction

The project represents one part of a broader effort by MnDOT to evaluate current practices, materials, and policies for pavement patching and repair, for both asphalt and concrete pavements, including evaluation of pothole patching practices, basic pavement maintenance, utility repair methods, and rapid repair materials.

Conventional pavement and pothole repair compounds often perform inadequately, especially in cold temperature situations (late fall, winter, and early spring), and/or require extended set-times (hours) before being drivable. As a consequence, poor repair performance contributes to vehicle damage and higher labor costs (via repeated repairs), while extended set-times lead to traffic delays and associated costs due to lost time, slowed commerce, etc. Likewise, alternative asphalt pavement repair/recycling technologies (examples: HeatWurx; Python Manufacturing) which rely on surface-downward infrared/radiant heating to achieve adequate asphalt pavement softening can take a considerable amount of time in cold wintertime temperatures.

The pavement and pothole repair shortcomings just described have led the NRRI to pursue two alternative approaches (both taconite-related) during the past several years; both are the focus of this project:

- The first approach is a prototype pavement/pothole repair compound formulation developed by NRRI that is fast-setting, taconite-based, and contains no petroleum or portland cement. The formulation can be water activated or activated by a chemical solution. NRRI testing has shown that the field-mixed compounds can achieve a set time of less than 15 minutes and be drivable in 30 minutes. Project objectives include: 1) confirming and documenting performance in the field, especially in sub-freezing and/or wet installation conditions; and 2) investigating the potential for developing a “flexible” compound that may be better-suited for hot mix asphalt (HMA) pavements.
- The second approach involves the use of a vehicle-based microwave heating system for in-place pothole/pavement repair/recycling, a system for which taconite materials can enhance microwave heating efficiency. Research initiated by David M. Hopstock, PhD, and carried out collaboratively by Hopstock and NRRI—beginning in 2003—suggested that microwave-absorbing taconite aggregate materials, when combined with portable microwave technology, could be an effective solution to cold-weather pothole repair. Project objectives include conducting further research and field-scale demonstrations that follow-up on the findings of an OPERA-supported project by Zanko and Hopstock (2011), “Taconite-Enhanced Pothole Repair Using Portable Microwave Technology.” <http://www.mnltap.umn.edu/about/programs/opera/annual/2011/projects/documents/2009-01.pdf>

These repair options have the potential to: 1) save municipal, county, and state maintenance departments thousands of dollars in labor costs annually; 2) reduce traffic disruption otherwise caused by frequent repair of repeatedly-failing patches; and 3) add efficiency and longevity to repairs.

To meet the overall goals of the project, the focus through June 30, 2013, had been to take the following approach relative to both repair methods:

- conduct a literature search/review that could be updated throughout the project;
- further develop and assess – in the laboratory and in field trials – innovative pavement repair options, with an emphasis on the two taconite-related options described above;
- based on consultation with MnDOT District 1 and the project TAP, conduct comparative testing and in-place analysis of a variety of repair methods and materials;
- monitor repair performance following field installation;
- develop preliminary informational sheets about both taconite-based products/repair procedures; and
- respond to and accommodate media interest, and present interim project findings at appropriate venues/conferences.

The remainder of the project (post-July 1, 2013) continued to build upon and update this interim work by focusing on the following:

- work collaboratively with others involved to formulate an overarching patching/sealing solutions effort;
- provide end-users/maintenance departments with a comparative “tool-kit” of repair options from which to choose that deliver superior performance and longevity; and
- develop final informational sheets about the products and repair procedures, and continue to present project findings at one or more venues/conferences.

Project findings are presented by Task and largely chronologically, per the project schedule and work plan. Task 1 findings include: a literature review; a summary of material acquisition; formula/equipment optimization; laboratory testing; and preliminary field testing activities. Task 2 activities and findings, include: descriptions of field- and demonstration-ready deployment testing; comparative testing of multiple repair materials and methods/heating products, including microwave versus HeatWurx; interim data compilation and analysis; post-repair performance monitoring and documentation; preparation of draft informational sheets about the two products and their repair procedures; a summary of media coverage; and descriptions of presentation of preliminary and interim results made at the TRB Mineral Aggregates Committee (AFP70) meeting on January 15, 2013; and the Center for Transportation Studies Research Conference on May 22, 2013. Task 3 largely continues and completes project work begun during Task 2; therefore, Task 3 is included in this final report rather than reported as a stand-alone task.

NOTE: Starting in early 2013 and continuing through late summer of 2015, much of the investigator’s time and attention was diverted from this project to MnDOT’s Highway 53 realignment project. As a result, *this* project’s tasks and reporting schedule were extended accordingly.

Chapter 2

Task 1

Task 1 activities include the following: Updated and expanded literature review; material acquisition; formula/equipment optimization/laboratory testing; preliminary field testing.

Task 1 Deliverables include: Summary/progress report of laboratory test results and preliminary field testing of improved repair formulations and technologies that would be ready for field testing in fall 2012. If possible, the report will include the necessary specification language one would use to purchase/contract for the use of these materials, perhaps following a review by MnDOT Environmental Services.

Literature Search and Review

Introduction

Patching potholes is becoming an increasingly difficult battle. Road maintenance crews are facing the challenge of keeping up aging infrastructure on shorter budgets. In order to make progress in a seemingly unending task, crews need patches/repairs that will retain integrity through several years of service. There are a number of different methods that could potentially fill the need for a long lasting and inexpensive road patch. Blow Patch, Cold Patch (throw and go), Concrete Panel Replacement, Crack sealing, hot mix blow and roll, hot mix wedge paving, infra-red recycling, mill and fill, microwave recycling, poly patching, rapid set and slurry crack sealing are many of the methods that are presently employed to repair the growing number of potholes while staying within the budget available to maintenance departments.

The goal of pothole repair/patching is to mend the road surface in such a manner that it does not need repeat attention and is relatively inexpensive. Ideally, a road surface marred by potholes should undergo full depth reclamation, but as this is quite expensive alternative methods need to be used (Johnson et al., 2009). The traditional method of using “throw and go” cold patch (as illustrated in Figure 2.1) is increasingly perceived as ineffective, and therefore costly.

Aside from the obvious challenges posed by attempting repairs under the wet conditions shown in Figure 2.1, throw and go patches do not bond well to the edges of the hole, and when insufficiently compacted they are left vulnerable to freeze/thaw expansion, raveling, and removal by plow trucks or even merely by traffic. Eighty to ninety percent of “throw and go” cold patches deteriorate in just one year (Skorseth, 2000), and a study by Marcus Berlin (Berlin and Hunt, 2007) found instances of “throw and go” patches that had been replaced *15 times* in a single year. The recurring nature of cold patch repair failures was also confirmed to the investigators during discussions with MnDOT District 1 in the fall of 2012 (Steven Baublitz, pers. comm.). Frequent repairs lead to high costs, especially labor. The cold patch also has a finite shelf life. If the stockpile becomes too warm, the binder will lose its elasticity and will more readily deteriorate when it is placed in a pothole (Skorseth, 2000).



Figure 2.1. “Throw and go” method of pothole repair.

Overview of Repair Methods and Materials

The City of Pittsburgh, PA, provides a good starting point for a review of repair methods and materials. Like many cold climate cities, Pittsburgh relies on hot mix asphalt (HMA) for repairs in the summer months and cold repair (aka Cold Patch) materials in the winter months when conventional hot mix production ceases. For example, the city’s Maintenance Divisions use a cold patch product that goes by the industry name of Poly Pave.

“Cold Patch is made with a Latex Modified Base Asphalt. It is an emergency cold-applied asphalt which is used mainly in the winter months when production of hot mix asphalt is not feasible. It is used for pothole patching only; it cannot be used for paving an entire street. Cold Patch is a pliable material that has enough density to remain in the pothole when applied. In the summer, when exposed to the heat, it forms a solid, permanent patch. Currently, the City of Pittsburgh Asphalt Plant produces over 900 tons of cold patch material a year. This material is used by the Department of Public Works and the Water Department: \$7.00 per square yard.” <http://pittsburghpa.gov/dpw/paving-processes>

This more conventional approach to cold weather pothole repair is repeated by maintenance departments across the northern tier of states.

Unique Paving Materials Corp. of Cleveland, OH, produces a widely-used cold mix repair material, commonly referred to as UPM. The product can be used year-round. The company has also produced a document titled, “How to Create a Performance-Based Specification for High-Performance Permanent Cold Mix” (Koehler, 2012), provided by Kurt Nelson of Unique Paving Materials (pers. comm., 2013). The UPM document also references an FHWA report (Maher et al., 2001), which summarizes the results of research conducted on pothole patching materials and repair procedures.

Beyond this cold patch approach to repairs, there are several road patch materials that are being studied as viable alternatives to conventional throw and go and/or cold patch, including rapid setting compounds that seem promising in providing a fix that is both quick and permanent. There are also several methods of removing the deteriorated portion of roadway and replacing it with pre-cast concrete, as well as methods that look at using different materials packed into the pothole as a means of repairing the pavement.

Anthony Conigliaro and Phil Watson have been investigating using recycled plastics as a pothole patch. They have investigated using a combination of ground up #3-#7 plastics as a remedy to broken pavements. Relying only on the densification properties of the plastic, the mixture is placed in the hole and compacted. Weather does not impact the patch; it does not need sealant and allows for immediate traffic flow. There is no required set time and it is a cold patch, so there is no need for heated containment or other specialized equipment (Conigliaro and Watson, 2000). “Boston’s Best Patch” has yielded favorable results from four Massachusetts municipalities and is currently being employed in several other locations.

Pre-cast concrete slabs can also be used to fix deteriorating road surfaces. The slabs can be poured and cured in a controlled environment then transported to the site. The slab can also be made with reinforcement bar in the wheel tracks, which increases the durability of the patch. This is a more labor-intensive and full-depth means of repairing roads, but it is a permanent fix that requires minimal attention later on. Traffic needs to be diverted as the hole is cut to size to match, and the base may need to be altered to accommodate the additional thickness of the slab. It may take up to eight hours to prepare a hole and place the slab. This method is still more rapid than pouring cement on site, which may need several days to be drivable (Berlin and Hunt, 2007).

NRRI is also looking at using other recycled materials in patching potholes. NRRI has worked with Microwave Utilities, Inc. (MUI) of Monticello, MN, on a pothole patch formulation that uses recycled asphalt shingles (RAS), magnetite-bearing taconite mining byproducts and/or co-products, and recycled asphalt pavement (RAP). The intense microwaves are able to soften the bituminous binder in both the RAP and the asphalt shingles when they are placed in the pothole. The hot mixture can then be packed into the hole. The magnetite-bearing taconite mining byproducts and/or co-products can significantly enhance microwave energy absorption and add strength as an aggregate, and the RAP and shingles provide aggregate and binder (Zanko and Hopstock, 2011). The microwave also heats and softens the surrounding pavement, which increases the bond between the patch and the existing surface (Clyne et al., 2010). This microwave-based patch system does not use virgin binder and utilizes a waste stream as the patch material. It is also one of the two repair methods that are the focus of the current study.

Potholes can also be filled with several rapid setting materials. A recent University of Minnesota Duluth Master's thesis by Dailey (2013), "Enhanced Performance Criteria for Acceptance of Rigid Pavement Patching Materials Used in Cold Climate Regions," identified: 1) several rigid repair products; 2) factors that make for a good (or poor) quality repair; and 3) which laboratory and field tests provide the most useful information about rapid repairs. The primary goal of Dailey's thesis was to develop an enhanced testing regimen for the approval of rapid set cementitious products to be used as patching materials in rigid pavements. The thesis also contains an extensive list of references.

A rapid setting alternative that the NRRI has developed and continues to investigate is a material (referred to as Rapid Patch) that does not use portland cement and is non-bituminous. The formulation is based on taconite mining byproducts and co-products, and it provides a rigid patch that can set in 15 minutes and be drivable in 30 minutes. The patch has been deployed at several Northern Minnesota sites, including both concrete and asphalt applications (e.g., Highway 169 near Keewatin, MN; and Highway 61 between Duluth and Two Harbors, MN), and at the MnROAD research facility operated by the Minnesota Department of Transportation (MnDOT) near Albertville, MN. The patching compound evaluated during the current project, and by Dailey (2013), is a three-part version of NRRI's patented formulation. Following combining the dry taconite components with a powder and liquid activator, the repair compound is placed in the pothole in a thick semi-liquid form and hardens very quickly. It has shown promise in both deep and shallow applications and is one of two repair options that are the focus of the current study (microwave repair being the other).

National Cooperative Highway Research Program (NCHRP) Synthesis 463 "Pavement Patching Practices: A Synthesis of Highway Practice" (2014) summarizes current practices for patching both concrete and asphalt pavements. It was undertaken to document the state of the practice for patching relatively small-scale surface defects in concrete and asphalt pavements. As it states, "The synthesis covers management or administrative issues, materials, methods, equipment, specifications and tests, traffic control, and other aspects of patching operations."

Another method of pothole repair that is gaining popularity across the nation is the use of hot spray injection patching. This method uses specialized equipment to spray a hot RS-2 emulsion into a pothole and a layer of dry aggregate to allow for immediate travel. Figure 2.2 shows a version of a spray patch vehicle ("Roadpatcher") unit owned by St. Louis County, Minnesota. The unit has a hopper that holds coated or uncoated sized aggregate and a tank to hold liquid activator/binder.



Figure 2.2. Spray patch vehicle (left) and coated aggregate used for patching (right).

This method has been found to be quite beneficial in terms of the longevity of the patch and in terms of cost (Maupin and Payne, 2003). Automated spray injection allows maintenance workers to remain inside the work truck and move along at a more rapid pace (Fig. 2.3). Barriers and flagging are not necessary for pothole patching, and it can be done under both hot and cold weather conditions. This method has also been found to be more cost effective, as two major costs to road maintenance are labor and traffic control. The automated system can be operated by a single driver and the indicators on the truck eliminate the need for flagging and barriers (Fowler et al., 2008). The patchwork done by the RA-300 Rosco system also lasts just as long as, if not longer than, conventional throw and go patches.



Figure 2.3. Spray patch vehicle deployed (left); close-up of spray nozzle and patching (right).

Table 2.1 gives a cost comparison of conventional “throw and go” patch (skin patching) to patches performed by the automated hot injection system.

Table 2.1. Cost of Skin Patch compared to spray injected patch (Maupin and Payne, 2003).

Beginning of Year	Skin Patching		Spray Injection	
	Unit cost/yd ²	Present worth/yd ²	Unit cost/yd ²	Present worth/yd ²
1	\$1.95	\$1.95	\$2.31	\$2.31
2	\$1.95	\$1.84	0	0
3	\$1.95	\$1.74	0	0
4	\$1.95	\$1.64	0	0
Total	\$7.80	\$7.17	\$2.31	\$2.31

The system uses compressed air to clean debris out of the hole, then a tack layer to provide better adhesion of the patch to the existing pavement. An asphalt emulsion and aggregate mix is then sprayed in the hole, and it is finished with a layer of dry aggregate to allow cars to pass over immediately. The spraying action of the patch adds enough compression to keep the patch together and bond the patch to the edges of the hole. If the truck is properly maintained and clean aggregate is used, these patches are expected to last four years. One study found that 39.5 tons of patch material was placed at a cost of \$3,950, and the same amount of conventional patch would cost \$4,564 (Maupin and Payne, 2003). There are a growing number of hot spray injection machines in operation due to their cost savings and rapid patching abilities.

A recent Ohio University study (Nazzal et al., 2014) evaluated the performance and cost-effectiveness of a tow-behind combination infrared asphalt heater/reclaimer patching method and compared it to throw and roll and spray injection methods. Figure 2.4 (from Nazzal et al., 2014) shows a combination propane-fueled infrared heater and reclaimer, while Figure 2.5 shows another type of infrared heater and its heating.



Figure 2.4. Tow-behind combination infrared asphalt heater/reclaimer. (Source: Nazzal et al., 2014)



Figure 2.5. Infrared heater (left) and its heating elements (right).
(Source: <http://www.surelineinc.com/asphalt.html>)

The Nazzal et al. (2014) study concluded, “...the infrared method can be more cost-effective than the spray injection method when used for winter pothole patching. For short term repairs, the throw and roll method was found to cost less than the infrared method if the user cost were not considered. However, for permanent repairs, the infrared method can be more cost effective than the throw and roll method. In summary, the tow-behind infrared heater/reclaimer was found to be an efficient and cost effective method for patching certain types of potholes as well as performing other pavement repairs.”

The current project also includes an assessment of an infrared heating system known as HeatWurx. It is discussed in upcoming sections and draws a somewhat different conclusion than Nazzal et al. (2014) regarding efficiency.

There are a growing number of quick patch alternatives as well. These are formulations of activator and aggregate designed to harden within a few minutes. Along with NRRI’s rapid set pothole patch, there are other commercially available products. The following tables (Table 2.2 through Table 2.5) compare several different patching methods as well as commercially available rapid setting compounds.

Table 2.2. Initial Set and Drivable times for different types of patch P.23 (Fowler et al., 2008).

Material	Initial Set Time (Minutes)	Return to traffic	Type
Wabo ElastoPatch	22	1 hr	Elastomeric Polyurethane
Delpatch	60	1 hr	Elastomeric Polyurethane
RSP	6	1 hr	Elastomeric Polyurethane
Fibrescreed	**	15 min - 1 hr	Visco-Elastic Polymer-modified bitumen
FlexKrete	8	1.5 hrs	Semi-Rigid Vinyl Ester
FlexPatch	63	1 - 2 hrs	Semi-Rigid Epoxy
RapidSet	24	1 hr	Rigid Hydraulic Cement
EucoSpeed	17	1 hr	Rigid Magnesium Phosphate
Pavemend	13	1.5 hrs	Rigid Magnesium Phosphate
MG Krete	?	?	Rigid Magnesium Phosphate

** Not chemically activated, temperature controlled

Table 2.3. The war against potholes (Oregon Department of Transportation (ODOT), 2002).

Product Name	Manufacturer	Binder Type
Bond-X	Seaboard Asphalt Products	Cutback
Elasti-Patch	Koch Materials	Cutback
HFSM-2SP/HFE-300S (control) ¹	Albina Asphalt	Emulsion
Instant Road Repair	International Roadway Research	N/A
King Patch	Pacific Asphalt Marketing	Natural Tar Sands
Optimix Cold Patch	Optimix	Cutback
Perma Patch	National Paving & Contracting	Cutback
QPR (formerly QPR 2000) ²	Quality Pavement Repair	Cutback
Tag 8000	Infratech Polymer	Emulsion
UPM High-Performance ³	Unique Paving Materials	Cutback

¹ Polypatch is the little used brand by Albina for this product.

² Currently being used by Bend and Lakeview ODOT maintenance crews.

³ Currently being used by Salem and Portland ODOT maintenance crews.

Table 2.4. The war against potholes (ODOT, 2002).*

Product	Number of Patches	1 month evaluation	6 month evaluation	12 month evaluation	24 month evaluation
Bond-X	4	Good	Fair	Fair	Poor
Elasti-Patch	5	Good	Fair	Fair	Fair
HFMS-2SP	14	Good	Fair	Fair	Fair
Instant Road Repair	10	Fair	Fair	Fair	Fair
King Patch	1	Poor	Poor	Overlaid	Overlaid
Optimix	1	Good	Fair	No report	No report
Perma Patch	8	Fair	Fair	Fair	Fair
QPR (formerly QPR 2000)	6	Good	Good	Fair	Fair
Tag 8000	4	Good	Good	Fair	Fair
UPM	7	Good	Fair	Fair	Fair

***NOTE:**

Good: Patch remained relatively flush with surrounding pavement and showed little sign of distress.

Fair: Patch showed sign of minor distress and little crowning or dishing.

Poor: Patch showed sign of significant distress or failed to remain in place.

Table 2.5. Cost of patch (Berlin and Hunt, 2007).

Material	Mix, Cost/ton	Binder, Cost/ton
Perma Patch	\$75?	
Instant Road Repair	\$350 (in buckets)	
Tag 8000	\$152-186	
Elasti-Patch		\$550
Bond-X	\$55	\$370
QPR 2000	\$38 (mixed at maintenance yard)	
UPM	\$55 - 68	
Optimix	\$55	
HFMS-2SP	\$55 - 68	\$325
HFMS-2S		\$249
Hot Mix	\$30	

An August 2015 discussion with MnDOT materials and maintenance engineers indicated that the price of one type of mastic product is approximately \$0.70 per pound. Crafcoc, Inc. is a supplier.

The following is a partial list of repair options and related contact information assembled during this project:

Albina Asphalt
TAG 8000
Infratech Polymer
Roger Johnson
#4 – 19747 Telegraph Trail
Langley, BC U3A 4P8
800-567-4888
604-888-8191 Fax
604-290-4320 Cell
www.albina.com

Bond-X
Seaboard Asphalt Products
Shawn Campbell
3601 Fairfield Rd.
Baltimore, MD 21226
800-536-0332 410-355-0330
410-355-0330 Fax
[sales@seaboardasphalt.com]

Crafco, Inc.
420 N. Roosevelt Ave.
Chandler AZ 85226
800-528-8242
602- 276-0406
480- 961-0513 Fax
www.crafco.com

Elastic-Patch
Koch Materials
Steve Vandebogart
Spokane, WA
509-487-4560 ext. 11
509-995-1924 Cell

HFMS-2SP/HFE-300S
John Gunter
3246 NE Broadway
Portland OR 97232
503-281-1161
503-362-6180 Fax
503-329-6104 Cell
800-888-5048

Instant Road Repair
Safety Lights Co.
Jeff Parson
2324 SE Umatilla
Portland, OR 97202
503-235-8531

Optimix Cold Patch
Jeff Axel
555 Broad Hollow Rd., Ste 216
Melville, NY 11747
516-293-6300
516-593-6317 Fax
Optimix, Inc. [optmx@erols.com]

Perma Patch
National Paving and Contracting
Robert Storrs
4200 Menlo Dr.
Baltimore, MD 21215
410-764-7117
410-764-7137 Fax
www.permapatch.net

QPR 2000
Quality Pavement Repair
Tony Fagnoli
800-388-4338
716-924-2116

UPM High-Performance
Unique Paving Materials
Jeff Bucell
3993 East 93rd St.
Cleveland, Ohio 44105
800-441-4880
216-441-0148 Fax

UPM
Porter W Yett Co.
Steve Yet
Portland, OR
503-282-3251

US Pro-Tec Inc.
23611-101 Chargin Blvd.
Beachwood, OH 44122
800-263-7511

Conclusion

This literature search and product review has identified several pothole repair options. The review process also showed there are a number of factors that go into choosing which pothole patch will be most suited to a particular situation. If a road is going to have a full depth reclamation in the near future, a patch need only be temporary; however, if the surrounding road is in reasonably good condition then a patch needs to be more permanent. The traffic volume a road sees, the extent of the damage to the road surface, the surrounding material, the safety of the maintenance crew to work in the location, the weather and the type of traffic that a road see; these are all things to consider when patching potholes. The goal is to have a versatile means of patching potholes that is inexpensive and simple to use.

Material Acquisition

All test materials needed for the project were largely in-hand at NRRI prior to the project's August 2012 official start date. These materials included: 1) sufficient quantities of recycled asphalt pavement/millings (RAP), recycled asphalt shingles (RAS), and the magnetite powder needed for conducting microwave-related work; and 2) sufficient quantities of the "Rapid Patch" repair compound's taconite-based components and powder and liquid activator components.

Formula/Equipment Optimization/Laboratory Testing

Important collateral work was conducted by NRRI prior to the August 2012 project start date for both the microwave and Rapid Patch repair options. This preparatory work allowed the project to hit the ground running with respect to field trial testing anticipated for the fall of 2012; brief descriptions follow.

Microwave

NRRI traveled to Monticello, MN, on July 24, 2012, to meet with representatives from Microwave Utilities, Inc. (MUI), observe their patching technique, view MUI's equipment, and discuss options for anticipated field demonstrations and potential longitudinal crack heating.

Microwave Utilities, Inc. (MUI) is a company that specializes in ground thawing using a patented microwave system capable of thawing frozen ground to a depth of six feet in just 60 minutes (pers. comm., Microwave Utilities, 2012). NRRI and Microwave Utilities have been collaborating to test pothole patching compounds that utilize the microwave-absorbing properties of the iron mineral magnetite. Magnetite is contained in iron ore (aka "taconite" ore) rock mined and processed on Minnesota's Mesabi Iron Range, and has the ability to readily adsorb microwaves and heat very quickly (Fig. 2.6).

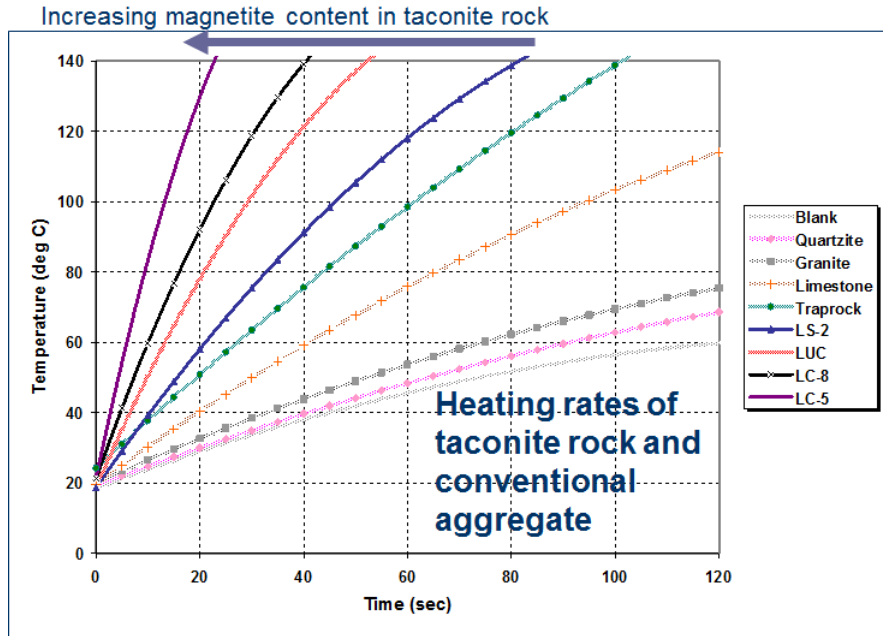


Figure 2.6. Microwave heating rates of taconite rock and conventional aggregate (Zanko and Hopstock, 2004).

By combining magnetite-containing aggregate and/or magnetite alone with recycled asphalt pavement (RAP), heating of the mixture and the contained asphalt binder is enhanced. This type of patching compound is placed in a pothole and is microwaved until the contained binder softens to a point where it is compactible. The microwave energy will also heat and soften the adjacent asphalt pavement, contributing further to a good repair bond. The addition of granular recycled asphalt shingles (RAS) can provide additional binder to the compound.

There are several benefits to patching potholes with this system. Due to the in-place heating mechanism, moisture will be driven off and the patch will more readily adhere to the surrounding pavement. Patch material can be premixed and stockpiled or can be mixed on site, and transportation of hot material is not necessary. This patching system is also ideal for cold weather situations.

An equipment demonstration was performed on an intact portion of pavement, using MUI's (at the time) latest equipment design (Figs. 2.7 and 2.8). With the microwave set at 50kW, the pavement was heated from 80° F to 200° F in just seven minutes. Two inches below the surface, the pavement reached temperatures over 300° F. The pavement was pliable and easily removed with a shovel (Fig. 2.9).



Figure 2.7. Microwave unit with articulating arm.



Figure 2.8. Microwave horn and shielding.



Figure 2.9. Microwave-heated pavement, easily removed with shovel (surface at 200° F).

Rapid Patch

With respect to the taconite-based Rapid Patch repair compound, NRRI conducted pre-project formulation modification into the summer of 2012, in response to a request by (at the time) the licensee of NRRI's patent. The repair compound is made without portland cement and also incorporates byproduct and co-product materials generated by Minnesota's iron ore (taconite) mining industry. The modified formulation is made up of two primary components: 1) a blend of taconite fine aggregate (tailings) and magnetite concentrate; and 2) a powdered inorganic activator, plus a liquid activator. Several laboratory tests were conducted on variations of the mix to evaluate its characteristics as well as help predict the performance of the mix when used in the field. Both initial set time and unconfined compressive strength were tested under standard laboratory conditions.

Similar procedures were followed in the production of the mix variations. The magnetite and tailings (the iron containing ingredients) were dried and allowed to reach equilibrium moisture in the laboratory (0.3% moisture on a wet weight basis); they were then measured to within +/- 0.1 gram of accuracy and combined. The powdered ingredients within the mix, known as the "white" ingredients, were weighed to within +/- 0.1 gram of accuracy, combined and set aside until ready to do the mixing.

Once ready to begin the mixing, the liquid was added to the white ingredients and the clock was started. The liquid and "white" ingredients were then vigorously stirred using an electric drill and paint paddle (Fig. 2.10) for one minute. The water-add activator had a tendency to bubble upon

mixing. By pre-mixing the white ingredients and the liquid, some of the bubbling would subside; the activator would be more uniform, and less air would be entrained in the mix. The taconite component was then added to the compound and continuously stirred for an additional minute.



Figure 2.10. Drill, paddle, and mixing bucket used for Rapid Patch lab test work.

Two minutes elapsed from the time the liquid was added until the mixing was completed. Previous testing conducted by NRRI indicated that the amount of time spent mixing had a significant impact on the final strength of the mix, due to the bubbling of the activator. After stirring, the mixture would either be placed in a Humboldt Vicat apparatus to conduct the initial set time test or it would be poured into prepared molds to cure for the unconfined compressive strength test.

The initial set time test was performed by making a batch of pothole mix, using the standard mixing procedure (described previously). Once the mix was prepared, it was poured into a wide, shallow cylinder made from a 3in. (I.D.) x 50mm section of PVC pipe which had been given a light coat of mineral oil. The mix was leveled off and the needle of the Humboldt Vicat apparatus (Fig. 2.11) was lowered so that the end of the needle met the top surface of the mix. Every sixty seconds, the weighted needle was released and allowed to sink into the mix for ten seconds. When the needle penetration depth became less than 25mm, the initial set had occurred. Following the initial set, this procedure was continued and the needle penetration depth was recorded until it became zero, at which point the final set had occurred. Each Vicat needle drop location was at least ¼” away from other test locations and ½” away from the edge of the cylinder. The initial set was calculated according to ASTM C191-08.



Figure 2.11. Humboldt Vicat needle used for initial Rapid Patch set time tests.

Batches for the unconfined compressive strength measurements were made similarly, but the mix was poured into 2" (I.D) x 4" molds and allowed to cure in the laboratory for either 24 hours or seven days. The hardened mix was then removed from the mold by the use of compressed air injected into a hole in the bottom of the mold. The cylinders were then weighed (± 0.05 gram accuracy) and their dimensions measured (± 0.0005 in. accuracy). These measurements were used in the calculation of the cured density as well as the pressure exerted on the cylinders at failure in the compression test. The failure pressure was calculated based on the applied load, which was measured by a load cell, and the cross sectional area of the top of the cylinder, which had previously been measured.

The unconfined compressive strength was tested using a load cell attached to a Universal Testing Instrument from Instron Corp (Fig. 2.12). The load cell had a capacity of 20 kip. Rubber caps were placed on the ends of the cylinders to assure uniform loading.



Figure 2.12. Setup of Universal Testing Instrument for performing unconfined compression test.

Based on NRRI's formulation testing, TCC Materials settled on the following final proportions, by weight, for the Rapid Patch road repair product:

- 66.5 lbs. Taconite-based Aggregate/Binder (bag)
- 18.0 lbs. Dry Powder Activator (bag)
- 1 gal. Liquid Activator (plastic jug)

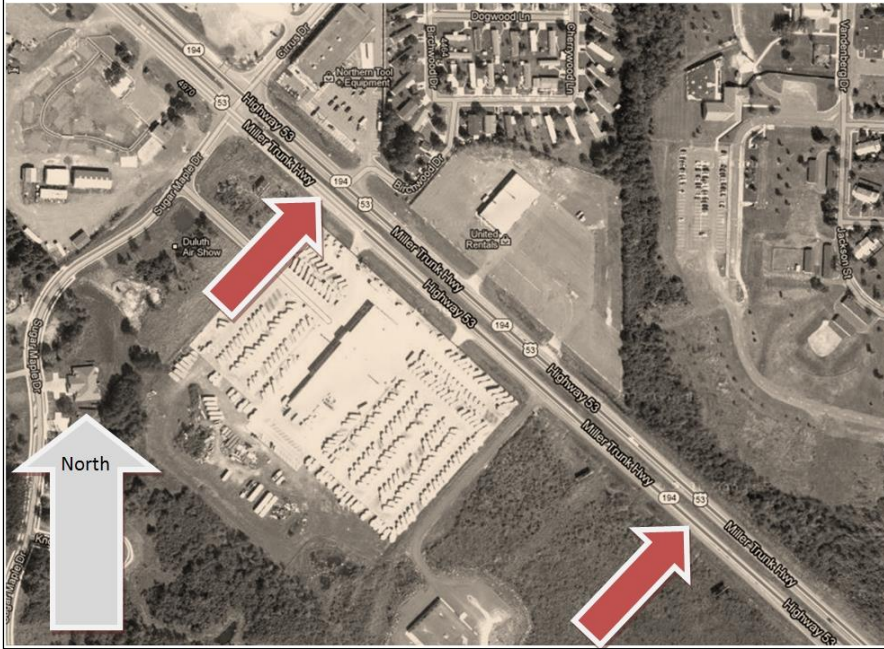
Preliminary Field Testing

Site Selection

A project planning meeting was held with MnDOT at NRRI on October 1, 2012. On October 11, 2012, field- and demonstration-ready deployment testing sites were chosen by NRRI and MnDOT District 1 at two locations: 1) in the southbound lane of Highway 53 (Miller Trunk Highway) across from NRRI and Northern Tool and Equipment (Fig. 2.13; also referred to as the "Bullyan" location); and 2) on Grand Avenue (Highway 23) in West Duluth, between 64th Avenue West and Raleigh Street (Fig. 2.14). The demonstration-ready deployment testing took place on October 30 (Highway 53) and October 31 (Grand Avenue). MnDOT District 1 provided traffic control for both. Test repairs were made via HeatWurx and microwave (October 30), plus with Rapid Patch on October 31. Five patches were completed on Highway 53 using Microwave Utilities, Inc. (MUI) system; two were installed using the MnDOT HeatWurx unit. MnDOT also provided NRRI with cores of pavement from the Highway 53 and Grand Avenue locations.

Microwave Utilities, Inc. (MUI) and David Hopstock, a microwave technology consultant, were contracted for the microwave repair demonstrations. A representative from TCC Materials/Cemstone was present on October 31 to observe the installation of the Rapid Patch repairs.

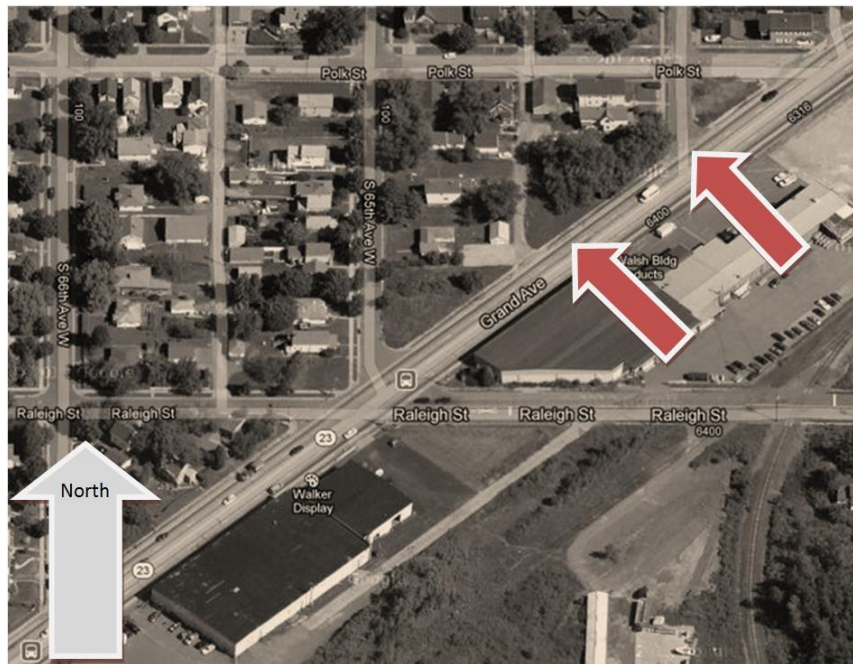
Highway 53 locations, near NRRI



Microwave and
HeatWurx:
October 30, 2012

Figure 2.13. Highway 53 field trial locations near NRRI.

Grand Avenue locations, West Duluth



Microwave,
Rapid Patch, and
HeatWurx:
October 31, 2012

Figure 2.14. Grand Avenue (Highway 23) field trial locations.

These sites were chosen due to the types of repairs required within a close proximity. By having the repairs in close proximity, a fair comparison could be conducted of the different patching techniques.

NRRI and MUI conducted additional microwave repairs (butt-joint reheating and a pothole) at (and across from) MnDOT's Nopeming truck station on Becks/Midway Road, just south of the I-35 exit to Midway Road (St. Louis County 13) (Fig. 2.15). All demonstration repairs were inspected and photo-documented on a near-weekly basis through the end of 2012. More detailed descriptions and illustrations of the condition of the fall 2012 repairs are presented in the Task 2 and Task 3 summaries.



Figure 2.15. November 1, 2012, microwave repair locations (Becks Road/Midway Road Nopeming Truck Station).

Chapter 3

Tasks 2 and 3

NOTE: Because Task 3 is essentially a continuation of Task 2, both are combined in one section. Combining both also provides continuity for the documentation of field performance monitored over the project’s duration.

Task 2 entailed continued formula/equipment optimization and laboratory testing; field- and demonstration-ready deployment testing; comparative testing of multiple repair materials and methods/heating products, including microwave versus HeatWurx; data compilation and analysis; post-repair performance monitoring; and presentation (including materials) at one or more venues such as the TERRA Pavement Conference and/or maintenance expo(s).

Task 2 Deliverables presented on the following pages include: summaries of field demonstrations; measurable/comparable field data collection (modeling); and descriptions of presentations made of project findings at one or more venues. Development of “repair alternatives tool-kit” sheet(s), including a brief technical summary for the taconite-based Rapid Patch that synthesizes Minnesota field uses and assessed/monitored level of performance was another Task 2 goal.

Task 3 represents the post-July 2013 continuation, augmentation, and conclusion of project activities begun during Tasks 1 and 2. Therefore, any work described below that took place between July 1, 2013 and August 31, 2015 represents Task 3 work, which emphasized follow-up performance monitoring and documentation of the condition of installed field repairs. The completion of Task 3, when combined with prior Task 1 and 2 reporting, also represents the completion of the final draft report for the overall project.

Because the completion of Task 3 (and the overall project) was delayed considerably by the investigator’s competing role as NRRI’s project manager and resource modeler on MnDOT’s Highway 53 realignment project during much of 2013 through mid-2015, the delay provided an opportunity to assess the condition and performance of repairs for a significantly longer period of time than originally planned. Pavement repair methods which are long-lasting (perform satisfactorily for a year or longer; ideally permanently) are the goal of maintenance departments everywhere, so the project’s delayed end date allowed for some of the installed test repairs to be followed for more than two years.

Task 2 Field Trials/Demonstrations and Task 2 and Task 3 Follow-up

To a significant degree, Tasks 2 and 3—more so than Task 1—focused on the field demonstrations that took place in fall 2012 and March 2013, particularly as it related to follow-up performance monitoring and comparison/documentation of repair materials and methods/equipment.

Discussions continued between NRRI and MnDOT about conducting cold weather (wintertime) repairs in early 2013. District 1, MnROAD, and/or other Metro area locations were considered.

A decision was made to conduct field testing near the same Highway 53 location (Bullyan) used for the October 30, 2012 tests. Therefore, on March 1, 2013, a second field test of both the microwave and Rapid Patch repair options was performed on Highway 53 across from NRRI in Duluth (Fig. 3.1), at the intersection of Cirrus Drive and Highway 53 (blue arrow; Location 1) and to the southeast near the Monaco Air sign (Location 2).

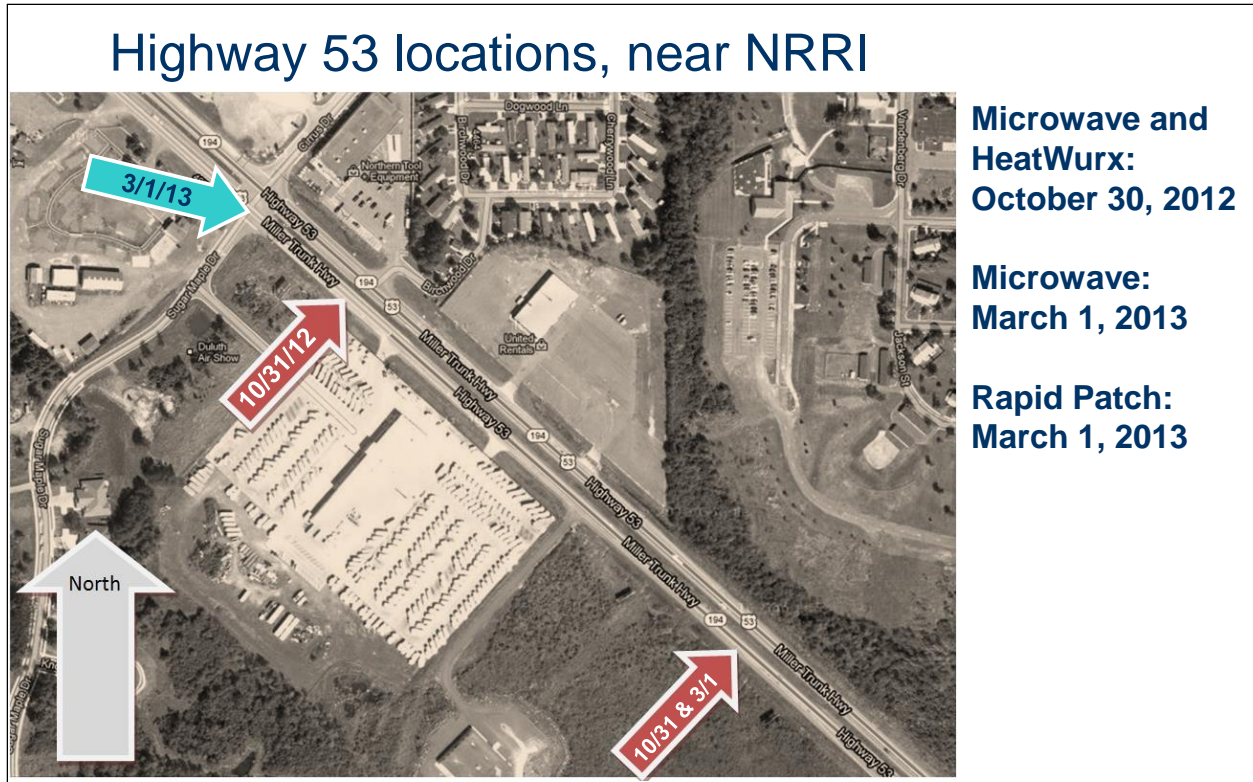


Figure 3.1. Location of March 1, 2013, field trial tests; Highway 53 near NRRI.

The March 1 field test was again coordinated with MnDOT District 1. As with the first (fall 2012) field tests, follow-up monitoring and documentation of the condition of the repairs was conducted. Again, Microwave Utilities, Inc. (MUI) was contracted for the microwave repair demonstrations. A representative from TCC Materials/Cemstone was present on March 1, 2013, to observe the installation of the Rapid Patch repairs.

Aside from NRRI's two taconite-based repair approaches, two other repair methods/equipment were observed and documented: HeatWurx and the Stepp Asphalt Recycler.

HeatWurx

On October 11, 2012, NRRI observed the infrared HeatWurx unit in operation for the first time. The unit was deployed to soften a high spot along a roadway so that it could be leveled and re-compacted. When NRRI arrived, the unit had been operating for about two hours. As Figure 3.2

shows, the unit has a broad footprint and is moved/positioned with a skid-steer. After the pavement is heated, crews can use rakes and shovels (Fig. 3.3) or a rototiller type of attachment (Fig. 3.4) to work/disaggregate the softened pavement prior to its re-compaction. The unit essentially acts as a hot in-place recycler.



Figure 3.2. HeatWurx unit and skid-steer.



Figure 3.3. Raking heated and softened pavement following use of HeatWurx.



Figure 3.4. "Roto-tiller" attachment for HeatWurx.

Importantly, the HeatWurx unit was deployed for the October 30 and 31, 2012, field trials, which allowed a direct comparison to be made between its method of heating (radiant/infrared) and microwave heating (Fig. 3.5).



Figure 3.5. Field trial comparison of microwave (left) and HeatWurx (right): October 30, 2012.

The October 30, 2012, field trial yielded the following comparative results:

- HeatWurx
 - Test 1: After 30 minutes, ~195° F at depth of 0.5 inches. After 2 hours and 4 minutes, a surface temperature close to 400° F was measured (starting pavement temperature ~35° F). After heating, the pavement was “tilled” (Fig. 3.6) and compacted; and
 - Test 2: After 60 minutes, ~180° F at depth of 2.0 inches. Tilled and compacted.



Figure 3.6. HeatWurx post-heating "tilling" of pavement.

- Microwave: 5-7 minutes to heat pavement and patch material to $>200^{\circ}$ F to a depth of 2 to 3 inches; easy to shovel (Fig. 3.7).



Figure 3.7. Working microwave-heated pavement with shovel.

Stepp Asphalt Recycler

The Stepp asphalt recycler (Fig. 3.8) heats granular RAP/asphalt millings on-board to a temperature approaching 350° F (Fig. 3.9) and dispenses the resulting hot mix as-needed. This mobile (trailer) device makes it possible to prepare hot mix asphalt repair materials year around while making use of readily available RAP. Small quantities of asphaltic additives (Fig. 3.10) can be added to each on-board batch of RAP hot mix to improve its binding characteristics, as was done during a February 26, 2013, repair of potholes near the intersection of Highway 53 and Mall Drive across from Walmart in Duluth (Fig. 3.11).



Figure 3.8. Stepp Asphalt Recycler, Grand Avenue (Hwy. 23), Duluth: November 13, 2012.



Figure 3.9. Stepp controls, showing recyler chamber temperature (341° F to 344° F).



Figure 3.10. Asphaltic additives used with Stepp recycler.



Figure 3.11. Stepp repairs Highway 53, Feb. 26, 2013. Note pre-heating of repair with torch (right photo).

On May 17, 2013, the Highway 53/Mall Drive Stepp repair site was revisited. As Figure 3.12 shows, some of the repair was missing, which suggests inadequate bonding.



Figure 3.12. Stepp hot repair condition on May 17, 2013.

The following observations are from the City of Columbus, Ohio, “Pothole Patching Fact Sheet, January 2011”:

“During winter, hot patching is most effective above freezing (32° F). However, hot patch, at 300 degrees F, does not bond well with the dramatically colder pavement in cold winter weather, including cold temperatures above freezing. The hot patch shrinks away from, and does not conform to, the surrounding asphalt and the contours inside the pothole. Because hot patch does not bond well with a cold pothole and pavement, it is like cold patch: a temporary fix.”

In November 2012, MnDOT used the Stepp equipment to repair potholes that formed between deteriorating joints; and transverse cracks along a section of concrete pavement on the Highway 61 expressway between Duluth and Two Harbors (Fig. 3.13). The Highway 61 expressway repairs were conducted to allow for a side-by-side comparison of two repair techniques: 1) the Stepp asphalt recycler; and 2) the Rapid Patch product.

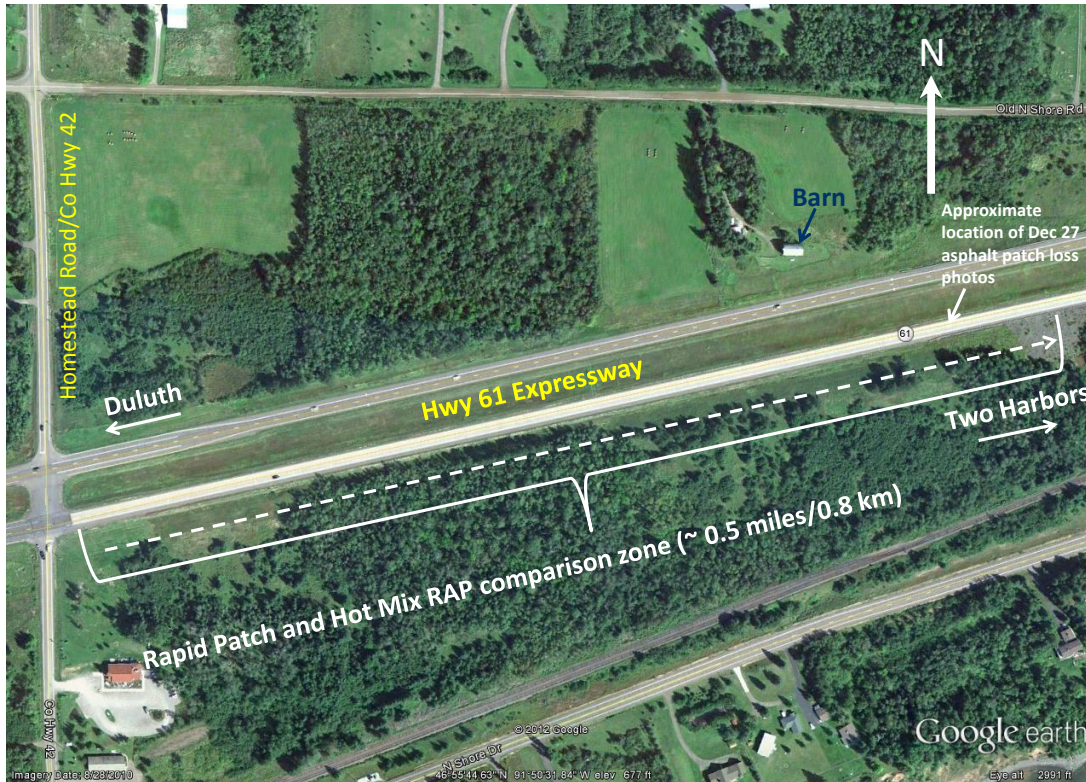


Figure 3.13. Highway 61 expressway repair location.

NRRI performed inspection and documentation of the Highway 61 repairs in November and December 2012. An illustrative/photographic summary of the Highway 61 repair documentation was assembled and provided to members of the project's technical advisory panel in late December 2012. Intermittent follow-up inspection and photo-documentation of the Highway 61 expressway repairs occurred through 2014, and are presented later in the next section (Performance Monitoring).

Performance Monitoring

As weather conditions and personnel availability allowed, repairs conducted during the October 30-November 1, 2012 and March 1, 2013 field trials/demonstrations were inspected and photo-documented on a near-weekly basis through the end of March 2013. Monitoring continued through August 26, 2015 (Tasks 2 and 3), but less frequently. Representative photos are

presented on the following pages to illustrate the repair techniques and the condition of the pavement repairs over time.

Climatological Data

Freeze/thaw cycles influence pothole formation and other pavement distresses. Therefore, climatological (air temperature) data for the entire project period were assembled to illustrate the seasonality and frequency of freezing and thawing in the Duluth area. Figure 3.14 is a histogram plot of the total number of hourly air temperature measurements above (or below) freezing that are either preceded or followed by an hourly air temperature measurement below (or above) freezing, per month. Because these are air temperature and not pavement temperature comparisons, the data likely overstate the frequency of actual freezing and thawing conditions in the pavement, where a pavement’s thermal mass would delay and temper the onset of freezing in the fall and thawing in the spring. On the other hand, a pavement’s capacity to absorb solar radiation on a sunny day can also warm it, at least surficially, above a freezing air temperature. Nonetheless, the data plot is informative because it clearly shows late fall (October and November) and late winter/early spring (March and April) being the most significant freeze/thaw times of the year. The latter period—typically referred to as “pothole season”—no doubt gets a head-start assist from freeze/thaw conditions of the previous fall.

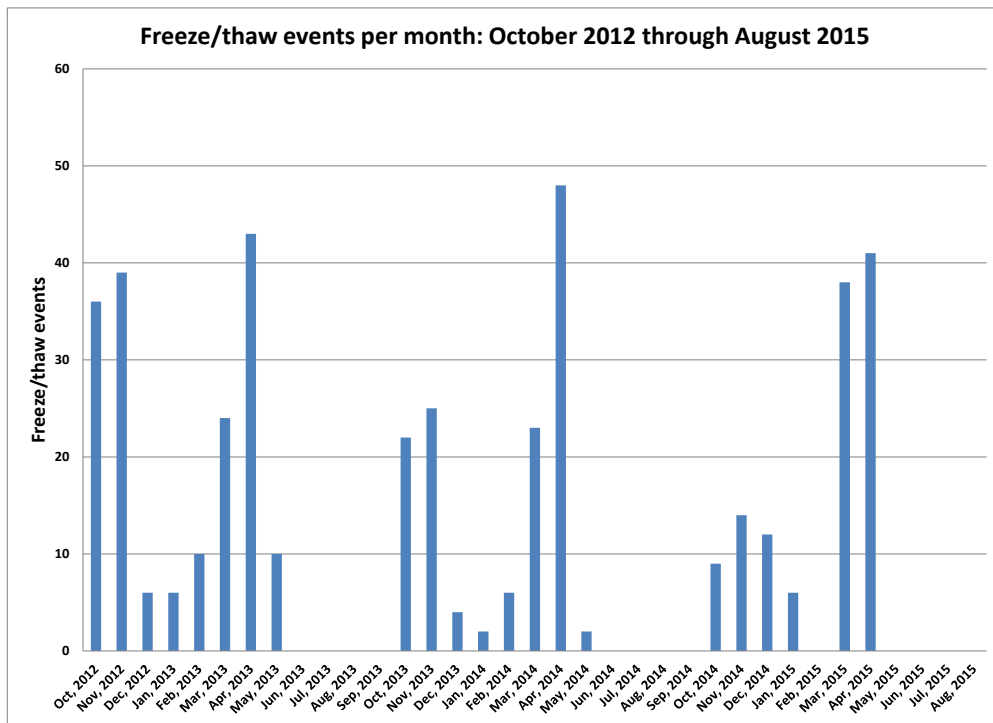


Figure 3.14. Monthly compilation of freeze/thaw events, based on air temperature. Base data source:

http://mesonet.agron.iastate.edu/request/download.phtml?network=MN_ASOS

Repair Materials and Techniques

This project has focused on Rapid Patch and microwave repair materials and methods.

1) Rapid Patch formulation:

66.5 lbs. Taconite-based Aggregate/Binder (bag)
18.0 lbs. Dry Powder Activator (bag)
1 gal. Liquid Activator (plastic jug)

Depending on the ambient temperature, the Rapid Patch compound evaluated during this project can be provided in either a summer or winter formulation (i.e., slower or faster workability/set times, respectively). The summer formulation was used for both the October 30-31, 2012, and the March 1, 2013 field trials/demonstrations.

2) Microwave mixes:

Three types of microwaveable pothole compounds were used at the Highway 53 location on October 30, 2012:

Hole 1: as-is RAP from a Lake County OPERA project (control);
Hole 2: RAP + magnetite powder (about 2.5% by weight); and
Hole 3 and 3-A: RAP + Recycled Asphalt Shingles (RAS)* + magnetite powder (about 2.5% by weight); also referred to as RAP-RAS-Mag.

***NOTE:** Enough RAS was added to result in a mix having an asphalt content (AC) of about 7% (the RAP's original AC was 5.3%; RAS asphalt content estimated at 20%).

Following October 30, the Hole 3 and 3-A mixture was used for remaining project work. It was also determined that the most effective and efficient repair resulted when this mixture was placed in the hole, microwaved for about 6 minutes, and combined (by shovel) with the adjacent heated asphalt pavement; in effect, the existing pavement becomes part of the repair. At this point, the repair can be compacted. However, further field testing and experience showed that adding a small amount of RAS to the heated mixture's surface and microwaving for 2 more minutes prior to compaction, this RAS addition resulted in a repair having a more tightly bound/cohesive surface (less prone to raveling). Lastly, RAP/millings screened to pass 0.5 inch appear to be a better choice than coarser (e.g., 0.75 inch) RAP/millings. Finer RAP screenings will typically have a higher AC.

In addition to the Rapid Patch and microwave repair approaches, HeatWurx and Stepp Asphalt Recycler repairs were also observed and documented.

Selected Repair Performance Examples: Through August 26, 2015

Project repairs were followed for over two years. What follows are selected examples which highlight features and performance of the various methods and materials used.

Example 1: Highway 53 – HeatWurx

Figure 3.15 documents the week-to-week condition of a repair (Location #1; Bullyan) done with the HeatWurx unit during the October 30, 2012, field trials. The repair deteriorated rapidly and was replaced with hot mix in late November 2012. A second nearby HeatWurx repair (Location #2; Monaco Air sign) failed similarly (Figs. 3.16 and 3.17), with the repair de-bonding from the underlying pavement, and also raveling. It, too, was replaced with hot mix by MnDOT in late November.

To be fair, at this point in time the HeatWurx unit was still in its earliest stages of use. Still, the premature failures could be partially attributed to the nature of IR heating itself. Temperature measurements made with a rigid probe indicated that the HeatWurx's surface-downward heating mechanism resulted in a steep temperature differential between the pavement surface (hot) and the deeper underlying pavement (cooler). If the temperature of the surficial asphalt becomes too hot, the overheated asphalt binder can lose some of its binding properties. That is why a "rejuvenator" is part of the HeatWurx process; it is added to impart additional binding capacity to the recycled pavement. However, it is also likely an insufficient amount of "rejuvenator" was added to the heated and milled asphalt prior to the repair's compaction. Another factor that probably played a role was the mechanical "tilling" of the heated pavement (refer back to Fig. 3.6), which also removed not only what was softened but likely incorporated some deeper asphalt that was merely warm and therefore relatively "dry" (binder not softened). Further, the "tilling" action exposed the disaggregated asphalt to the ambient air, which may have accelerated its cooling. Therefore, when all of these contributing factors are considered and the disaggregated asphalt was recombined and re-compacted, the asphalt probably lacked the cohesive properties it needed for producing a durable and lasting repair.



Figure 3.15. HeatWurx repair #1 (Bullyan location), showing progressive loss of material.



Figure 3.16. HeatWurx repair #2, Highway 53 (Monaco Air sign) location, October 30, 2012.



Figure 3.17. HeatWurx repair #2, Highway 53 (Monaco Air sign) location: failing condition on November 13, 2012.

Example 2: Highway 53 – Microwave and Rapid Patch Repairs

Figures 3.18 through 3.27 compare the condition of microwave repairs installed on October 30, 2012, and microwave and Rapid Patch repairs installed on March 1, 2013, through May 17, 2013.

October 30, 2012 microwave repairs - Bullyan Location

As described previously, NRRI chose a microwavable repair compound comprised of:

RAP + + Recycled Asphalt Shingles (RAS) + magnetite powder (about 2.5% by weight).

Enough RAS was added to result in a mix having an asphalt content (AC) of about 7%. Therefore, to every 50 lbs. of RAP (AC of 5.3%), about 12.5 lbs. of RAS (estimated AC of 20%) were added.

The condition of the selected October 30, 2012, microwave repair (noted as Hole 3) is shown in the following sequence of photos, from its installation on October 30, 2012, through May 17, 2013 (Fig. 3.18). The aforementioned repair compound was placed in the hole (slightly overfilled to accommodate compaction); heated with MUI's microwave for 6 minutes at 50kW; shoveled, raked, and combined with the softened adjacent pavement; and compacted. The temperature of the pre-compacted mixture was noted to average 105° C (220° F). As Figure 3.18 shows, the repair held up well following installation, exhibiting a minor amount of surface loss (raveling).



Figure 3.18. Highway 53 microwave pothole (Hole 3) repair; note the 12 inch ruler for scale in the November 6 photo.

Figure 3.19 shows the repair's condition on July 30, 2013. While continuing to exhibit minor raveling, it generally remained a sound repair. The surrounding pavement, however, continued to deteriorate, which led MnDOT to mill-and-fill this section of Highway 53—including this repair.



Figure 3.19. Highway 53 microwave pothole (Hole 3) repair condition on July 30, 2013.

Two other microwave repairs were performed on October 30, 2013 (Holes 1 and 2). Hole 1 used as-is RAP (no magnetite nor RAS). Later that day, the center of the repair was replaced with a patching material that MUI had brought to Duluth and was interested in testing. Hole 2 was a small pothole repair along a transverse crack; RAP + magnetite only (no RAS) was used. It was heated for four minutes at 50kW power and compacted. This repair attained a temperature of about 80° C to 105° C (180° F to 220° F). Figure 3.20 compares the condition of both repairs, within one week of installation (November 6, 2012) and two months later (January 7, 2013). As Figure 3.20 shows, the center of the Hole 1 repair (the MUI test patch portion) lost material with time, while the as-is RAP remained relatively intact. The Hole 2 repair remained intact until it was also removed by the fall 2013 mill-and-fill repairs described previously.

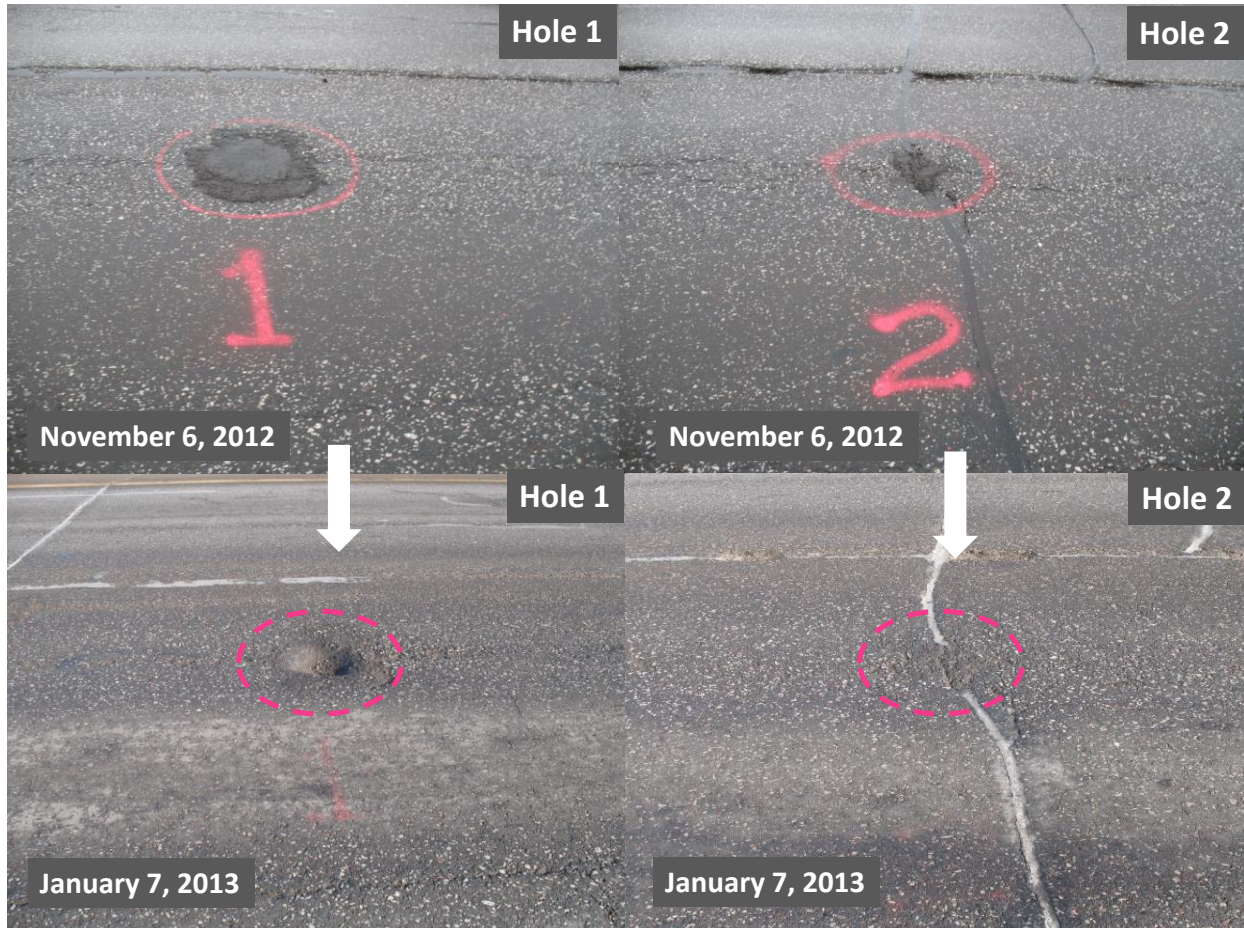


Figure 3.20. Highway 53 microwave pothole repairs (Holes 1 and 2): November 6, 2012 condition (top); and January 7, 2013 condition (bottom).

The test material MUI brought to Duluth for the October 2012 field trials exhibited similar loss/degradation when used in test repairs on Grand Avenue on October 31. Based on those results, MUI reformulated their microwaveable compound, and tested the new formulation during the March 1, 2013, field trial in Duluth.

March 1, 2013 Rapid Patch and microwave repairs (Location 1: Cirrus Drive and Hwy 53)

This second project field trial/demonstration in Duluth was truly an opportunity to conduct cold-temperature repair tests (Fig. 3.21). Again, MnDOT District 1 personnel provided traffic control and prepared the pavement and potholes for repair. A representative from TCC Materials (Rapid Patch) was present, and Microwave Utilities, Inc. (MUI) provided the microwave equipment and operators.



Figure 3.21. Temperature conditions (17° F; -8° C) and pavement preparation for March 1, 2013, field trial/demonstration.

The Rapid Patch repairs were installed at two locations along Highway 53 in Duluth: 1) near the traffic lights at the intersection of Cirrus Drive and Highway 53 (Fig. 3.22); and 2) about a quarter mile to the southeast, at the same location of the October 30, 2012, HeatWurx #2 repair (next to the Monaco Air sign). Microwave repairs were also made at the Monaco Air sign location.



Figure 3.22. Location of first March 1, 2013, Rapid Patch repair; Highway 53, Duluth (NRRI building in background).

Figure 3.23 summarizes the Rapid Patch repair preparation and installation performed at the Cirrus Drive/Highway 53 intersection location on March 1, 2013.



Figure 3.23. Rapid Patch preparation and repairs at Cirrus Drive/Highway 53 intersection location, March 1, 2013.

As described previously, the Rapid Patch compound can be provided in either a summer or winter formulation (i.e., longer workability and slower set time in the summer, or quicker workability and faster set times in the winter). Unfortunately, the summer formulation was used during the March 1, 2013 installation and took much longer to set up than it did in the fall, despite the exothermic reaction that occurs when the compound is mixed. As the tire tread imprints in the March 4 photo of Figure 3.24 indicate, the compound remained soft at its surface more than an hour after installation. Still, it had firmed sufficiently to resist serious deformation. Given that the ambient temperature was -8 C° (17° F), this outcome showed that a winter formulation would have been the better choice for the cold conditions. Figure 3.24 also documents the condition of the Rapid Patch Cirrus Drive/Highway 53 repair over time. Note that most of the repair was missing from the smaller of the pothole repairs by May 17, 2013, while the other larger repair remained intact.

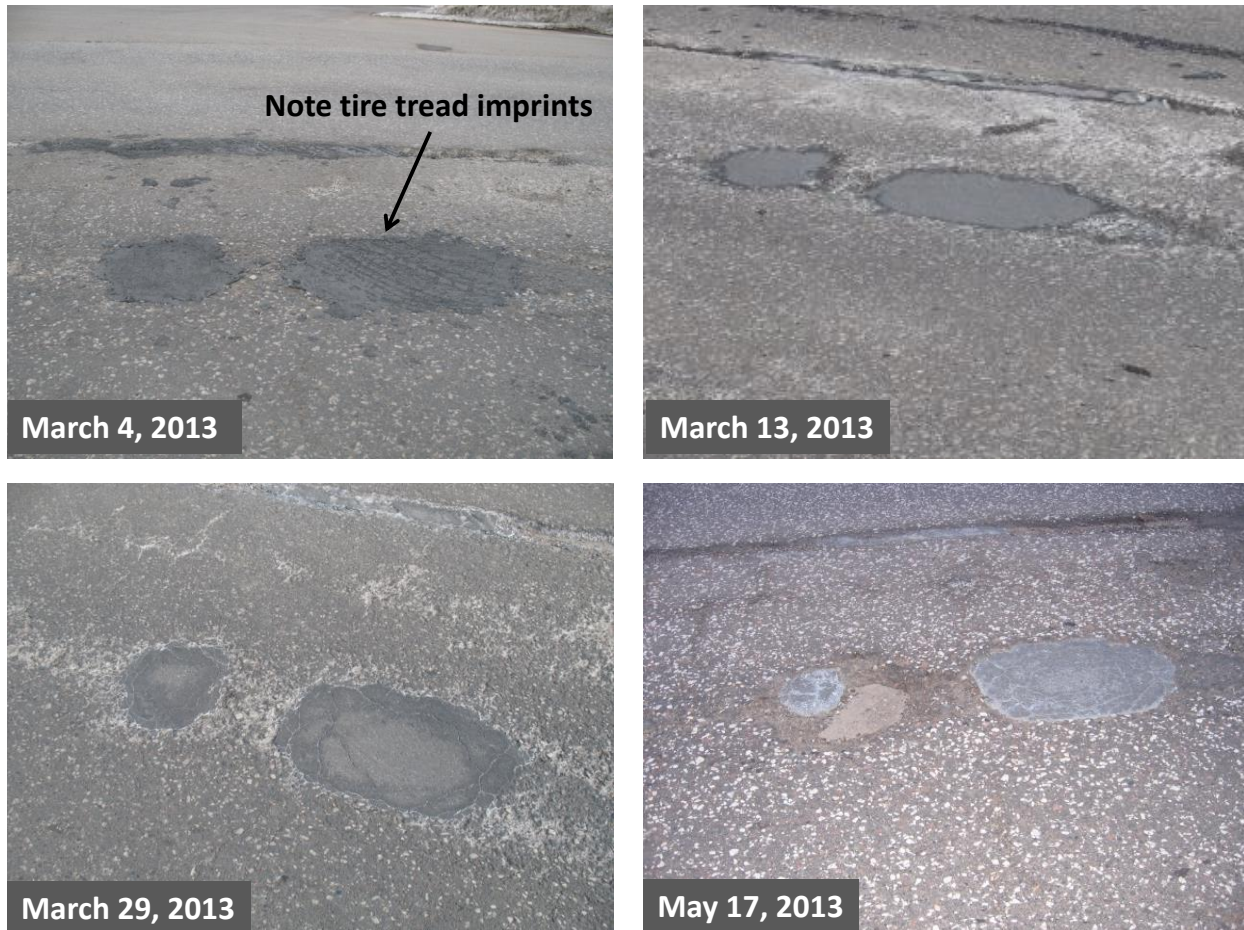


Figure 3.24. Documentation of condition of the Rapid Patch Cirrus Drive/Highway 53 repair over time (March 4 through May 17, 2013).

Figure 3.25 shows the repair's condition on July 2, 2013, compared to its condition shortly after installation (March 4). By July 2, most of the material placed in the longitudinal crack was missing, while most of the larger "tread-imprinted" repair remained intact. Figure 3.26 shows the repair as of July 30, 2013. Despite its cracked appearance, the repair stayed in place. Later in 2013 a mill-and-fill was performed to repair the longitudinal and wheel-path cracking prevalent along this stretch of Highway 53, and the repairs at this location—as they were at the Bullyan HeatWurx and microwave repair location—were paved over (Fig. 3.27).



Figure 3.25. Condition of Hwy 53/Cirrus Drive Rapid Patch repair on March 4 and July 2, 2013.



Figure 3.26. Condition of Hwy 53/Cirrus Drive Rapid Patch repair on July 30, 2013.



Figure 3.27. Mill-and-fill of Hwy 53/Cirrus Drive repair location.

In summary, the Rapid Patch repairs at this location had mixed performance, either failing relatively quickly or lasting through the summer. As Figure 3.23 (A) and the May 17 photo in Figure 3.24 show, the larger hole had: 1) steeper/deeper edges than that of the smaller hole (whose edges were more tapered and therefore shallower); and 2) a greater base-of-hole surface area relative to the hole's overall footprint; together, this may have provided a better bonding surface for the Rapid Patch compound and contributed to its relative longevity.

March 1, 2013 Rapid Patch and microwave repairs (Location 2: Monaco Air sign and Hwy 53)

Figure 3.28 shows the pre-repair condition of target potholes, and notes where each repair was to be placed. Note also: 1) the large rectangular patch to the right of the notation, "NRRI compound" in Figure 3.28; it was a hot-mix repair installed in late November 2012 that replaced the original October 30, 2012, HeatWurx repair; and 2) the two patches to the immediate right of both MUI arrows; they are an epoxy product previously placed by MnDOT at this location.

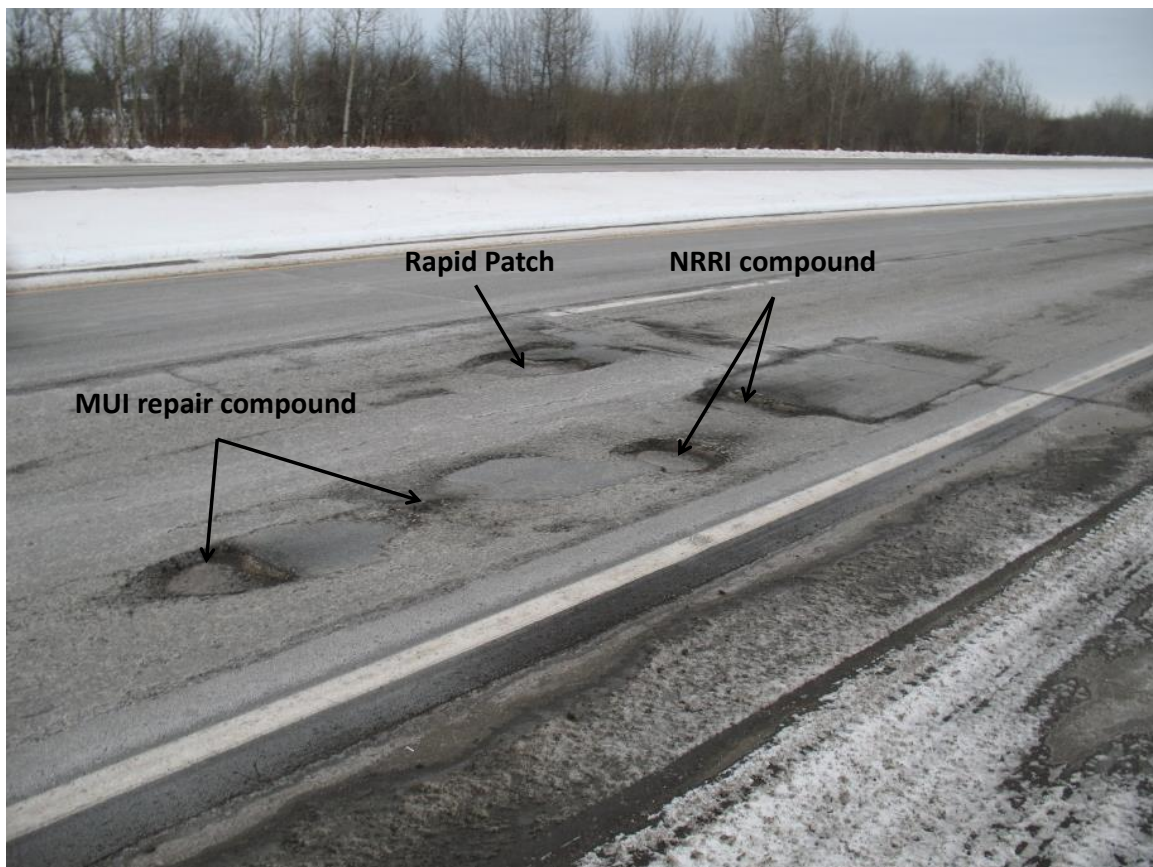


Figure 3.28. Highway 53 Monaco Air sign location for March 1, 2013 field trial; target holes prior to patching.

At this second March 1 repair location on Highway 53 (near the Monaco Air sign), a Rapid Patch repair and four microwave repairs (two using MUI's repair compound formulation, and two using NRRI's RAP + RAS + magnetite mixture) were performed side-by-side. Figure 3.29 shows MUI's microwave unit being positioned (upper photo) and heating (lower photo), as indicated by the steam rising from the microwave horn. To overcome the cold conditions and accelerate the set time of the summer-formulated Rapid Patch repair, its pothole (directly behind the microwave horn in the lower photo of Figure 3.29) was briefly pre-heated with MUI's microwave unit. The warmed pavement resulted in a faster Rapid Patch set.



Figure 3.29. Positioning microwave unit (upper photo) and microwave heating (lower photo), Highway 53 Monaco Air sign location: March 1, 2013.

This was an excellent field trial and demonstration location choice for conveniently monitoring a variety of repairs over time. Figure 3.30 begins the documentation of this location's repairs and shows their condition on March 1 and May 17, 2013.

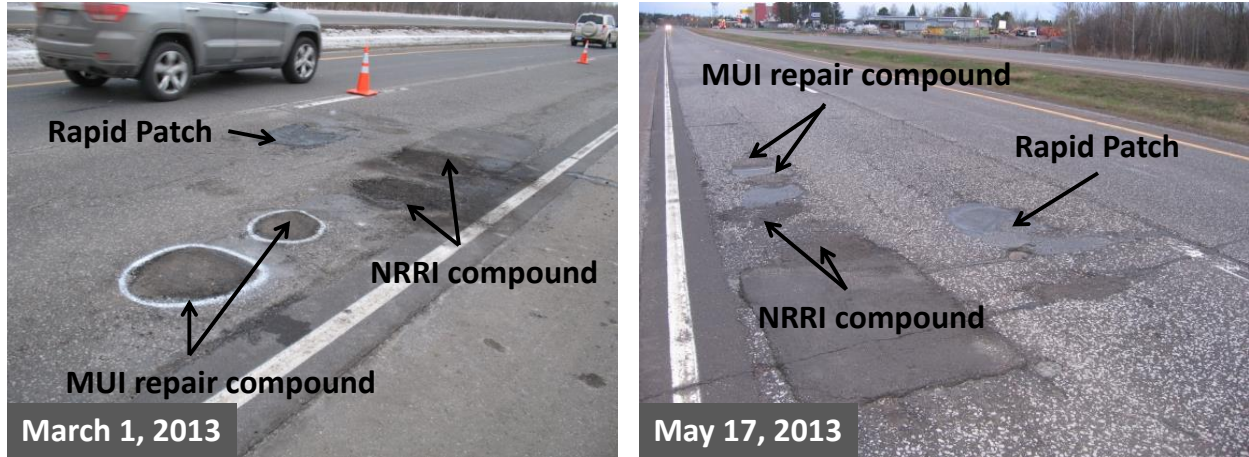


Figure 3.30. Condition of Highway 53 (Monaco Air sign) repairs: March 1 and May 17, 2013.

Figures 3.31 through 3.36 continue and complete the Task 2 and 3 documentation of the condition of the Highway 53 Location 2 (Monaco Air sign) repairs through August 26, 2015. Figure 3.31 (July 30, 2013) show the relative position of the repairs.

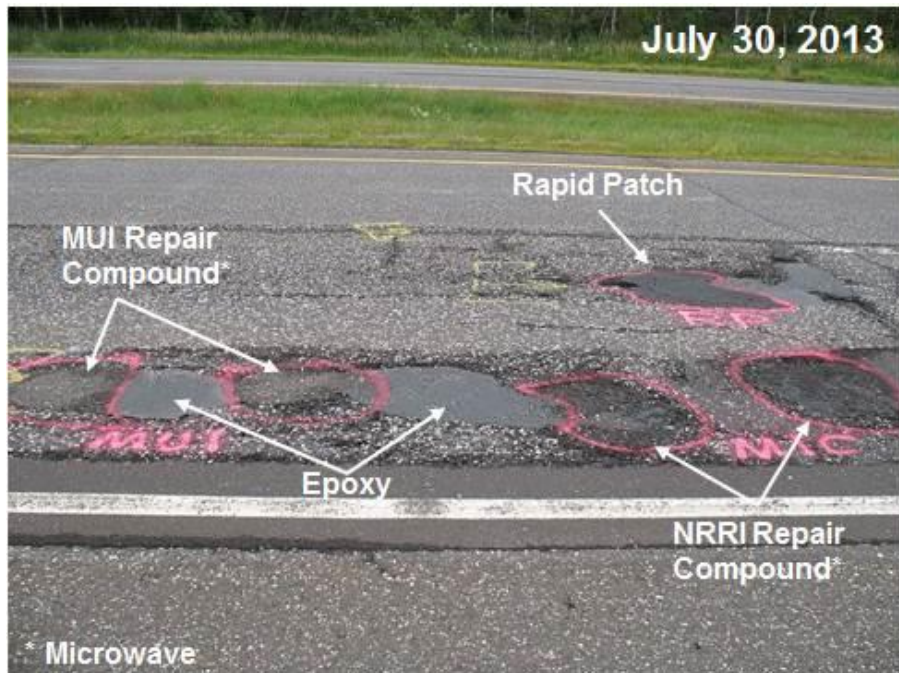


Figure 3.31. Condition of Highway 53 (Monaco Air sign) location repairs: July 30, 2013.

Figure 3.32 shows the condition of the repairs on October 10, 2013, seven months after their installation. The Rapid Patch repair had been (presumably) removed and paved over during an earlier mill-and-fill of the wheel paths.

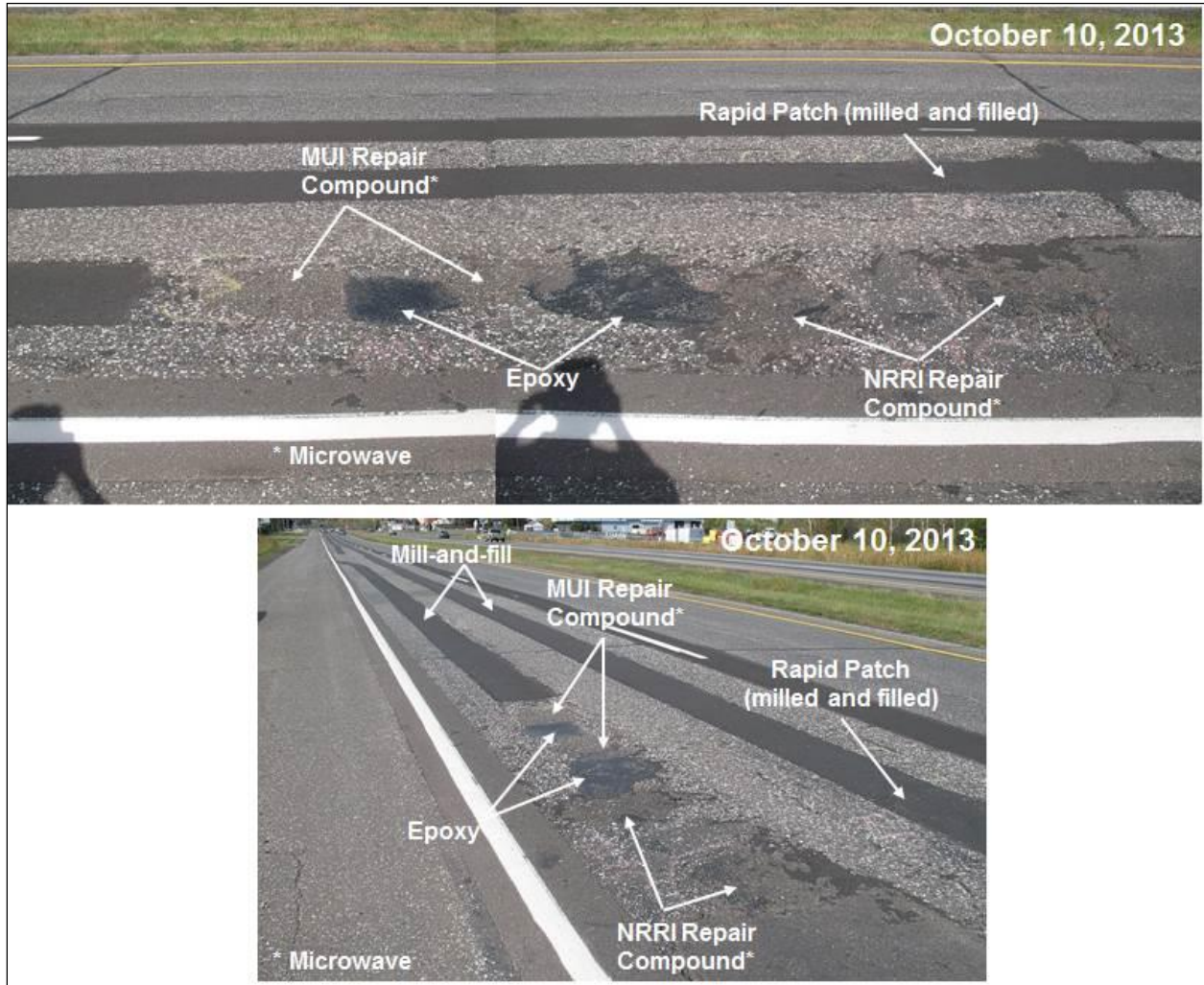


Figure 3.32. Condition of Highway 53 (Monaco Air sign) location repairs: October 10, 2013.

However, Figure 3.33 (February 14, 2014) shows the Rapid Patch repair had only been partially milled out and filled; its hard cementitious properties evidently prevented a full-depth milling and filling to be achieved, with the thin veneer of fill wearing away and exposing the Rapid Patch. Importantly, Figure 3.33 shows that each repair was largely intact nearly one full year after installation.



Figure 3.33. Condition of Highway 53 (Monaco Air sign) location repairs: October 10, 2013 and February 14, 2014.

Figures 3.34, 3.35, and 3.36 complete the photo documentation of the Highway 53 Monaco Air sign location repairs, viewed looking easterly and northwesterly, respectively. The upper photos of Figures 3.34 and 3.35 were taken on December 26, 2014; and the lower photos on August 26, 2015. By December 26, 2014, the pavement surrounding the repairs had deteriorated further, with a large new pothole forming between the fog line and the two epoxy repairs, and two smaller potholes forming on either side of NRRI's RAP-RAS-Mag microwave repair. As the August 26, 2015, photos show, the new pothole nearest the epoxy repairs had been filled in with

an asphaltic repair (UPM?), **but the original March 1, 2013, repairs (and the epoxy repairs) were still largely intact.** Their longevity suggests very good bonding was achieved at the repair and pavement interface, preventing moisture penetration and premature failure.

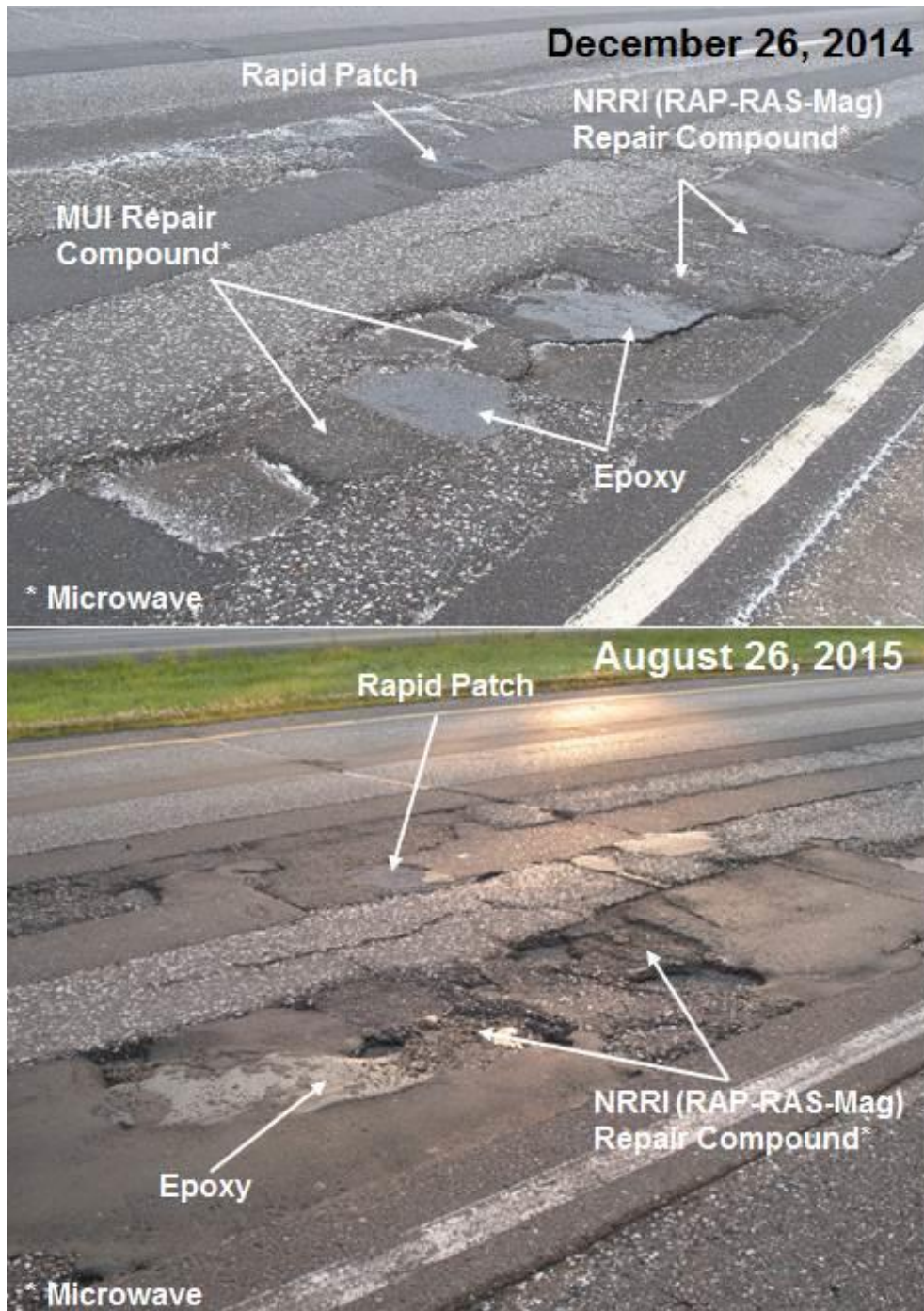


Figure 3.34. Condition of Highway 53 (Monaco Air sign) location repairs, looking easterly: December 26, 2014 (top) and August 26, 2015 (bottom).

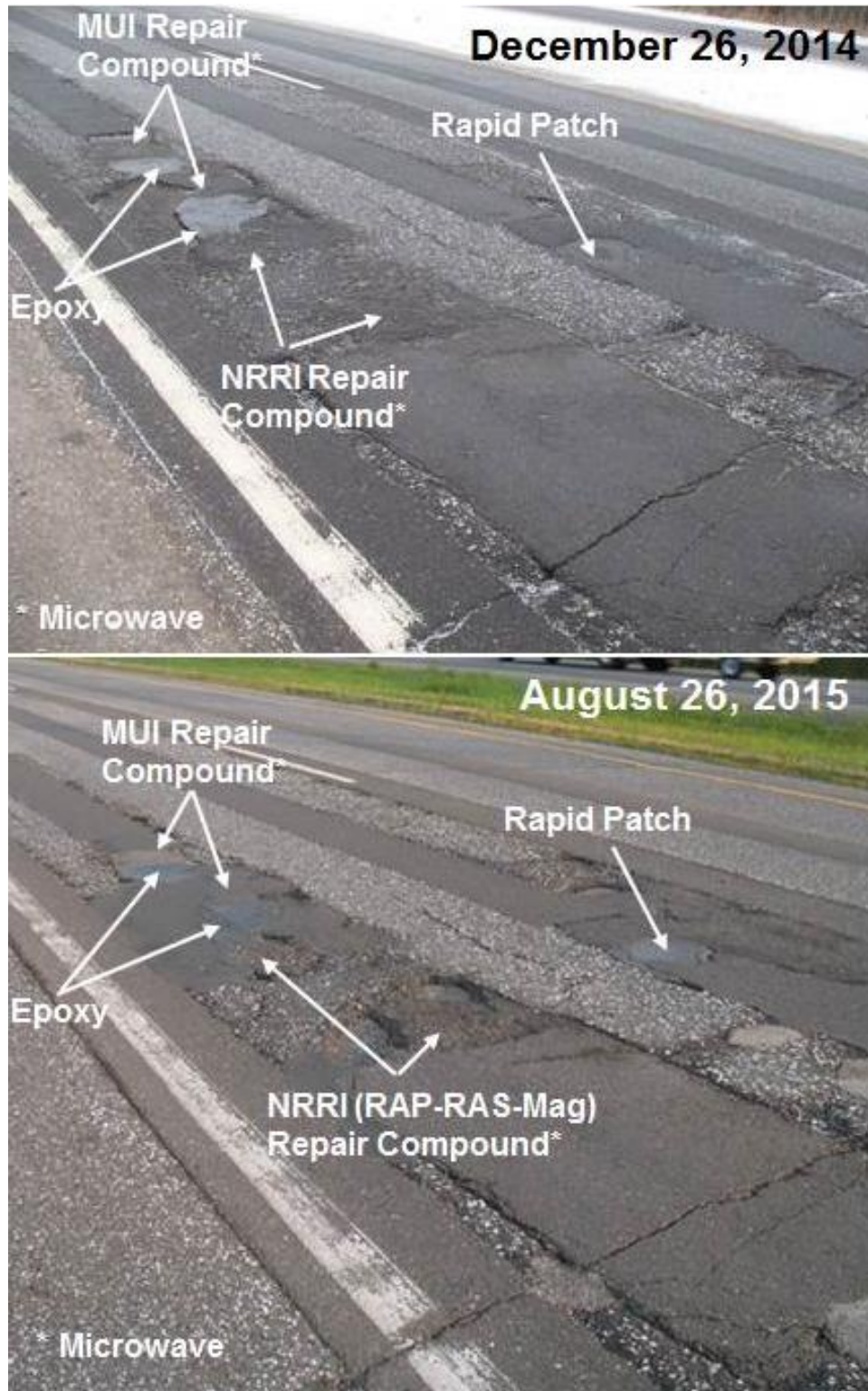


Figure 3.35. Condition of Highway 53 (Monaco Air sign) location repairs, looking northwesterly: December 26, 2014 (top) and August 26, 2015 (bottom).

Lastly, Figure 3.36 is a closer view of the NRRI RAP-RAS-Mag microwave repairs (dashed outlines) and the Rapid Patch repair, with a one-meter measuring stick for scale. Based on their condition 2.5 years after installation, the repairs studied at this location could—at a minimum—be considered semi-permanent.

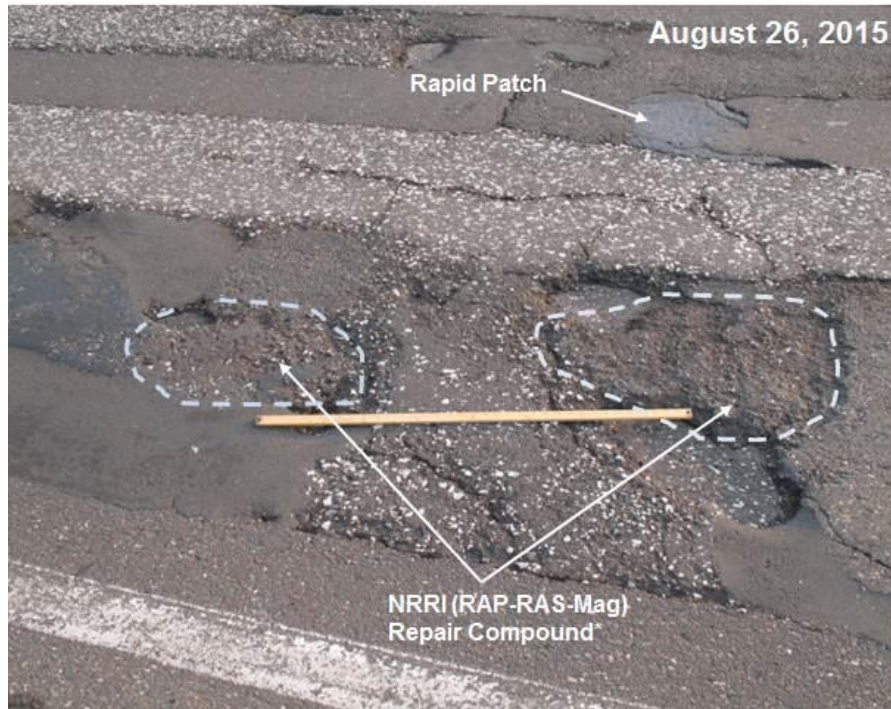


Figure 3.36. Highway 53 (Monaco Air sign) location, NRRI RAP-RAS-Mag microwave repairs (dashed outlines) and the Rapid Patch repair: August 26, 2015.

As of September 29, 2015, this section of Highway 53 had undergone a complete mill-and-overlay rehabilitation (Fig. 3.37). No pothole repairs should be necessary for quite some time.



**Figure 3.37. New mill-and-overlay of Highway 53 at Monaco Air sign field trial location:
September 29, 2015.**

Example 3: Grand Avenue – Rapid Patch repairs (October 31, 2012)

The final example shows Rapid Patch repairs performed on Grand Avenue (Highway 23) in West Duluth, near 64th Avenue West (Fig. 3.38).

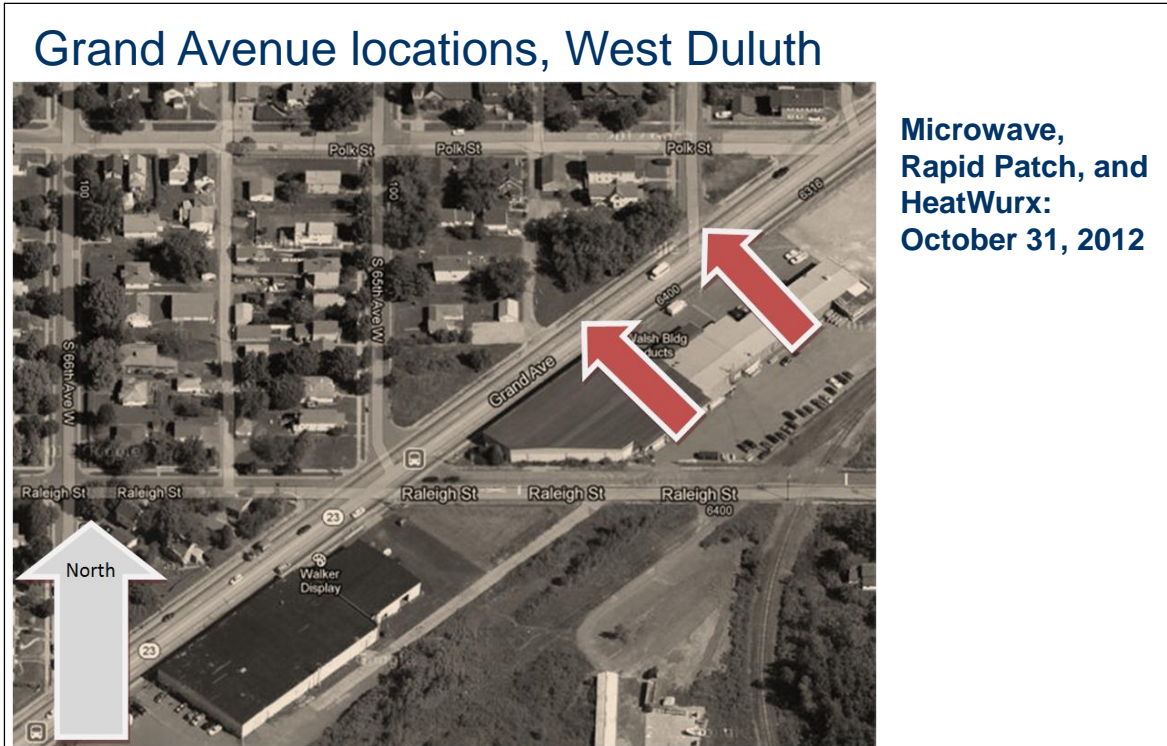


Figure 3.38. Grand Avenue October 31, 2012, field trial locations.

At this location, the asphalt pavement overlies an older concrete pavement. Three repairs were made: 1) around a manhole cover; 2) in the middle of the nearby west-bound driving lane; and 3) at the right-hand lane wheel path edge of Grand Avenue, at the intersection of a longitudinal and transverse crack.

1 –Manhole repair

Potholes often form at the margins of steel manhole covers and other metal utility coverings. The physical difference between asphalt and steel can lead to differential expansion and a poor bond, allowing moisture to penetrate the interface and promoting failure of the asphalt. The rigid nature of the Rapid Patch compound was believed to be a good match for this type of repair, and a major focus of the October 31, 2012, demonstration.

Prior to the repair, MUI’s microwave unit was also tested on top of the manhole cover to evaluate how the microwaves interacted with the steel (Fig. 3.39). The unit straddled the cover and pavement, and was operated at 50kW. After a few minutes of microwave treatment, the manhole cover remained much cooler (100° F to 110° F) than the adjacent asphalt pavement (200° F), showing that the microwave energy was being reflected by the steel. However, the reflected microwaves also caused interference with the incoming microwaves, tripping the unit’s safety mechanism; this required the equipment be shut down and reset.



Figure 3.39. Preparing microwave for manhole repair test: 64th Avenue West and Grand Avenue.

Following microwave treatment, loosened pavement and debris surrounding the manhole was removed, and the Rapid Patch repair was performed (Fig. 3.40).



Figure 3.40. Rapid Patch manhole repair: 64th Avenue West and Grand Avenue.

Figures 3.41 and 3.42 show that aside from some cracking, the repair remained well bonded to the manhole rim and pavement, well into the spring of 2013.



Figure 3.41. Rapid Patch manhole repair: initial set, and condition on January 7, 2013.



Figure 3.42. Rapid Patch manhole repair: Condition on May 5, 2013.

The extended project time allowed for longer-term monitoring and photo-documentation of this repair. Figures 3.43, 3.44, and 3.45 show the condition of the repair on July 30, 2013, December 26, 2014, and August 26, 2015, respectively—a span of over two years.



Figure 3.43. Rapid Patch manhole repair: Condition on July 30, 2013.



Figure 3.44. Rapid Patch manhole repair: Condition on December 26, 2014.



Figure 3.45. Rapid Patch manhole repair: Condition on August 26, 2015.

Note the excavator track in the upper right-hand corner of Figure 3.46. The photo was taken literally minutes before the segment of pavement at the repair location was to be removed, as part of a major rehabilitation of Grand Avenue (Fig. 3.46).



Figure 3.46. Rapid Patch manhole repair prior to removal: August 26, 2015.

While the repair exhibited cracking and some material loss, most of the repair remained in place after nearly 34 months of service.

2 – Driving lane

About 200 feet west of the manhole repair, a Rapid Patch repair was placed in the right hand westbound driving lane. A hole was prepared (created) by heating a cold-patch repair and pavement with MUI’s microwave equipment (Fig. 3.47) and removing the asphalt, exposing the rigid concrete pavement below. The surface temperature of the underlying concrete pavement, as measured with an IR thermometer, was about 110° C (230° F); the edge of the surrounding asphalt pavement ranged from about 80° C to 90° C (~180° F to 200° F). This “hot hole” was filled with the Rapid Patch. The heat accelerated the patch’s set time.



**Figure 3.47. Preparing Grand Avenue Rapid Patch repair with microwave unit:
October 31, 2012.**

The repair was monitored and photo-documented; its condition over time is shown in Figure 3.48. Considering its location (straddling a large transverse crack in pavement in relatively poor condition) and its rigid nature, the Rapid Patch repair remained resilient through the winter of 2012-2013. Figure 3.49 shows the repair to be in good condition on July 30, 2013. By February 14, 2014 (Fig. 3.50), the repair was showing some degradation and material loss, but most of its volume was still in place 16 months after installation. Later in 2014 it was covered by an asphaltic patch.



Figure 3.48. Rapid Patch repair condition over time: Grand Avenue driving lane.



Figure 3.49. Rapid Patch repair condition, Grand Avenue driving lane: July 30, 2013.



Figure 3.50. Rapid Patch repair condition, Grand Avenue driving lane: February 14, 2014.

3 – Right-hand lane wheel path

Three repairs were made at this location (one Rapid Patch and two microwave). As a test, the Rapid Patch repair was microwaved for two minutes at 3kW after it was placed in the hole. After two minutes, its surface temperature ranged from 80° F to 110° F. Figure 3.51 shows the relative positions of the repairs. Note that all three straddled a longitudinal reflective crack. The Rapid Patch (TCC) repair was also intersected by a transverse crack. MUI tested their own microwavable compound, and NRRI used its RAP + RAS + Magnetite mix.

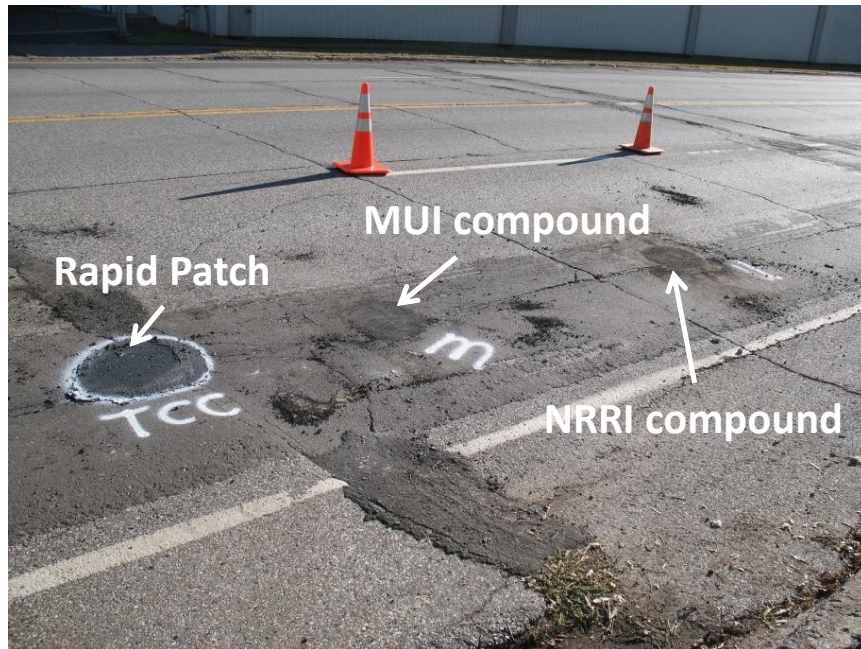


Figure 3.51. Three-hole repair, October 31, 2012, Grand Avenue: TCC Rapid Patch (left); MUI microwave (center); NRRI microwave (right).

Of the three repairs, only the Rapid Patch repair survived past March of 2013. Figure 3.52 shows the condition of the Rapid Patch repair over time (through May 5, 2013), and Figure 3.53 shows its July 30, 2013 condition and position, next to the patches which replaced the two prior microwave repairs. While cracked, the Rapid Patch repair remained largely intact.



Figure 3.52. Rapid Patch repair condition through May 5, 2013; Grand Avenue wheel path.



Figure 3.53. Rapid Patch repair condition on July 30, 2013. Replaced microwave repairs to the right.

MUI's microwavable compound began abrading/raveling shortly after its October 31 placement, as it did in Hole 1 on Highway 53 (described earlier); NRRI's compound retained its integrity longer, but still exhibited abrasion/raveling. Figure 3.54 compares the condition of both repairs on January 7 and February 6, 2013, respectively. The two microwave repairs (MUI and NRRI) were eventually replaced (re-patched) in March of 2013.



Figure 3.54. MUI and NRRI microwave compounds, Grand Avenue repair comparison.

Other Significant Examples

Becks Road/Midway Road Nopeming Truck Station

Two additional (and supplemental) microwave repairs were performed on November 1, 2012, near MnDOT's Becks/Midway Road Nopeming Truck Station (Fig. 3.55). The location was suggested by Peter Eakman of St. Louis County.



Figure 3.55. November 1, 2012, microwave repair locations: Becks Road/Midway Road, Duluth.

Nopeming Truck Station Butt Joint

The first repair tested the microwave's ability to "anneal" a butt joint (the abutting joint between asphalt placed at two different times) at the truck station's entrance (Fig. 3.56). The second was a pothole repair.

The microwave butt joint test was performed on the inbound lane to the truck station; the outbound lane was left untreated (Fig. 3.56-A). MUI's microwave equipment was positioned to straddle the joint at six successive (and partially overlapping) setups. The microwave was operated at 50kW for seven minutes at each setup. After seven minutes, a thermocouple probe

showed that the asphalt ranged from about 200° F to 225° F (93° C to 107° C) at a depth of three inches (7.5 cm). The pavement was worked with shovels to mix the hot and softened asphalt from either side of the joint (Fig. 3.56-C), and compacted (Fig. 3.56-D). A small amount of RAS was added to the final two setups (nearest to the center of the entrance) to determine if that would provide a better “finish” to the repair.



Figure 3.56. Microwave butt joint repair test, Nopeming Truck Station entrance, November 1, 2012.

Figure 3.57 shows the condition of the butt joint repair on February 6 and May 5, 2013. While a crack is present along the entire length of the butt joint, the crack on the un-microwaved (control) half is significantly wider than the crack on the microwaved half (Fig. 3.58).

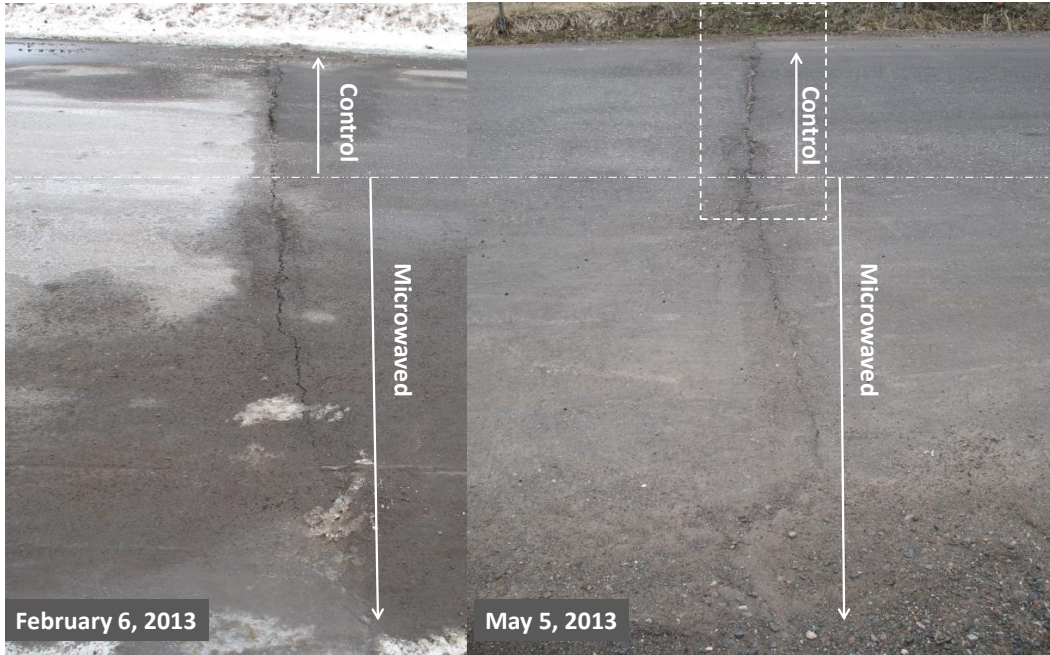


Figure 3.57. Microwave butt joint repair test condition, Nopeming Truck Station entrance: February 6 and May 5, 2013.

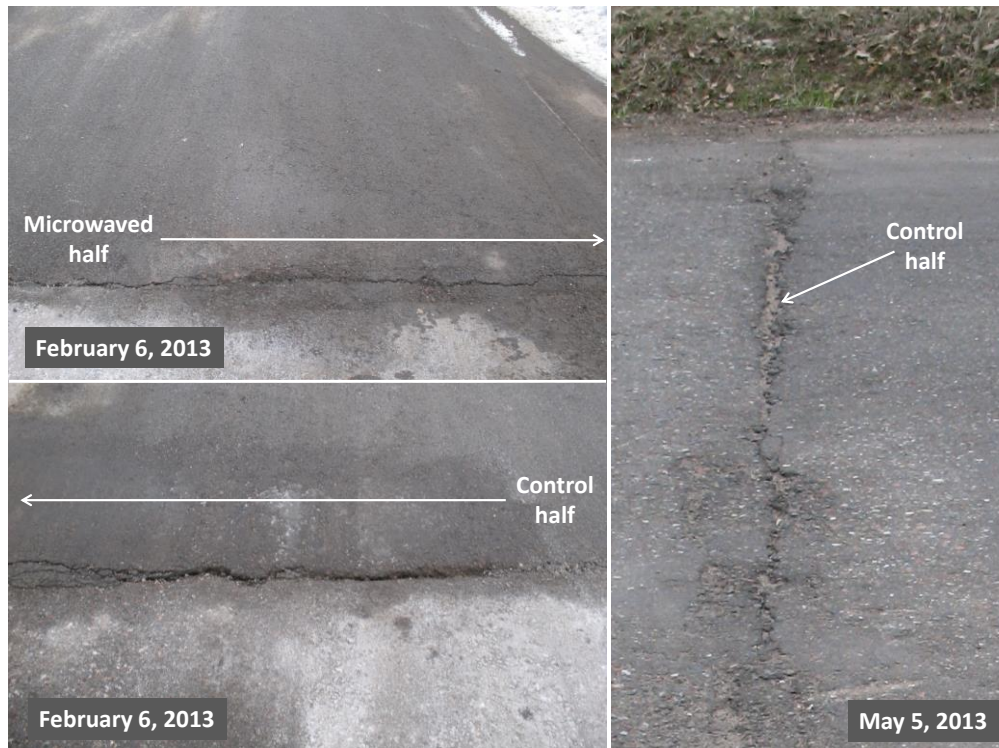


Figure 3.58. Another view and comparison of microwave butt joint repair test condition: February 6 and May 5, 2013.

Figure 3.59 shows the condition of the repair just over one year later, on November 18, 2013.

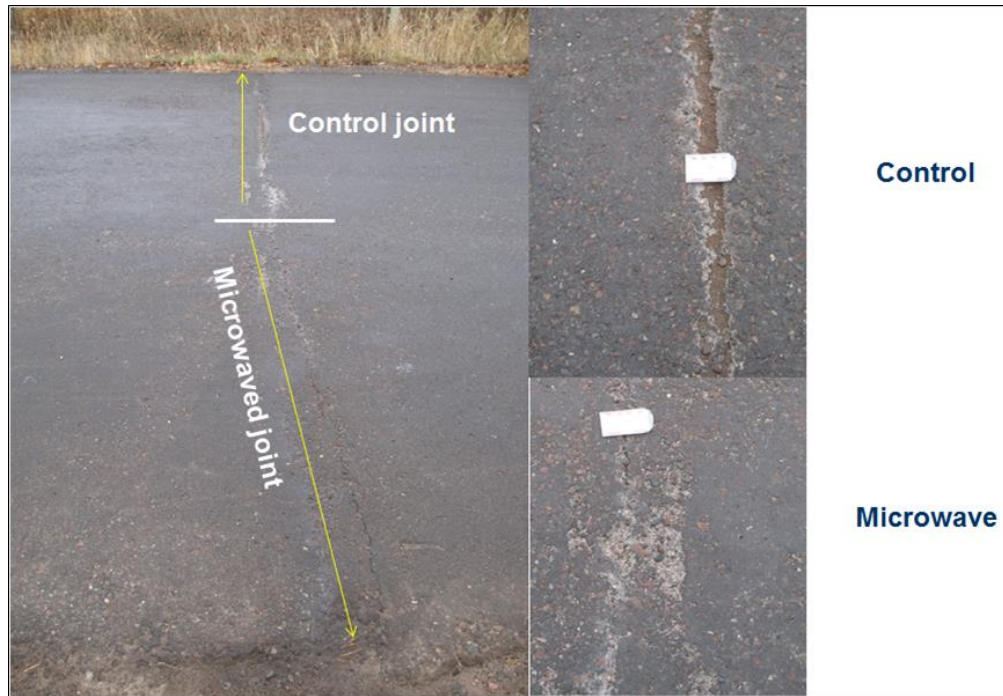


Figure 3.59. Condition of butt joint microwave repair on November 18, 2013.

Figure 3.60 shows the condition of the repair on August 26, 2015, more than 2.5 years after the test was performed. The reference scale in both photos is slightly more than three inches (or 8cm) wide and clearly shows how the microwave treatment resulted in a significantly narrower joint.

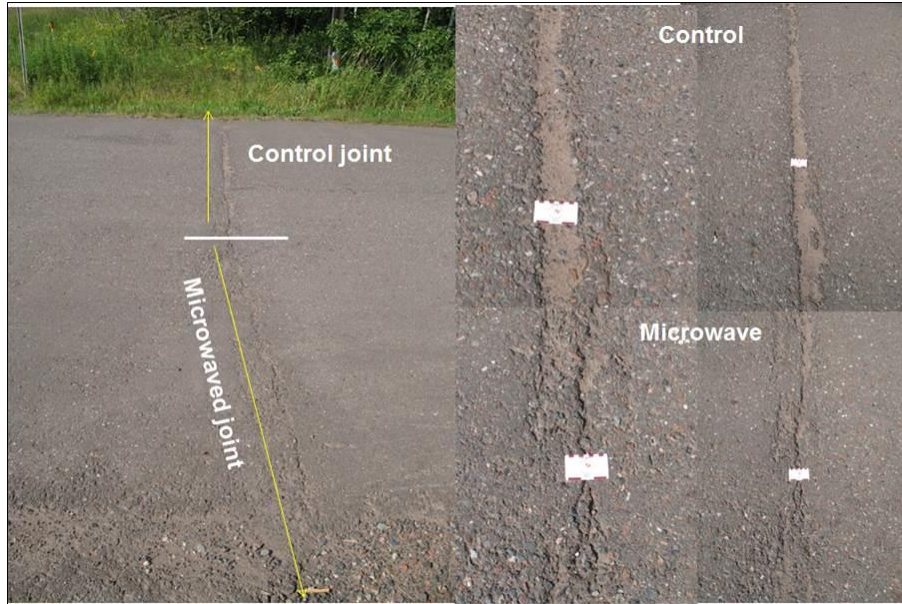


Figure 3.60. Condition and comparison of microwaved and control portions of butt joint repair: August 26, 2015.

The butt joint test is important in that it illustrates the potential for using microwave technology to improve the bond along the longitudinal joint between adjacent lanes/lifts of asphalt pavement. During a repaving project, the temperature differential between two adjacent asphalt lifts (one cool and one freshly laid) can result in inadequate compaction density and a weak bond at the interface (joint), leading to longitudinal crack formation and longer-term maintenance issues. Follow-up testing of this microwave “annealing” concept is recommended, as illustrated schematically in Figure 3.61.

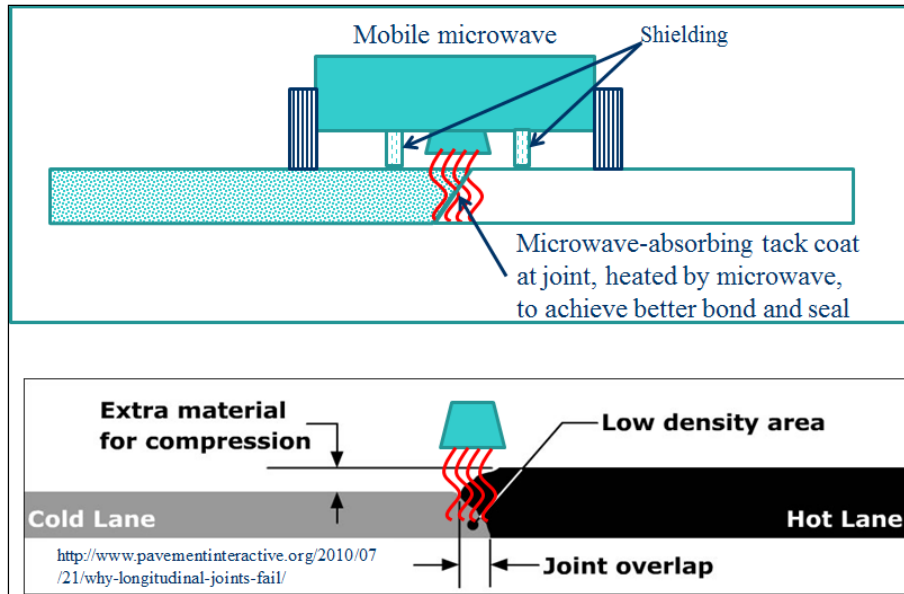


Figure 3.61. Schematic drawing of potential microwave joint/crack heating concept.

Becks Road/Midway Road Pothole

A microwave repair was also performed at the Becks Road/Midway Road location (refer to Figure 3.55) on November 1, 2012. Figure 3.62 (left photo) shows the transverse crack pothole near the fog line of the southbound lane; the smaller two photos show the equipment deployed and the compacted repair.



Figure 3.62. Becks Road/Midway Road pothole (left) and microwave repair (right): November 1, 2012.

The repair was performed as follows: The hole was first pre-heated for six minutes at 50kW. The softened asphalt was then shoveled and stirred, and NRRI's RAP-RAS-Mag mix was added and mixed to provide sufficient volume to fill the hole when compacted. The mixture was tamped slightly with a shovel, and microwave energy was applied for two more minutes at 50kW. A portable compactor was used to complete the repair. The temperature of the repair was measured at about 210° F (100° C). The entire repair took about ten minutes to perform.

Figure 3.63 shows the repair's condition on four dates spaced about eight months apart following the November 1, 2012 test: July 30, 2013; May 6, 2014; December 26, 2014; and August 26, 2015. A one meter measuring stick and an 8 cm (3 inch) pocket scale are shown for reference. The superimposed dashed line approximates the margin (interface) of the repair. The fact that the repair margin remained sound (no cracking whatsoever) for over 2.5 years indicates just how effective microwave heating can be for repairing asphalt pavement, because the pavement itself actually becomes an integral part of the repair. The redevelopment of cracks *within* the repair (Fig. 3.63) is merely a reflection of the poor pavement and underlying mechanism that was responsible for forming the pavement's transverse cracks in the first place.

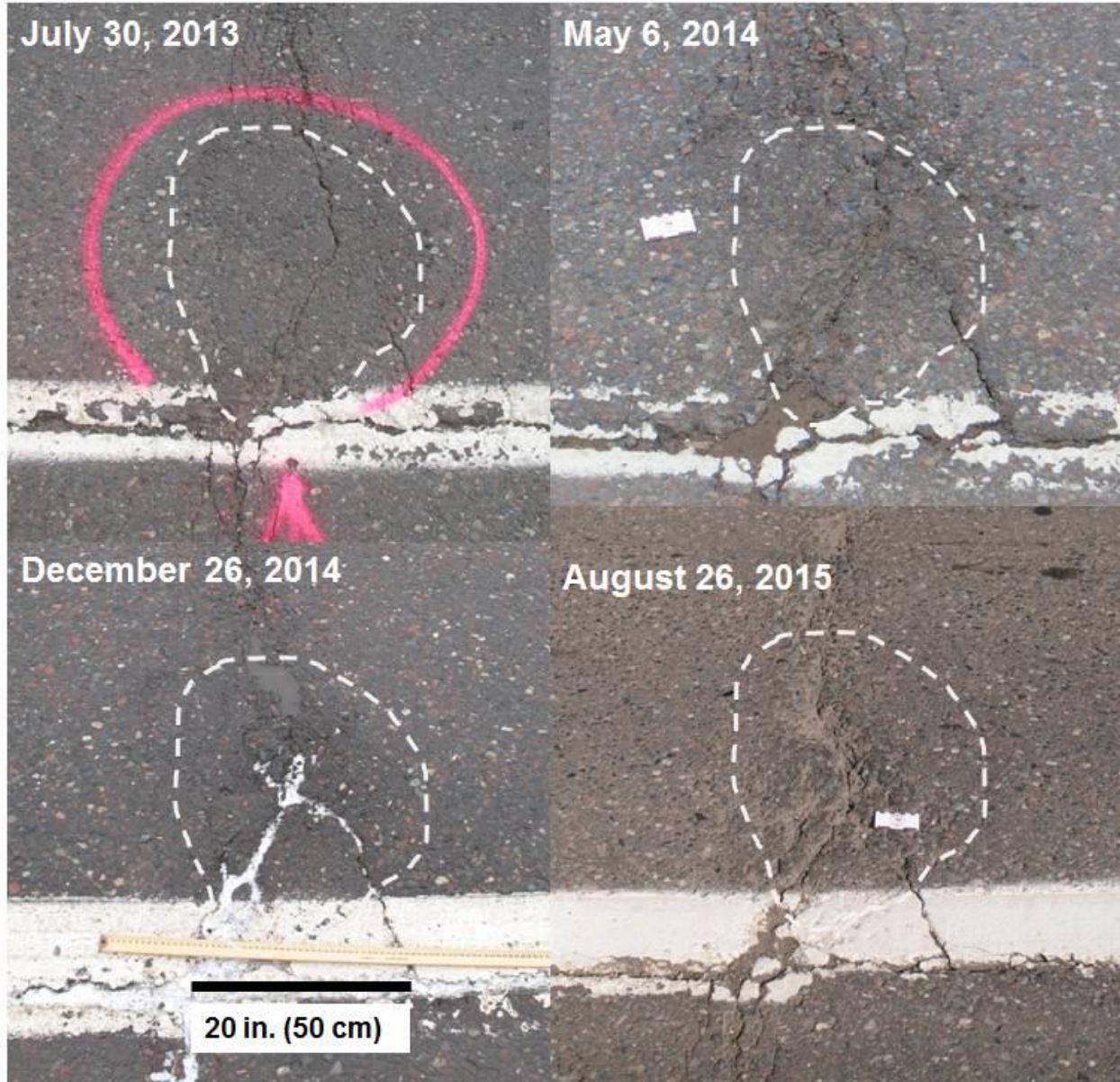


Figure 3.63. Condition of Becks Road/Midway Road microwave pothole repair: July 30, 2013 to August 26, 2015.

Highway 61 Expressway: Rapid Patch and Stepp Asphalt Recycler repairs

As described earlier, in November 2012, MnDOT used Rapid Patch and the Stepp equipment to repair potholes that formed between deteriorating panel joints and transverse cracks along a section of concrete pavement on the Highway 61 expressway between Duluth and Two Harbors (Figs. 3.64 and 3.65).



Figure 3.64. Location map of Rapid Patch and Stepp hot mix RAP repairs; Highway 61 expressway.



Figure 3.65. View of Highway 61 expressway Rapid Patch and Stepp hot mix RAP repairs: November 22, 2012.

The Highway 61 expressway repairs were conducted to allow for a side-by-side comparison of two repair techniques: 1) the Stepp asphalt (RAP) recycler; and 2) the Rapid Patch product. NRRI performed inspection and documentation of the Highway 61 repairs in November and December 2012. An illustrative/photographic summary of the Hwy 61 repair documentation was assembled and provided to members of the project's technical advisory panel (TAP) in late December 2012. Intermittent follow-up inspection and photo-documentation of the Highway 61 expressway occurred through 2014. Figures 3.66-3.68 show how the Rapid Patch repairs performed relative to the Stepp asphalt repairs. The cementitious nature of Rapid Patch makes it well-matched for rigid concrete pavement repairs and maintenance.



Figure 3.66. Highway 61 expressway asphalt patch repair failure: December 27, 2012.

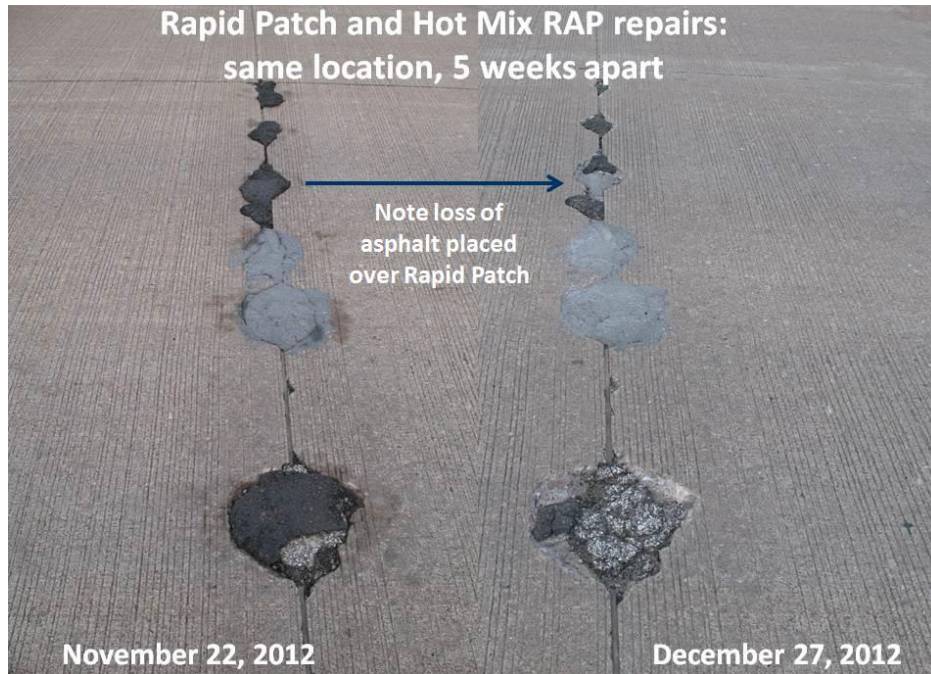


Figure 3.67. Comparison of Rapid Patch and Stepp hot mix RAP repairs: November 22 and December 27, 2012.

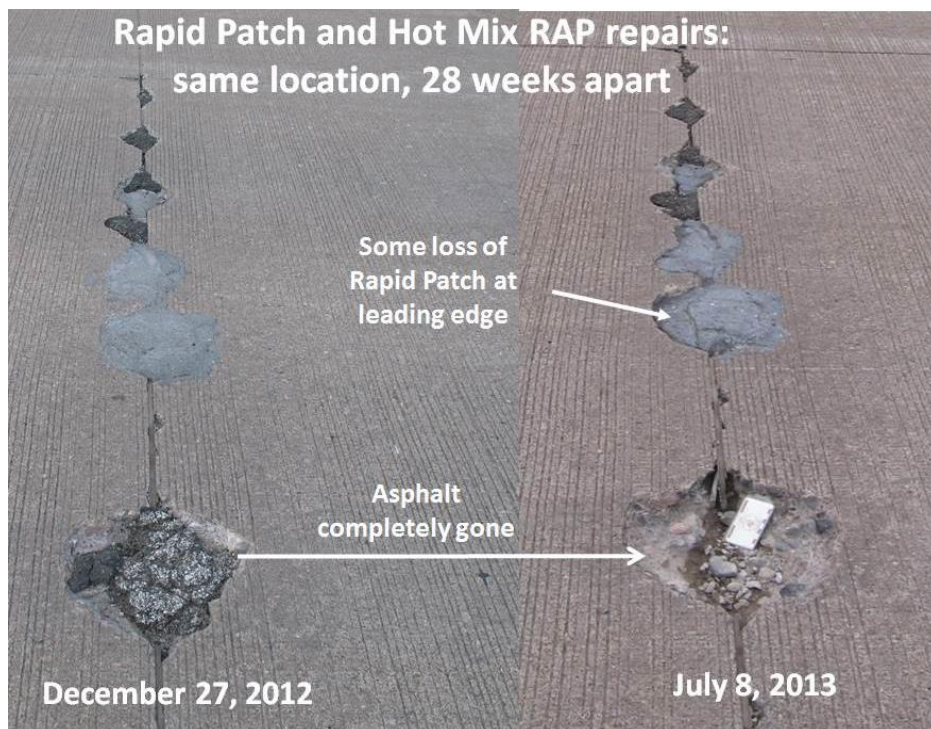


Figure 3.68. Comparison of Rapid Patch and Stepp hot mix RAP repairs: December 27, 2012 and July 8, 2013.

Figure 3.69 shows the condition of a failing Rapid Patch repair on December 26, 2014, more than two years after its installation. Of note are the white spots exposed in the remaining repair; they are portions of inadequately blended and poorly reacted white powder activator. Clumping of the white activator was an issue cited by maintenance personnel and others during this project. However, in October 2014 it was noted that more recent Rapid Patch repairs had been performed.



Figure 3.69. Failing condition of a Highway 61 Rapid Patch repair 2 years after installation: December 26, 2014.

The early failure of the Stepp repairs along the Highway 61 expressway location might also be partially attributable to the quality of RAP used in the Stepp recycler. As maintenance personnel have indicated, RAP quality can be highly variable depending on its age, asphalt binder content, and asphalt binder type, which can result in a recycled repair product that is less cohesive, bonds poorly, and/or becomes too stiff and brittle upon heating. It appears the Stepp recycler would perform best if provided with a consistent source of higher quality RAP whose binder properties are not adversely affected by the heat of the recycler. Hot mix repairs applied to dissimilar (PCC) and colder pavements can also have bonding problems.

Highway 169: Keewatin bridge deck Rapid Patch repair (November 2010)

Well before the start of this project, NRRI developed the prototype formulation for the Rapid Patch repair compound. An early field test was conducted with MnDOT District 1 to fill a saw-cut on a concrete bridge deck near Keewatin, MN. The installation (Fig. 3.70) was made on November 4, 2010, on the northbound lane of Highway 169. The sequence of photos in Figure

3.71 show the repair remaining in very good condition through May 30, 2014, more than 3.5 years after its installation. By May 30, 2014, some loss had occurred at the leading edge of the repair (by snowplow?) and along the margins of the repair, and a thin transverse crack had developed midway in the repair.



Figure 3.70. Installation of Highway 169 Keewatin bridge deck Rapid Patch repair: November 4, 2010.



Figure 3.71. Photos showing condition of Highway 169 Keewatin bridge deck repair from May 16, 2011 through May 30, 2014.

MnROAD: I-94 Mainline Rapid Patch test (September 1, 2011)

Pre-project installation of the prototype Rapid Patch formulation also took place at MnROAD in September 2011, as summarized in a draft document sent to the investigator titled, “MnROAD Partial Depth Patching Activities – 2011” (Johnson, 2013; revised February 19, 2014):

“In September 2011 MnDOT began a study of the field performance of partial-depth concrete repairs installed on portions of MnROAD’s mainline, interstate-highway test facility along westbound I-94 between Albertville and Monticello, Minnesota.”

TCC Materials provided the Rapid Patch compound, which was installed at six locations in MnROAD’s I-94 Mainline Cell 9 (Fig. 3.72), numbered as Transverse Joints 154, 155, 156, 159, 161, and 162.

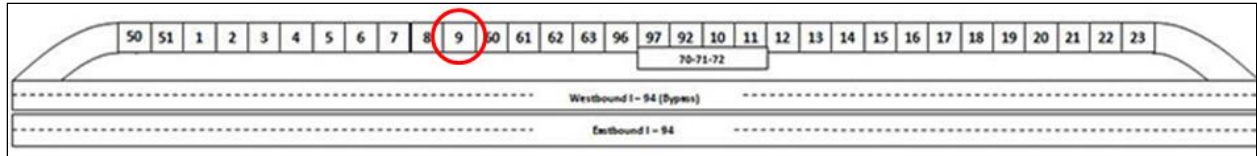


Figure 3.72. MnROAD's I-94 mainline map, with Cell 9 highlighted (Map Source: MnDOT).

Figures 3.73 and 3.74 show the Rapid Patch installation at joint location 162. Photographs taken with a thermal imaging camera by NRRI reveal the development of the exothermic reaction that occurs as the Rapid Patch compound sets (Fig. 3.75).



Figure 3.73. Rapid Patch repair location on MnROAD I-94 mainline: Joint location 162, September 1, 2010.



Figure 3.74. Rapid Patch installation on MnROAD I-94 mainline: Joint location 162, September 1, 2011.

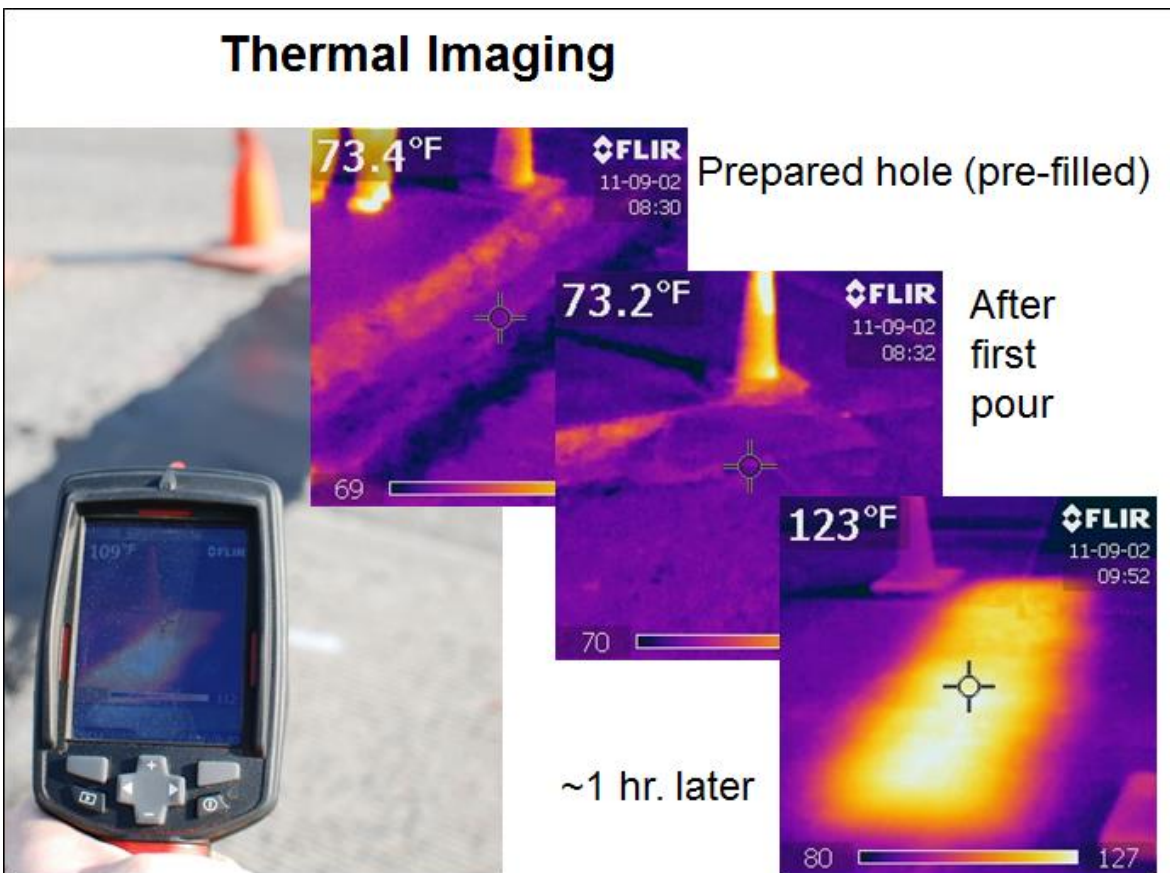


Figure 3.75. Thermal imaging showing exothermic reaction as Rapid Patch repair set and cured: September 1, 2011.

MnDOT evaluated and documented the condition of each repair over time. Johnson's (2013; revised February 19, 2014) draft summary document indicates that overall, the repairs had a mixed performance, showing about 90% survival rate after one year and declining to about 65% after two years. In all instances the repairs developed cracks, which is not unusual for this compound. However, as the photos of Figure 3.76 show (also extracted from the Johnson summary), the repair at Joint 162 was exhibiting perimeter edge loss, cracking, and deteriorating cracked blocks by the fall of 2012, and required a maintenance asphalt patch. By April 2013, the repair had degraded significantly, with more than half replaced by a secondary patch. Interestingly, this repair and the repair made at Joint 156 exhibited similar degradation characteristics. Because of the large size and volume of these two repairs, the Rapid Patch compound had to be placed in separate pours (see Figure 3.75). So rather than being a single monolithic repair, the separate pours may have formed a repair with internal boundaries of differential bonding and strength. The ambient pavement temperature was also 73° F (23° C) on the day of the installations, and the NRRI representative on site later reported that the compound had set up very quickly, perhaps exacerbating the effect of the separate pours.



Figure 3.76. Photo sequence of Rapid Patch repairs, MnROAD I-94 mainline Cell 9, Joint 162 location: 2/24/2012 to 4/14/2013 (Johnson, 2014).

The MnROAD findings, when considered with the earlier Keewatin Highway 169 bridge findings and the later Highway 61 expressway and current project findings, suggest that the Rapid Patch formulation could (and should) be: 1) simplified (to reduce or eliminate the powder activator); 2) refined to extend or better control its mixing, workability, and set times; and 3) adapted to a mechanized and larger-quantity deployment system to allow for uniform placement. Even so, as a rapid repair compound, it has performed reasonably well—in many cases lasting at least a year after installation.

Additional Task 3 Field Testing and Demonstrations

An additional field test and demonstration of microwave technology took place in September and November 2013, in Monticello, MN.

Microwave Field Test: September 10, 2013

The impetus for conducting this test was the promising outcome of the Task 2 butt joint repair demonstrated at MnDOT's Nopeming Truck Station on Becks Road/Midway Road near Duluth. Because pavement deterioration along inadequately compacted longitudinal joints is a persistent and significant maintenance problem, the butt joint repair outcome suggested that microwave technology was a potential solution for achieving more effective longitudinal joint heating, and therefore better joint compaction.

A microwave-based longitudinal joint heating system would first require a microwave antenna (aka horn or applicator) configuration that focused microwave energy more narrowly than the broader distribution of energy used for pothole repair. Therefore, an initial field test was performed with MUI on September 10, 2013, near MUI's Monticello location to provide an early indication of how a more focused system could be designed and adapted to the existing equipment platform (Fig. 3.77).



Figure 3.77. Modified microwave equipment: September 10, 2013 field test, Monticello, MN.

NRRI observed and documented the test, using a thermal imaging camera provided by UMD's Swenson College of Science and Engineering. The test showed that microwave energy distribution could be easily altered, as shown in Figure 3.78. Configuration 1 shows the energy/heating focused at four corners, pre modification. A modification to the horn resulted in the energy/heating pattern shown in Configuration 2 (additional and larger central heating zone). Configuration 3 shows a more uniformly distributed heating/energy pattern, which was of the type generated during the project's 2012 and 2013 pothole repairs. The footprint dimension of the heated areas shown in Figure 3.78 is about 28 x 28 inches (71 x 71 cm). Figure 3.79 shows the position of several test setups, their corresponding thermal images, and softened (shovelable) pavement.

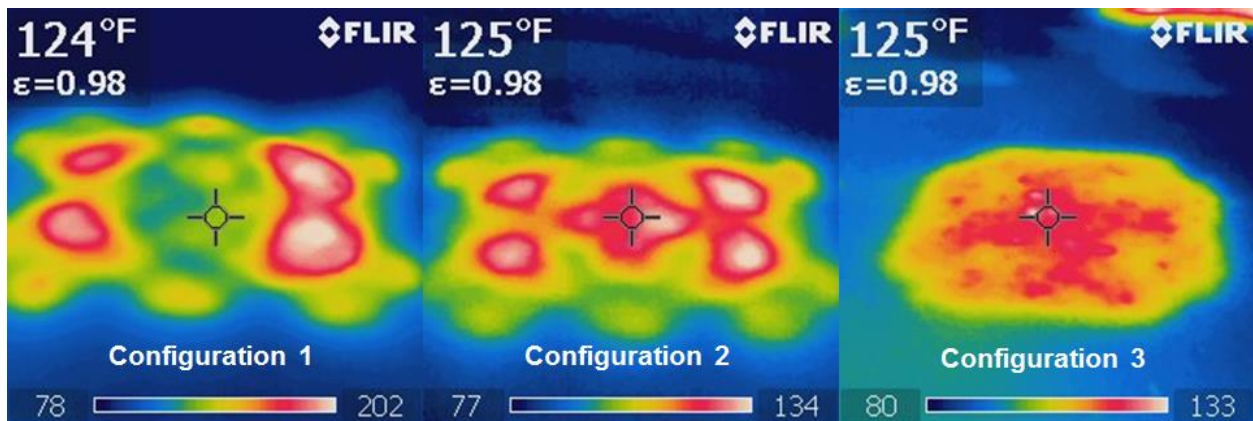


Figure 3.78. Thermal images of microwave energy/heating patterns for three different equipment configurations.

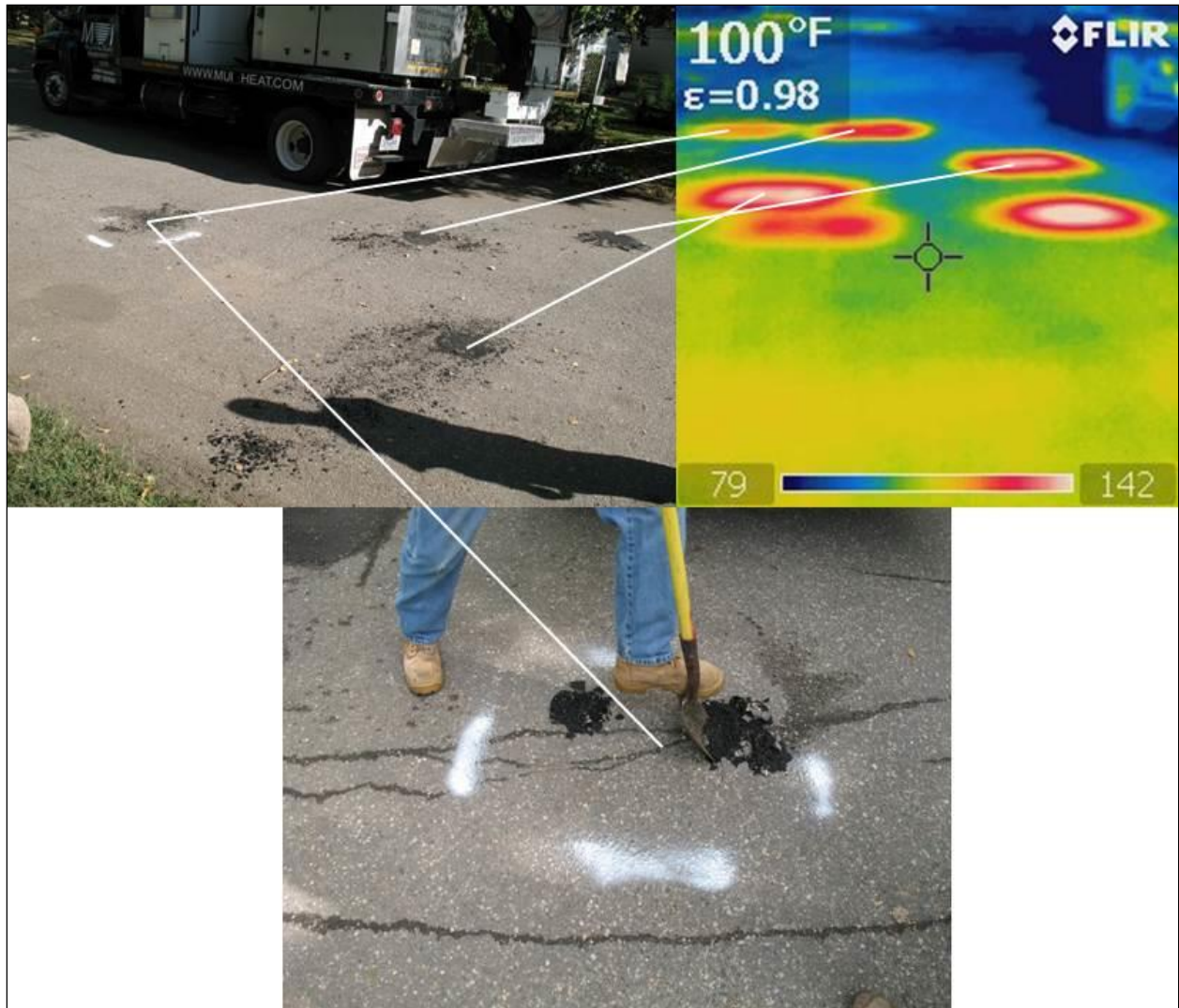


Figure 3.79. Relative position of microwave heating test setups, their corresponding thermal images, and softened (shovelable) pavement.

The test also showed how the equipment, which operates at a frequency of 915 MHz, generated microwave energy which penetrated deep into the pavement. After 12 minutes of 50kW heating using a centrally-focused configuration, the temperature of the gravel at the base of a location where the asphalt pavement was 25 cm (10 inches) thick reached over 100° C (~220° F), while the temperature near the pavement's surface approached 200° C (~400° F). This test result in particular indicated that much of the microwave energy was being transmitted deeply into the pavement rather than being absorbed more fully in the upper pavement. Recall that MUI originally designed its equipment to thaw frozen ground to depths greater than a 0.5 meters (1.5 feet). Deeper microwave energy penetration is a function of the longer-wavelength microwaves generated at the 915MHz frequency. While the 915MHz frequency matches MUI's ground thawing needs very well, it is not necessarily optimal for shallower (5 to 10 cm / 2 to 4 inches)

HMA repair applications, especially when the aggregate component of the HMA mix is not a strong microwave absorber.

Importantly, this additional field test provided helpful insights into how the microwave system could be modified to more efficiently heat HMA at shallower depths for applications such as longitudinal joint heating. The investigators have also worked with microwaves operating at 2450 MHz, which is the frequency (and shorter wavelength) at which common countertop/kitchen microwaves operate. For pavement repairs, the microwave energy should be focused on the uppermost 10 cm (4 inches) of pavement, which likely makes a microwave heating system operating at the 2450 MHz frequency a better option. A 2450 MHz-based system would more easily allow multiple smaller (e.g., 6 kW) microwave-producing magnetrons to be configured in a linear array, with the microwave energy focused along a relatively narrow path, coincident with and parallel to the longitudinal joint.

Based on what the September 10, 2013, field test indicated, the investigator and his project collaborators intend to pursue this microwave repair concept further.

Microwave Demonstration: November 14, 2013, Monticello, MN

MUI was asked to conduct an additional field demonstration of its technology and equipment in Monticello on November 14, 2013. Prior to this demonstration, MUI performed another for MnDOT on October 30 in St. Cloud, Minnesota. The Monticello demonstration highlighted all aspects of how the microwave repair technology and methodology works (Fig. 3.80), and the type of heating it achieves (Fig. 3.81).



Figure 3.80. Microwave equipment and repair demonstration: November 14, 2013, Monticello, MN.

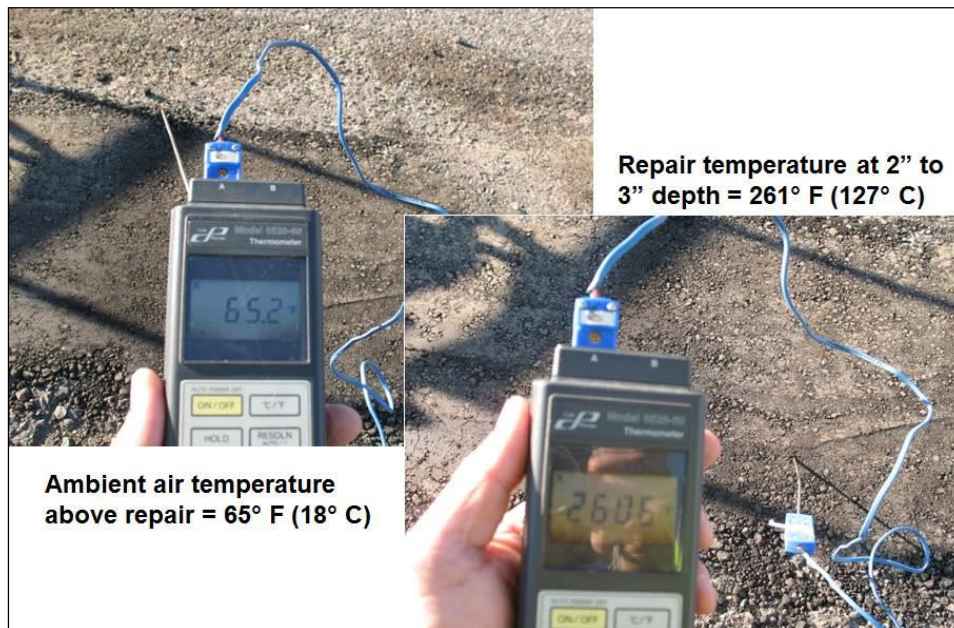


Figure 3.81. Photographs showing air temperature and internal temperature of microwave repair: November 14, 2013, Monticello, MN.

Measurable/Comparable Field Data Collection: Pavement Heating Modeling

David M. Hopstock, PhD., a microwave technology consultant, used project data to develop a mathematical model for heating rate comparisons between microwave and infra-red technologies. Hopstock's work is presented below.

Modeling of Microwave and Infrared Heating of Asphalt Pavement: David M. Hopstock, PhD

The objective of the modeling work was to obtain a better understanding of asphalt pavement heating and repair by both the microwave and infrared heating techniques. The results can be used to compare the practicality of the two techniques. They also enable one to quickly estimate the effect of changing conditions from those observed in the original testing. Parameters that can be varied in the model include the ambient temperature and wind speed, the input power density, and the magnetite content of the pavement and patching materials.

To simplify the modeling, programming, and debugging effort, what is inherently a three-dimensional problem was reduced to a one-dimensional model. The only distance variable considered was the depth, with lateral variations neglected. Because the thermal conductivity of asphalt concrete is relatively low, conduction of heat laterally from the area where the energy is applied can be neglected as a first approximation. The modeling results are most representative of what can be expected in the center of that area. If a reasonable representation of reality can be obtained by a one-dimensional model, those results can serve as a justification and starting point for the greater time and effort required to develop a two- or three-dimensional model.

Another simplification made in modeling was to consider parameters such as microwave absorption coefficient, thermal conductivity, and heat capacity to be constants. These factors actually have some temperature dependence, but the dependence is small enough not to substantially affect the results. A third simplification was to ignore the effect of moisture. If a significant amount of water has penetrated the pavement, or if there is a high moisture content in the patching compound, the temperature versus time curve will plateau at a temperature near the boiling point of water (100° C, or 212° F) until the moisture is driven out. The model assumes a negligible moisture content.

The application of microwave or infrared heating to asphalt pavement repair is a two-stage process—first, heating of the distressed area to the temperature at which the pavement is softened enough to be easily removed and possibly incorporated into the repair material and, second, heating of the repair material to the ideal temperature for compaction. The modeling can be applied to either stage with proper choice of parameters. In comparing the microwave and infrared techniques we looked primarily at the first stage.

An outline of the approach taken to modeling microwave heating and estimation of key input parameters was originally reported in 2004 (Zanko and Hopstock, 2004). A similar approach was developed by Bruce Allen (Allen, 1995) and incorporated into a model of asphalt paving under cold weather conditions (Chadbourn et al., 1998). The Allen model did not contain a microwave heating term and was primarily concerned with cooling, rather than heating of the pavement.

At any location within the pavement, the heat balance is given by

$$\{Thermal_energy_stored\} = \{Net_heat_input_by_conduction\} + \{Microwave_energy_absorbed\} \quad (1)$$

In the previous work we showed that the microwave power per unit area P penetrating to a depth z is given by

$$P(z) = P_0 e^{-2\alpha z} \quad (2)$$

where P_0 is the power per unit area initially entering the material, and α is the microwave absorption coefficient. The reciprocal of the absorption coefficient is the penetration depth λ . At the penetration depth the microwave power has been reduced to 13.6% of its initial value. The microwave energy per unit volume absorbed at depth z is found by differentiating the right side of equation (2). In terms of the penetration depth,

$$\{Microwave_energy_absorbed\} = \frac{2}{\lambda} P_0 e^{-2z/\lambda} \quad (3)$$

From standard heat conduction theory, equation (1) can then be rewritten

$$\rho C_p \frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2} + \frac{2}{\lambda} P_0 e^{-2z/\lambda} \quad (4)$$

where T is the temperature, ρ is the material density, C_p is the heat capacity per unit mass, and κ is the thermal conductivity. (Definitions and units of the symbols used are given in Table 3.1.)

Table 3.1. Input Parameters to the Model.

<i>Quantity</i>	<i>Symbol</i>	<i>Units</i>	<i>Value</i>
Ambient air temperature	T_a	°C	5.0
Initial temperature of pavement	T_o	°C	7.0
Density of pavement	ρ	kg/m ³	2295
Mass heat capacity of pavement	C_p	J/kg/°C	791
Thermal conductivity of pavement	κ	W/m/°C	1.78
Thermal diffusivity	D	m ² /s	0.981 x 10 ⁻⁶
Microwave penetration depth	λ	m	0.281
Wind speed	v	m/s	2.235
Convective heat transfer coefficient	h	W/m ² /°C	19.1
Emissivity of pavement	ε	dimensionless	0.95
Stefan-Boltzmann constant	σ	W/m ² /K ⁴	5.669 x 10 ⁻⁸
Microwave power density	P_0	W/m ²	98,850 or 0
Incident radiant energy	H_{ri}	W/m ²	0 or 13,250
Radiation absorption coefficient	A	dimensionless	0.85
Increment of time	Δt	s	20
Increment of distance	Δz	m	6.35 x 10 ⁻³
Stability parameter	S	dimensionless	0.486

At the surface ($z = 0$) the situation is more complicated in that we need to apply boundary conditions. The heat balance at the surface is given by

$$\{Thermal_energy_stored\} = \{Net_heat_input_by_conduction\} + \{Microwave_energy_absorbed\} + \{Radiant_energy_absorbed\} - \{Energy_loss_by_convection\} - \{Energy_loss_by_radiation\} \quad (5)$$

All heat energy terms can be expressed on a per unit area per unit time basis. The heat is considered to be stored in a thin layer of thickness $\Delta z/2$, where Δz is the thickness increment used in the finite difference solution. The thermal energy stored per unit area per unit time is then given by

$$\{Thermal_energy_stored\} = \frac{\Delta z}{2} \rho C_p \frac{\partial T}{\partial t} \quad (6)$$

The net heat input by conduction is given by

$$\{Net_heat_input_by_conduction\} = -\kappa \frac{\partial T}{\partial z} \quad (7)$$

The microwave energy absorbed term at the surface ($z = 0$) in thickness $\Delta z/2$ becomes

$$\{Microwave_energy_absorbed\} = \frac{\Delta z}{2} \frac{2P_0}{\lambda} = \frac{\Delta z P_0}{\lambda} \quad (8)$$

Note that the microwave energy absorbed at the surface is inversely proportional to the penetration depth.

Radiant energy is considered to be any energy reaching the surface with a wavelength short enough that the penetration depth is negligible and all the energy that is not reflected from the surface is absorbed at the surface. This could be solar radiation, as considered by Allen (1995), or infrared radiation from a heating source, as considered in this report. The radiant energy absorbed is given by

$$\{Radiant_energy_absorbed\} = AH_{ri} \quad (9)$$

where H_{ri} is the incident radiant energy per unit area per unit time, and A is the absorbance.

The energy loss by convection can be estimated from Newton's law of cooling, given by

$$\{Energy_loss_by_convection\} = h(T_s - T_a) \quad (10)$$

where h is the convective heat transfer coefficient, T_s is the temperature at the surface, and T_a is the ambient temperature. Many different correlations have been published between the heat transfer coefficient and the air velocity at the surface. Five published equations were plotted and compared. It was found that a correlation originally developed by Alford et al. (1939) gives good compromise values falling within the range of the other correlations. The numerical value of h is given by

$$h = 7.4 + 6.39v^{3/4} \quad (11)$$

where h is expressed in $W/m^2/K$ and the air velocity v is given in m/s .

The energy loss by radiation is given by the Stefan-Boltzmann law, which indicates that the loss of heat by radiation goes as the fourth power of the absolute temperature. Since it is convenient to express temperatures in degrees Celsius rather than Kelvin, the energy loss per unit time per unit area is expressed by

$$\{Energy_loss_by_radiation\} = \varepsilon\sigma[(T_s + 273.15)^4 - (T_a + 273.15)^4] \quad (12)$$

where ε is the emissivity and σ is the Stefan-Boltzmann constant, $5.669 \times 10^{-8} W/m^2/K^4$.

The equations were solved by the explicit finite difference method, which is covered in many textbooks, such as Forsythe and Wasow (1960) and Smith (1978). Applications of the method to heat transfer problems are illustrated in Holman (1976) and in Kreith (1973). The following approximations are made:

$$\frac{\partial T}{\partial t} \approx \frac{T_m^{n+1} - T_m^n}{\Delta t} \quad (13)$$

$$\frac{\partial^2 T}{\partial z^2} \approx \frac{T_{m+1}^n - 2T_m^n + T_{m-1}^n}{(\Delta z)^2} \quad (14)$$

$$\frac{\partial T}{\partial z} \approx \frac{T_{m+1}^n - T_m^n}{\Delta z} \quad (15)$$

The superscripts refer to time increments, such that $t^{n+1} = t^n + \Delta t$, and the subscripts refer to distance increments, such that $z_{m+1} = z_m + \Delta z$.

By use of the approximations in equations (13), (14), and (15), as well as the other equations given above, the heat balance equations (1) and (5) can be solved to obtain explicit equations for T_m^{n+1} as a function of the other variables. This solution can then be set up in an Excel spreadsheet, in which the first column is the initial temperature vs. depth profile, and each successive column indicates the temperature profile at the next time increment t^{n+1} .

Certain precautions must be taken in applying the explicit finite difference solution. The thermal diffusivity D (units of m^2/s) is defined by

$$D = \frac{\kappa}{\rho C_p} \quad (16)$$

For the solution to remain stable, the dimensionless stability parameter S must be less than 1/2, where S is given by

$$S = \frac{D \Delta t}{(\Delta z)^2} \quad (17)$$

It was also found that, to avoid excessive errors due to discretization, the ratio $\Delta z/\lambda$ should be less than 1/5. In practice it was found not to be difficult to meet these criteria.

Chadbourn et al. (1998, pp. 33-35) validated their model by comparing their model results to field data and model calculations of Corlew and Dickson (1968) on cooling of a layer of hot-mix asphalt. With our Excel model we repeated the calculation using the same initial conditions and parameters used by the previous authors. Despite the fact that our method of solution was much simpler to implement than the implicit formulation of Chadbourn et al. (1998), which involved solving a large system of simultaneous linear equations, our results were in excellent agreement with those of the previous authors.

After preliminary verification of the Excel model we moved on to extending the model to microwave and infrared heating of pavement. We applied the model to simulating the conditions of tests that were conducted in Duluth, MN, on October 30, 2012. We did not know the precise composition of the asphalt concrete pavement on which the tests were done. However, we knew that the aggregate used was of a basaltic nature, containing small quantities of microwave-absorbing iron minerals such as magnetite, ilmenite, and hematite. We have found that the microwave properties of this aggregate are similar to those of a non-absorbing aggregate with the addition of about one percent pure magnetite. To estimate the properties of the pavement we

used the Excel spreadsheet described in Zanko and Hopstock (2004). We estimated the weight fraction of bitumen in the asphalt concrete at 6% and the void fraction at 8%. The temperature of the pavement was taken to be the temperature measured that day, 40° F (4.4° C).

The input variables to the model are given in Table 3.1. In separate runs the simulated heating was done by microwave power or by infrared. For the microwave power density, the 50 kW produced by the generator was assumed to spread over a 28 x 28 inch (71 x 71 cm) area. In the spreadsheet calculation the resultant power density of 98,850 W/m² was assumed to be reduced by 10% by reflection of the microwaves. For the infrared calculation, 35 kilowatts of IR power from the HeatWurx unit was taken to spread over a 54 x 78 inch (137 x 198 cm) area. This might have been a slight overestimate, because, despite the nameplate specification of 35 kilowatts, the HWX-30 unit may only produce 30 kilowatts. Solar radiation input was taken to be zero, because the areas in question were shielded by the applicators.

We found that, despite all of the simplifications and uncertainties in parameter estimates, the simulated temperature results closely followed what was observed in the field. Of particular significance is that microwave heating penetrates to several inches in depth, while with infrared heating the temperature increase is concentrated at the surface. As was observed in the field, with microwave heating the maximum temperature is not obtained at the surface, but at a depth of about one inch. With infrared heating, on the other hand, because of the sharp temperature decrease from the surface to the interior, there can be scorching of the asphalt at the surface, while at depth of greater than an inch the asphalt has not softened.

Examples of modeling results were presented at the CTS Research Conference on May 22, 2013, and the results match up quite well with what was seen in the project's "real world" field trials.

To reiterate, the model includes energy input from microwaves and/or from less penetrating radiation—IR and/or solar. Cooling takes place from the pavement surface by a combination of convection and radiation. For the physical and thermal pavement characteristics, Hopstock used the Excel model he developed and reported on in 2004 (Zanko and Hopstock, 2004). A magnetite content of 1% by weight was assumed, which gave a microwave penetration depth of 28.1 cm (about 11 inches). This percentage appeared to be the right number for the penetration depth, and is consistent with a basaltic aggregate (basaltic aggregate has been shown to have greater microwave-absorbing properties relative to aggregate types such as granite, limestone, and quartzite).

Conditions similar to those observed in Duluth on 10/30/2012 were used in the modeling. Pavement heating by both microwave and IR (HeatWurx) methods was simulated using a starting ambient pavement temperature of 40° F (4.4° C).

Simulation modeling of 50 kW microwave input power for six minutes results in a temperature of 95° C (203° F) at a depth of two inches (5 cm) (Fig. 3.82). That is very similar to what was observed in field testing. At that duration of heating (six minutes), the maximum temperature of 111° C (232° F) occurs between 0.5 inch and 0.75 inch (1.25 cm and 2 cm) pavement depth.

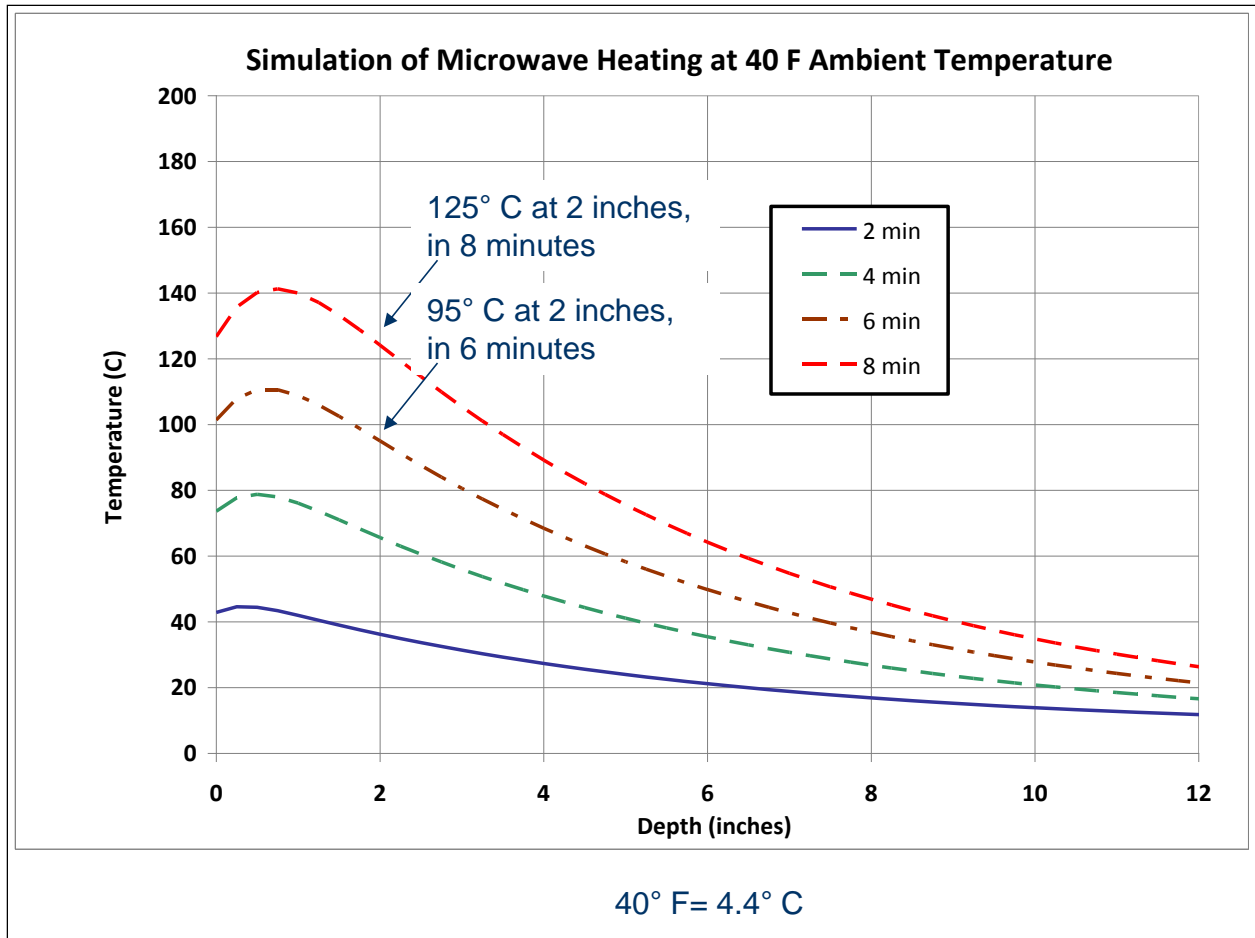


Figure 3.82. Simulation of microwave heating of asphalt pavement at 40° F ambient temperature.

Next, the model simulated the HeatWurx unit operating the same day, producing 36 kW of IR energy (Fig. 3.83). Figure 3.83 clearly shows the surface-downward heating mechanism of IR heating. After 30 minutes the surface attains 186° C (367° F), but one inch (2.5 cm) down, the temperature is only 113° C (235° F), and two inches (5 cm) down it is at a rather cool 62° C (144° F) hardly enough to soften the asphalt pavement. At three inches (7.5 cm), the temperature of 32° C (90° F) is merely warm. Again, this result is very similar to what we observed in field testing, and is a very dramatic example of the advantage of microwave over IR heating, especially for situations where delamination potholes form at the interface of an upper lift (wear course) with a lower lift (base course) of asphalt. If heating does not adequately penetrate below the wear course, a good repair bond may not be achieved.

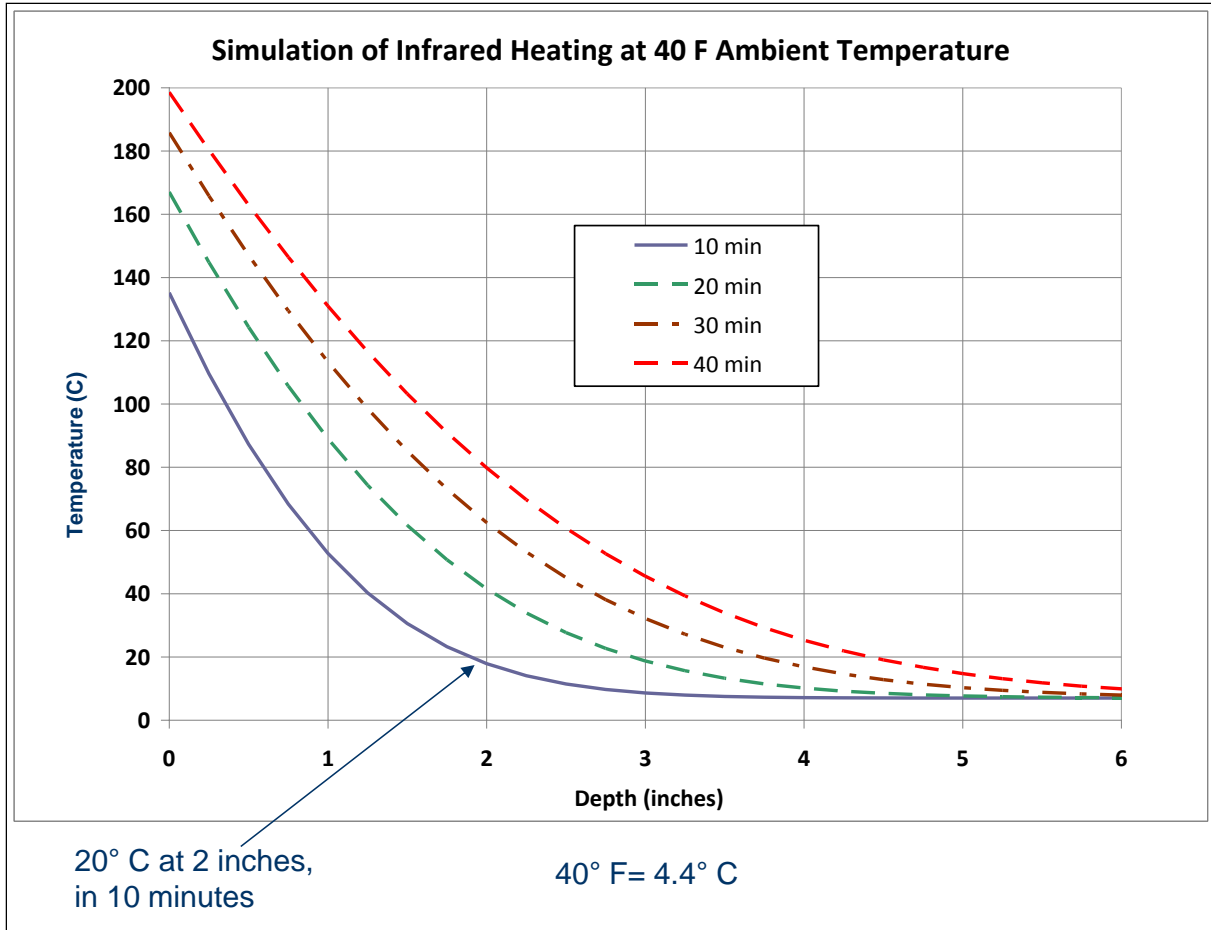


Figure 3.83. Simulation of infrared heating of asphalt pavement at 40° F ambient temperature.

The HeatWurx HWX-30 simulation applied the unit’s 36 kW IR output (45 kVA input) over a 4.5 x 6.5 foot area. Modeling showed after 40 minutes of heating the surface getting close to 200° C (~390° F), a temperature at which noxious vapors are released and destruction of polymeric asphalt binders can occur. But softening of the asphalt (temperatures above 125° C, or ~260° F) occurs only down to about one inch (2.5 cm) depth. Below a one-inch depth, the asphalt is still relatively cool and hard. The temperature is only about 80° C (~175° F) at two inches (5 cm). This corresponds fairly accurately to what we observed on 10/30/12.

The results apply strictly to heating pavement in place, but apply roughly also to heating the patching compound, where the depth corresponds to the depth of the compound once compacted. Again, the Hopstock model takes the penetration depth of the microwaves to be 11 inches (28 cm), which corresponds to a weight fraction of magnetite of about 1.0%. That is reasonable for asphalt in place made with a basaltic aggregate. It also corresponds to adding 1% magnetite concentrate to RAP made with granite aggregate. The plot of temperature versus depth (Fig. 3.82) shows that maximum temperature occurs not at the surface, but at a depth of about one inch (2.5 cm). The temperature at two inches (5 cm) is about the same as the temperature at the

surface. After eight minutes at 50 kW output from the antenna used by MUI, everything in the first two inches is heated to at least 125° C (~260° F) and is soft enough to be removed with a shovel. The simulation results correspond very closely to what we observed in the field.

Hopstock’s model also evaluated what would happen if the ambient temperature were 0° F (-18° C). A plot of temperature versus time and depth shows the temperature at a depth of two inches (5 cm) equals the surface temperature and is above 125° C (~260° F) when the microwave treatment time equals 10 minutes (Fig. 3.84). So the conclusion is that reducing the ambient temperature from 40° F to 0° F (4.4° C to -18° C) increases the time requirement by only about 25%, from 8 min to 10 min to achieve the same pavement heating.

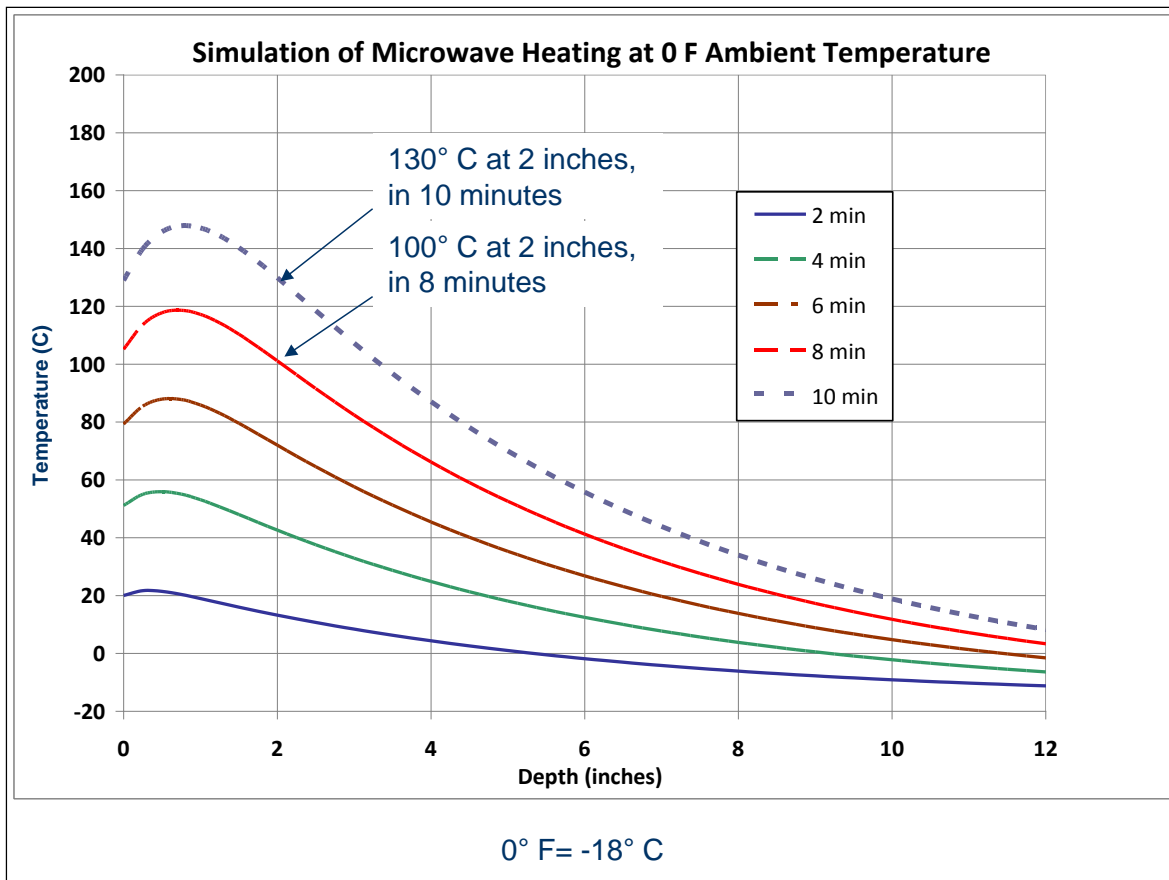


Figure 3.84. Simulation of microwave heating of asphalt pavement at 0° F ambient temperature.

Also modeled was the effect of decreasing the ambient temperature to 0° F on IR (HeatWurx) heating. As in the case of microwave heating, the time requirement to reach the same temperatures increased by about 25%, in this case from 40 to 50 minutes.

While the model is admittedly simple, it captures fairly realistically (in at least a semi-quantitative manner) real-life phenomena. Some of the key simplifications include:

- It is a one-dimensional model that does not capture edge effects;
- It does not take into account water that can boil off as steam. There is considerable thermal energy lost in converting water to steam. But apparently reasonable results are obtained if the water content is low—less than 1%. Also not taken into account is vaporizing or burning off some of the asphalt, as might occur with IR heating. Field measurements showed that a surface temperature above 200° C (~400° F) was indeed reached with the HeatWurx unit;
- The input parameters include some rough estimates, some of which may be off by as much as 10% to 20%; and
- Calculations have only been done for fully dense pavement. The parameters will be even more approximate for unconsolidated filling compound. They could be roughly estimated by using the 2004 spreadsheet with a much higher percentage for the void fraction.

Investigation of Potential to Impart Flexibility to Rapid Patch Repair

The potential for imparting a degree of flexibility to the rigid Rapid Patch repair underwent a limited investigation during the project.

First, a preliminary test of crumb rubber was performed. Testing indicated that increasing the amount of rubber weakened the Rapid Patch compound. Unlike an asphalt-based mix, the cementitious inorganic Rapid Patch compound likely does not adhere well to crumb rubber. Therefore, crumb rubber was not pursued further.

Past experimentation with polyvinyl alcohol (PVA) by David Hendrickson of NRRI indicated it was a viable alternative. A review of Prof. Victor Li's (University of Michigan) work with PVA for developing flexible concrete shows that he uses PVA fibers (Wang and Li, 2005).

“Large aggregates were excluded in ECC mix design, and only fine sand was incorporated. The silica sand used here had a maximum grain size of 250 μm and an average size of 110 μm. The PVA fiber had a diameter of 39 μm, a length of 12 mm, and overall Young’s modulus of 25.8 MPa. The apparent fiber strength when embedded in cementitious matrix was 900 MPa. The fiber surface was treated with oil coating to reduce interface bond and the oiling content is 1.2%.” (Wang and Li, 2005)

The key to his success appears to be the use of very fine aggregate (fine silica sand that is less than 250μm in size) instead of conventional coarse aggregate. As Li has reported, coarse aggregates disturb placement of the fibers and destroy ductility. <http://www.progressiveengineer.com/profiles/victorLi.htm>

MnDOT completed a study of using PVA in cementitious overlays (Akkari, 2011), but used coarser aggregates in the test mixes to match the specifications required for thin overlays. The MnDOT study concluded: “...the modified PVA-ECC with the low doses of fiber examined in this study are not suitable for the overlay at MnROAD.” Based on Li's work with much finer (<250μm) aggregate, it is not surprising that MnDOT reached that conclusion.

A review of a PVA fiber manufacturer's (Nycon) product (TUFF-SLAB) also notes the influence of alkalinity on the performance of its PVA fibers.

“Nycon-PVA fibers are the only fiber that develops a molecular bond to concrete, which is activated when the PVA comes into contact with the mix alkalinity. The Nycon-PVA fiber unique molecular bond to the cement paste provides improvement to the abrasion resistance and impact resistance of concrete – without any loss of compressive strength.”
<http://concreteproducts.com/equipment/4233-nycon-pva-macro-micro-fiber-blend-toughens-slabs.html#.VktGcyu0cT0>

Because the PVA fiber's molecular bond is enhanced by the alkalinity of a cement mix, this may prove problematic for the Rapid Patch pothole repair compound, which instead relies on an acidic reaction. Indeed, limited initial testing indicated that adding PVA significantly reduced (by more than 50%) the compressive strength of the Rapid Patch specimens. However, the preponderance of aggregate contained in the Rapid Patch formulation was also coarser than Li's maximum of 250µm. Because a finer (and simplified) formulation may yield better results with (and even without) PVA, NRRI intends to pursue this option in follow-up research, along with an evaluation of non-PVA reinforcing fibers and other additives.

Presentations

With respect to the presentation of findings at one or more venues as a project (and Task) deliverable, the PI made several presentations:

- 1) to the TRB Mineral Aggregates Committee (AFP70) in mid-January of 2013, which included a brief review of the project:
 - a. Title of presentation: A Brief Overview of Current Taconite Mining Byproduct/Co-product Utilization Activities;
 - b. Type of presentation: Conference;
 - c. Date of presentation: January 15, 2013;
 - d. Where presented (list name of event and location): 92nd Annual Meeting -Transportation Research Board, Washington, D.C.;
 - e. Presenter(s): Lawrence M. Zanko;
 - f. Audience size: 35;
 - g. Describe the audience: AFP70 Mineral Aggregates Committee; and
 - h. URL, if available: n/a.

- 2) to the CTS Research Conference on May 22, 2013:
 - a. Title of presentation: Evaluate and Develop Innovative Pavement Repair and Patching: Taconite-Based Repair Options;
 - b. Type of presentation: Conference;
 - c. Date of presentation: May 22, 2013;

- d. Where presented (list name of event and location): 24th Annual Transportation Research Conference;
 - e. Presenter(s): Lawrence M. Zanko;
 - f. Audience size: 20;
 - g. Describe the audience: Researchers, engineers; and
 - h. URL, if available: <http://www.cts.umn.edu/events/conference/2013/>.
- 3) to the project TAP:
- a. Title of presentation: Evaluate and Develop Innovative Pavement Repair and Patching: Taconite-Based Repair Options;
 - b. Type of presentation: Research Presentation and Discussion;
 - c. Date of presentation: December 17, 2013;
 - d. Where presented (list name of event and location): CTS – MnDOT Office of Maintenance Partnership Meeting CTS classroom;
 - e. Presenter(s): Lawrence M. Zanko;
 - f. Audience size: 15;
 - g. Describe the audience: CTS and MnDOT personnel; and
 - h. URL, if available: (n/a).
- 4) to University for Seniors program:
- a. Title of presentation: New and alternative uses for byproducts of taconite mining;
 - b. Type of presentation: Classroom;
 - c. Date of presentation: January 29, 2014;
 - d. Where presented (list name of event and location): University for Seniors, University of Minnesota Duluth;
 - e. Presenter(s): Lawrence M. Zanko;
 - f. Audience size: 25;
 - g. Describe the audience: Retired citizens; and
 - h. URL, if available: (n/a).
- 5) to the 87th Annual Meeting of the SME Minnesota Section 75th Annual University of Minnesota Mining Symposium:
- a. Title of presentation: Overview of Taconite Mining By-Products and Dredged Material Reuse Efforts;
 - b. Type of presentation: Conference;
 - c. Date of presentation: April 22, 2014;
 - d. Where presented (list name of event and location): 87th Annual Meeting of the SME Minnesota Section 75th Annual University of Minnesota Mining Symposium, Duluth, MN;
 - e. Presenter(s): Lawrence M. Zanko;
 - f. Audience size: 40;
 - g. Describe the audience: Mining industry professionals, engineers, agency personnel; and

- h. URL, if available: <http://www.d.umn.edu/ce/learningopportunities/conferences/sme/index.html>.

Media Coverage

The project has received newspaper, television, radio, and University of Minnesota media coverage. While neither intended nor planned as a project deliverable, such coverage nonetheless lends important visibility, and shows the public how collaborative applied research efforts by MnDOT and the University of Minnesota (NRRI), facilitated by the Center for Transportation Studies, are attempting to improve the condition and state of repair of our roads.

Below is a listing of media outlets/sources and dates for the stories that ran during the project:

- WDIO 10/13 and KBJR-6 (Northlands News Channel): October 31, 2012
 - Beth Petrowske of MnDOT also video-documented the October 31, 2012, repairs on Grand Avenue.
- Minnesota Business: March, 2013
- Star Tribune: April 13, 2013 (Fig. 3.85)

Tests of new mixtures, technology may cure potholes

Updated: April 13, 2013 - 9:18 PM

University of Minnesota Duluth researchers think they may have found the perfect recipe for filling potholes: a mixture of old shingles, taconite tailings and old asphalt heated by a portable microwave.

UMD's Natural Resources Research Institute is teaming with a Monticello firm to test the product, which bonds to pavement even in cold weather, said Larry Zanko, senior research fellow at the NRRI.

The mixture, when heated, softens and can absorb electromagnetic waves produced by a microwave oven, he said.

The goal, Zanko said, "is to find solutions that will last for a season, so crews don't have to go back two and three times. We think it is quite promising."

Microwave Utilities Inc. has devised a 50,000-watt microwave mounted onto a truck that can heat frozen ground to up to 280 degrees. It also extracts moisture from the pavement, a key ingredient in pothole formation, said firm spokesman Kirk Kjellberg.

Field tests on Hwy. 53 and Grand Avenue in Duluth have yielded positive results, and have drawn attention from the Minnesota Department of Transportation. The agency along with the Center for Transportation Studies at the Twin Cities campus of the University of Minnesota provided \$40,000 in grants for study and testing.

TIM HARLOW

<http://www.startribune.com/local/202869321.html>

Figure 3.85. Startribune pothole repair story: April 13, 2013.

- KARE-11: April 30, 2013 (Fig. 3.86)



Figure 3.86. KARE 11 pothole repair story: April 30 2013.

- UM News: June 3, 2013
- WCCO/CBS MINNEAPOLIS (WCCO): June 6, 2013
- CTS Catalyst: July, 2013
- Hometown Focus: May 30, 2014

Chapter 4 Conclusions

The two repair alternatives evaluated during this project merit further development and consideration, as the field performance of both suggests they have long-term potential for more widespread use. Based on feedback from maintenance personnel who used and/or observed both repair alternatives during the project, both alternatives would benefit from operational modifications that would reduce the deployment time required to complete a repair and increase the number of repairs that can be accomplished during a single shift. Doing so would lead to greater acceptance and more widespread use.

The Rapid Patch compound appears to be better suited for rigid and relatively deep repairs, where the surrounding or underlying pavement is Portland cement concrete (PCC). Two installations stand out, performance-wise:

- The Highway 169 bridge deck near Keewatin, MN. This deep saw-cut repair performed very well for over three years following its November 2010 installation (before the start of this project).
- a utility repair made around a steel manhole cover at 64th Avenue West and Grand Avenue (Highway 23), Duluth, during the project's October 31, 2012, field trial. While cracked, the repair was still largely intact as of August 26, 2015.

The compound has also shown fair to moderately good performance in transverse joint repairs made in a PCC segment of TH 61 northeast of Duluth, relative to repairs made with the Stepp Asphalt Recycler in 2012, and 2014 repairs made with the taconite compound and UPM.

Because of its demonstrated positive performance in a variety of applications (current and previous), this compound will be further refined and developed by NRRI. For example, in addition to evaluating the potential of imparting resilience (flexural) properties to the compound through the addition of fibers, NRRI is working to simplify the formulation (making it a two-part system instead of three-part), adjust its component gradation, and to automate (mechanize) its deployment to minimize or avoid entirely hand-mixing and hand installation by maintenance crews. The investigator also sees its potential as a higher-volume "foundation filler" to be placed before installing thinner overlying applications of more expensive flexible repair materials such as mastic, thereby reducing the quantity and cost of using such materials.

Microwave-based repairs were shown to be the least temperature-dependent of the two taconite-based repair options and of most pavement repair options in general. Whereas the Rapid Patch compound appears best-suited for rigid repairs in PCC pavements under cool to moderate ambient temperature conditions, the microwave repair approach is best-suited for repairing potholes in hot mix asphalt (HMA) pavements at all ambient temperatures, including very cold. Modeling indicates that microwave repair of asphalt pavement at a temperature of 0° F (-17.7° C) would take only about 25% (about two minutes) longer than microwave repairs made when the asphalt pavement temperature is 40° F (4.4° C). The modeling results are in good agreement

with what was measured during project field trials, where individual repairs took about 10 minutes to complete.

Because the microwave equipment heats the existing pavement to the point that the pavement itself becomes part of the repair, an excellent bond is achieved. In the investigator's opinion, it is this microwave-induced thermal bond between the repair and the surrounding pavement that makes the technology superior to most other methods for repairing potholes in HMA pavements, especially wintertime repairs. Nearly as important, the project also demonstrated that an effective microwave pothole repair compound can be made almost entirely from inexpensive and abundant recycled materials such as recycled asphalt pavement (RAP) and shingles (RAS), as opposed to cold and hot mix repair compounds that rely on specialized asphalt formulations, virgin asphalt, and/or binders.

The microwave's ability to "anneal" a butt joint (the abutting joint between asphalt placed at two different times) was also tested at MnDOT's Nopeming Truck Station location in November 2012. The test, in part, was conducted to also assess the potential for using microwave technology to improve the bond along the longitudinal joint between adjacent lanes/lifts of asphalt pavement. The difference between the microwaved and non-microwaved portions of the butt-joint is significant, and suggests that follow-up development and testing of this microwave "annealing" concept is warranted.

The project has also shown that some pavements are in such poor condition that no repair should be expected to last very long; or—conversely—that the repair itself may outlast the surrounding pavement. The key to a resilient and long-lasting repair is achieving an impermeable and tight bond at the pavement and repair interface. Preventing infiltration and accumulation of moisture at this interface is crucial for preventing repair failure. Lacking a good bond, repeated freezing and thawing at the interface can further weaken the repair and enlarge the crack surrounding the repair, due to: a) the force of expanding ice during freezing conditions; and b) the equivalent of hydraulic fracturing ("fracking") occurring when the tires of vehicles force liquid water and suspended fine aggregate particles into those cracks during wet, non-freezing conditions.

Preparation is also important for achieving a good bond. No repair will perform adequately if the pavement surrounding and underlying the failure is poorly prepared. At a minimum, loose debris and excessive moisture within the failure should always be removed prior to the repair. Compressed air, stiff brooms, weed torches, and portable compactors are common tools that are and can be used for this purpose.

It was also observed that the more closely a repair compound's stiffness is matched to the pavement type being repaired, the more likely a better repair will result. For example, a softer repair like an asphalt-based cold-patch placed within a more rigid pavement is more likely to deform and push, whereas a rigid repair placed within a more "flexible" pavement may be more prone to de-bond at the dissimilar repair/pavement interface.

Maintenance crews and engineers continue to stress the need for more effective and more efficient (mechanized/automated) pavement repair and maintenance solutions. The ideal repair would be a repair that lasts at least a year, can be performed in all seasons, and can be installed

easily and relatively quickly—all while keeping traffic delays to a minimum. At this point in time, no single repair method achieves this ideal. However, the two alternatives studied during this project represent potentially important steps in that direction, and at a minimum, they represent additions to the “tool-kit” of maintenance and repair options that can be applied to pothole and other pavement failures and distresses.

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Appendix A
Rapid Patch and Microwave Information Sheets

Rapid Patch Informational Sheet



Rapid-Patch™ Fast Set Pavement Repair

All Weather, Fast Setting Patching Material for Concrete and Asphalt Pavements

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Product Description

Rapid Patch™ Fast Set Pavement Repair is a high strength, fast setting, non-shrink, patching material for concrete and asphalt surfaces including roads, city streets, highways, bridge decks, railroad crossings, man hole repairs, commercial and industrial applications. This product is ideally suited to be used in cold weather applications for a one-time fix of potholes or man hole repairs in winter, spring or fall.

Fast Set Pavement Repair is a two-component patching material that sets by an exothermic chemical reaction, resulting in a material that generates a large amount of heat. This heat-generating ability means the patching material will set quickly, even at ambient temperatures that are much colder than conventional patch materials. The materials quickly react to form a cohesive mass that can be used to fill void spaces, such as potholes in roads. In addition, the reactive nature of the angular aggregate surfaces significantly strengthens the patch material.

When/Where to Use

- Concrete/asphalt repairs at least 1" deep
- One-time pothole repair
- Roads, streets and highways
- Municipalities
- Commercial or industrial projects
- Man hole or drain repairs
- Bridge decks & railroad crossings

Advantages

- Fast-setting (10-30 minutes)
- Cold weather application
- Easy to mix and handle
- Excellent freeze/thaw and salt-resistance properties
- Pedestrian traffic in 15-30 minutes
- Vehicular traffic in 30-60 minutes
- Patch bonds to hole in pavement
- Material will not shrink

Typical Yield

Mixing one 63# bag of aggregate and one 27# bag of activator materials (with water) will yield approximately .65 cubic foot

Packaging

Mix the following components at a 1:1 ratio:

- 63 lb. bag (27.2 kg) of aggregate / binder
- 27 lb. bag (12.3 kg) of activator materials

Surface Preparation

All surfaces must be structurally sound and non-flexing. Remove all dust, waxes, sealers, old adhesive residue, curing compounds, oil or other foreign materials prior to application.

Mixing and Application

- Step 1: Add activator powder (27 lb. bag) to paddle mixer
- Step 2: Add 6 pints of water to activator and mix until it reaches a uniform slurry (30-60 seconds)
- Step 3: Add Rapid Patch™ Concrete Aggregate / Binder (63 lb. bag)
- Step 4: Mix for two minutes until lump-free. If necessary, additional water may be added for desired consistency. Mixture should be nearly flowable.

Clean Up

Clean tools with water. If material has begun to harden, warm soapy water may be helpful for cleaning hands and tools.

Notes

- Mixture behavior is very sensitive to temperature. Higher temperatures equate to faster set times and less pot life. Factors to consider include the temperature of the materials prior to mixing, ambient temperature, and temperature of the substrate the patch will be placed upon.
- Thicker patches will build heat faster and set more rapidly. Thin areas will set more slowly.
- Proper consolidation is critical for repair durability.
- Use potable water for mixing.
- Clean trowel frequently during the application
- Do not over-work or over-trowel
- Materials must be conditioned to 50° F or warmer, if ambient temperature is below 32°F.



WARNING: INJURIOUS TO EYES!

KEEP OUT OF REACH OF CHILDREN!

Precautions

This product contains reactive chemicals. Contact with the mixture or the components can cause irritation to skin. The materials mixed onsite are acidic in nature and on contact with water may irritate the eyes and skin. If contact with eyes occurs, flood eyes repeatedly with clean water and see a physician immediately. Do not rub eyes. Wash hands thoroughly after handling or before eating. Do not take internally. This product may contain silica. Inhaled silica dust may cause respiratory or other health problems.

Warranty

Seller warrants that its product will conform to and perform in accordance with the product specifications. The foregoing warranty is in lieu of all other warranties, express or implied, including, but not limited to, those including merchantability and fitness for a particular purpose. Because of the difficulty in ascertaining and measuring damages hereunder, it is agreed that, the seller's liability to the buyer at no point for any particular project shall exceed the total purchase price of said product.



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Microwave Repair Informational Sheet

The following informational sheet is based on what was originally developed by Zanko and Hopstock (2011) for the project, *Taconite-Enhanced Pothole Repair Using Portable Microwave Technology*, LRRB Local Operational Research Assistance Program (OPERA) for Local Transportation Groups, Project Number 2009-01. It has been modified to reflect the current project's findings.

Repair Concept

By combining magnetite-containing aggregate and/or magnetite powder alone with recycled asphalt pavement (RAP), heating of the mixture and the contained asphalt binder is enhanced. This type of patching compound is placed in a pothole and is microwaved until the contained binder softens to a point where it is compactible. The microwave energy will also heat and soften the adjacent asphalt pavement, contributing further to a good repair bond. The addition of granular recycled asphalt shingles (RAS) can provide additional binder to the compound.

There are several benefits to patching potholes with this system. Due to the in-place heating mechanism, moisture will be driven off and the patch will more readily adhere to the surrounding pavement. Patch material can be premixed and stockpiled or can be mixed on site, and transportation of hot material is not necessary. This patching system is also ideal for cold weather situations.

Procedure

Equipment

- Mobile microwave equipment having minimum operating power output of 40kW;
- Portable generator;
- Air compressor or leaf blower;
- Propane torch (weed burner);
- Gasoline-powered tamper/compactor; and
- Hopper or truck containing loose but well-blended mixture of repair compound, i.e., recycled asphalt pavement (RAP)/millings, microwave-absorbing taconite materials (Tac), and recycled asphalt shingles (RAS).

Field Tools

- Shovels;
- Stiff broom;
- Wheel barrow;
- 5-gal buckets; and

- Hand-held infrared thermometer for recording ambient (starting) pavement temperature and final patch temperature.

Repair Steps

Clean loose debris and/or blow water from pothole. In sub-freezing temperatures, preheat pothole and pavement adjacent to hole with microwave unit to melt or debond any ice or snow in the hole, and to soften the pavement. Remove or blow out loosened/melted ice/snow. Place mixture of recycled asphalt pavement (RAP)/millings, microwave-absorbing taconite materials (Tac), and recycled asphalt shingles (RAS) into the pothole. Overfill the hole by about two inches to allow for final compaction. Heat mixture of RAP, Tac, and RAS until temperature reaches at least 230° F at base of mixture in the hole. Sufficient heating takes place in about 8 to 12 minutes at a 40kW power level. Compact heated mixture with portable gasoline-powered compactor.