Evaluation of High Performance Pavement and Bridge Deck Wearing Surface Repair Materials

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This project provided for a laboratory and field testing of several high performance repair materials for pavements and concrete bridge decks. The main purpose was to provide ODOT with materials and procedures to shorten road and bridge closures. The project was relatively complex with several phases. First, the repair materials for testing and the locations needed to be selected. This required a thorough review of the available literature, including the practices used by other state transportation agencies. Next, the repair materials were installed on pavements and bridge decks on three separate installation projects in ODOT District 8, two by the Great Lakes Construction Company (TGLCC), and two with ODOT maintenance crews. There was a cold weather installation on bridge decks and concrete pavements in March 2014, with two products rated for low temperatures, followed by a larger installation on concrete pavement with four other products in June 2014. The first two installations were carried out by TGLCC. These installations were monitored for two years from the first installation. In June 2015, five bridge deck patches with two materials were installed by the ODOT maintenance crews. In addition, a parallel laboratory testing program of the selected materials was carried out to evaluate performance and engineering properties. Finally, the specification recommendations were developed based on the literature review and project results. The phases of the project are documented in five separate graduate theses published at Cleveland State University.

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Completion of this study was assisted by a number of groups and individuals, without which this study could not have been completed. The research team would like to acknowledge and thank Jeff Jones, Jeff Darrah, Tony Gamiere, Eric Martin, Chris Robertson, Greg West, and Marcus Werner from the Great Lakes Construction Company, along with ODOT District 8 for their assistance, support, and coordination to make the field installation and testing possible. Special thanks to product representatives Chris Burford and Uriah Carpenter for coming out for the installation of their corresponding products. Recognition is also given to the Technical Panel members who assisted during the project, Gary Middleton (lead), Joe Bassil, Brandon Collett, Bill Davis, and Jennifer Elston.

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Executive Summary

This project provided for a laboratory and field testing of several high performance repair materials for pavements and concrete bridge decks. The main purpose was to provide ODOT with materials and procedures to shorten road and bridge closures. The project was relatively complex with several phases. First, the repair materials for testing and the locations needed to be selected. This required a thorough review of the available literature, including the practices used by other state transportation agencies. Next, the repair materials were installed on pavements and bridge decks on three separate installation projects in ODOT District 8, two by the Great Lakes Construction Company (TGLCC), and two with ODOT maintenance crews. There was a cold weather installation on bridge decks and concrete pavements in March 2014, with two products rated for low temperatures, followed by a larger installation on concrete pavement with four other products in June 2014. The first two installations were carried out by TGLCC. In June 2015, five bridge deck patches with two materials were installed by the ODOT maintenance crews.

These installations were monitored for two years from the first installation. In addition, a parallel laboratory testing program of the selected materials was carried out to evaluate performance and engineering properties. Finally, the specification recommendations were developed based on the literature review and project results. The phases of the project are documented in five separate graduate theses published at Cleveland State University.

For even a small repair project, the amount of time necessary to establish traffic control and prepare for patching is significant, and thus the difference between a material that can be opened to traffic in one hour versus two hours is not necessarily that great in terms of the total closure, although it some cases such as the closure of the I-75 bridge deck in downtown Cincinnati, that small difference can be important. Materials that require the use of a bonding agent, which typically has an additional cure time before the repair material can be applied, add to the length of the required work zone closure.

It is imperative to adequately locate the limits of unsound material by sounding or other methods. Otherwise, the patch may not encompass all of the deteriorated area, and new distress may form next to the patch.

The high performance repair materials investigated in this study did not work well with asphalt pavements, even when recommended for that use by the manufacturer. Conventional asphalt patching techniques are likely to be more reliable and economical.

In this case, the lowest cost repair material performed nearly as well as the highest priced materials that cost more than 20 times as much. Many of these materials were developed for airfield repair, which has much more stringent consequences for poor performance than typical bridges and highways. Thus, it is recommended that the higher cost materials be used only if there is some other parameter which justifies the use (e.g. hot or cold weather application or complicated structural elements such as bridge expansion joints).

For larger patches, the use of small batches is problematic. The time to mix a large number of batches is an issue as is the possible formation of cold joints as the material sets while additional material is mixed. Furthermore, mixing many small batches can increase the time of closure. In the cases of large patches, it would be better to extend the material with clean, sound pea gravel and use a larger capacity field mixer. This has a number of potential benefits: It will reduce the cost of the patch by about half, will reduce the heat generated by the patch, which can be a problem with large volume patches in hot weather and will also help to prevent cold joints in the patch. The pea gravel is dimensionally stable and will also reduce the shrinkage of the patch, reducing the risk of cracking and debonding.

It should be noted that at this point the patches have only been observed for two winters. Each winter will be different in terms of cold, freeze thaw, snowfall and salt application. All of the patch locations and dimensions are documented in Lesak (2014) and Susinskas (2016) and ODOT District 8 maintenance personnel are aware of both the existence and the general locations of the patches. If any of those patches fail in the future, the information is readily available to identify what material was used. It is recommended that District 8 personnel continue to monitor the patches and refer to these documents in case performance problems are observed.

Introduction and Problem Statement

The Ohio Department of Transportation identified the need to specify durable, more permanent high performing pavement and bridge deck patching materials that allow for expediting pavement and bridge deck wearing surface repair for worker and user safety. Currently, either temporary or generally specified in-kind or like materials are being used to perform pavement patching. Usually, the Department provides generically specified cementitious or cold mix asphalt materials for patching wearing surfaces with varied performance characteristics.

Current products used for this purpose are generally those that have been used for many decades and for which competition exists. New or proprietary products are difficult to specify unless incorporated into a construction project for research purposes, an approved equal is permitted, or procurement of the product complies with the Department's direct purchasing requirements. This creates a situation in which a product with highly desirable characteristics is precluded from use.

Repair is a complex problem. The general principle is to repair with like materials, that is to say, concrete with cementitious materials, and asphalt with hot mix or cold patch materials. However, some materials are difficult to supply or mix in small quantities. Asphalt repair materials may be difficult to compact effectively in small patches. For concrete, rapid hardening cementitious materials are preferred over conventional concrete to reduce traffic interruptions.

Durable repairs may have different material properties from those used in initial construction. For example, bond strength and dimensional stability, such as limits on shrinkage or expansion, may be much more significant than for repair materials than for normal construction materials. High early strength cementitious materials may also have high stiffness (modulus of elasticity), which can lead to stress concentrations and early patch failure. In many instances, products that perform well in the laboratory may turn out to not perform nearly so well in the field. Also, products are continually being reformulated or removed from the market and replaced with other materials. This makes it difficult to maintain approved product lists.

Installation procedures also have a significant effect on performance. Removal of existing distressed material must be carried out carefully in order to prevent undue damage to the remaining pavement or bridge deck or to reinforcing steel. Patch holes must be clean and dry, and may need to have tack coat or some other bonding agent applied. Curing of cementitious materials and proper compaction of asphalt materials may be difficult to carry out on a small scale, but are critical to long term performance of repairs.   All of this is complicated by weather related issues. Proper preparation of the substrate may be very difficult in cold and/or wet conditions. Repair materials may not set or cure properly in cold weather and, since some generate a large amount of heat during curing, use in excessively hot weather may be problematic.

Research Objectives and Background

Research Objectives

The goals and objectives of this study were to:

- Identify/determine acceptable field performance criteria for comparative analysis of selected products.
- Install the products at locations arranged in cooperation with ODOT District 8.
- Evaluate the products based on field performance criteria.
- Provide updated field performance evaluation criteria based on the field performance analysis.
- Provide a comprehensive standard material and performance based generic specifications in the Standard ODOT Construction and Material Specifications or Supplemental Specifications format based on desired ASTM or equivalent material properties and field performance analysis.
- Provide a decision matrix for use of the recommended products as set forth in the deliverables section.

These products were installed throughout the entire year in order to determine seasonal installation acceptability, especially in the winter months, for use by ODOT Maintenance forces. Evaluation also had to include at least one summer and one freeze thaw cycle to adequately evaluate product performance in all weather conditions. The evaluation timeframe was three years to include 2 winter periods, 2014 through 2016.

Key Points

The key points to this research were to:

- Review previous research by other experts and transportation agencies to determine what test methods were typically used, and what products and product categories were typically specified.
- Install products under carefully controlled and monitored field conditions, using consistent best practices for installation.
- Provide for two full winters of exposure.
- Regularly monitor patch performance, and determine timing and reasons for any material failures.
- Complement the field testing with parallel laboratory testing, in order to predict and explain any differences in field performance.
- Provide specification recommendations for economical and long lasting patches.

Literature Search and Synthesis

There is considerable research on the topic of concrete repair. The selection of the repair materials for this project was documented by Sommerville (2014). She recommended ten specific repair materials for testing. Literature was reviewed including reports from the U.S. Army Corps of Engineers airfield repair research program (Priddy and Rushing, 2012) and the National Transportation Product Evaluation Program (NTPEP 2004, 2005, 2006, 2007), as well as standards and specifications from other state transportation agencies. This included a thorough review of the test methods and standards typically used for repair materials for concrete. Woods (2016) developed a list of repair materials that appear on five or more state approved products lists. This is provided as Appendix A.

In addition, the research team consulted with the technical panel and ODOT District 8 about specific materials to investigate. The products were selected to provide a range of material types, for example, selecting from among conventional portland cement based materials, ultrafine portland cement, high alumina cement, magnesium phosphate concrete, polymer modified concrete, polymer concretes, and epoxy compounds. Chapter IV of Sommerville's thesis (2014) also provides a detailed discussion of asphalt repair.

Lesak (2014) continued the literature review with a focus on documenting field testing methods, including visual inspection, delamination testing, and various types of nondestructive evaluation for internal cracking and damage, such as ultrasonic pulse velocity (UPV) and impact echo. He also reviewed methods of extracting and testing cores, although those were not used in the field in this research.

Amini (2015) expanded on Sommerville's work with an extensive discussion of bonding in concrete repair systems and of the test methods used in the experimental program. His literature search synthesized the factors that affect the performance of the bond in the field. These include the workability of the repair material, the tensile strength, and the surface preparation including cleanliness and removal of laitance.

General Description of the Research

The project was relatively complex with several phases. First, the repair materials for testing and the locations needed to be selected. This required a thorough review of the available literature, including the practices used by other state transportation agencies. Next, the repair materials were installed on pavements and bridge decks on three separate installation projects in ODOT District 8, two by the Great Lakes Construction Company, and two with ODOT maintenance crews. These installations were monitored for two years from the first installation. In addition, a parallel laboratory testing program of the selected materials was carried out to evaluate performance and engineering properties. Finally, the specification recommendations were developed based on the literature review and project results. The phases of the project are documented in five separate graduate theses (Sommerville, 2014; Lesak, 2014; Amini, 2015, Susinskas, 2016; and Woods, 2016) published at Cleveland State University, all of which are available online at http://www.csuohio.edu/engineering/civil/student-theses-0.

Field Performance Criteria

Satisfactory repair materials should exhibit the following field performance characteristics:

- High early strength
- High durability
- Installation efficiency
- No surface damage
- No internal cracking
- No separation from underlying pavement/ bridge deck (debonding)
- No other indications of distress

Selection of Repair Materials and Locations for Field Testing

Repair materials and procedures for both concrete pavements/bridge decks and asphalt pavements were evaluated. Installations were to be made in both cold and warm weather, so some materials appropriate for low temperature installation were needed. For concrete repair in cold weather, Roklin Systems Inc. FlexSet, a polymer concrete, and IMCO Technologies Inc. MG Krete, a magnesium phosphate material, were used. These could be installed in temperatures as low as – 10° F (– 23° C) for FlexSet and 14° F (– 10° C) for MG Krete (Sommerville, 2014, Lesak, 2014). FlexSet could also be used to repair asphalt pavement as well as concrete. The cold weather repairs were done in March 2014.

For warm weather installation, the selected materials were Southern Resins SR-2000, D.S. Brown – Delpatch, SpecChem RepCon 928, and Quickcrete FastSet DOT mix. Only the SR-2000 could be used on asphalt pavement as well as concrete. The other three are only suitable for concrete repair. The warm weather patching occurred in June 2014. The products selected and their characteristics are shown in table 1.

Table 1: Characteristics of Products Tested

Product	**Material Category**	**Cost per ft.^{3} (m^3)**	**Primer Needed**	**Opening to traffic, hours**	**Temperature range, °F (°C)**
FlexSet	Polymer concrete	$ 235.00 ($ 8,300)	No	0.5	– 10 to 140 (– 23 to 60)
MG Krete	Magnesium phosphate	$ 122.22 ($ 4,320)	No	2	Above 14 (above – 10)
SR-2000	Polymer concrete	$ 175.00 ($ 6,180)	Yes	2	35 to 120 (2 to 50)
Delpatch	Polyurethane estomeric	$ 232.43 ($ 8,200)	Yes	1	Above 45 (above 7)
FastSet DOT Mix	Rapid hardening	$ 11.32 ($ 400)	No	1.5	Not provided*
Repcon 928	Polymer modified	$ 57.36 ($ 2,025)	No	3	45 to 85 (7 to 29)*

* Use cold mixing water for high temperatures

Originally, in place of the Quickcrete product, a different product, Watson Bowman Wabo Elastopatch, had been selected. However, when the contractor attempted to order the material, it was no longer available due to an aggregate shortage. This illustrated one of the difficulties with specifying proprietary materials of this nature, which is that new products are frequently introduced and existing products are discontinued, so that approved product lists become out of date. The Quickcrete product was selected even though it is already on the ODOT approved list as it provides a useful comparison. It is a material ODOT workers are already familiar with and it is significantly cheaper than the other materials in the study, at approximately $ 11.32 per cubic foot ($ 400 per cubic meter). The other products cost between a low of $ 57.36 per cubic foot for RepCon 928 to a high of $ 235 per cubic foot for FlexSet ($ 2,025 to $ 8,300 per cubic meter, respectively). The costs were list prices. In this project, the contractor was able to get them at lower cost but that since pricing occurs on a case-by-case basis and is subject to market forces (shortage or surplus), list price provides a more reliable comparative measure.

The locations of the March and June 2014 installations are shown in figure 1. Location A consisted primarily of a badly deteriorated bridge deck, with some nearby asphalt potholes for patching. Locations B, C, D, E, and F were all reinforced concrete pavement, with a few asphalt potholes for patching. The reinforced concrete pavement here along eastbound US 35 has considerable shallow concrete spalling due to a construction defect which resulted in shallow steel reinforcement placed very close to the pavement surface. As the reinforcement has corroded, thin chunks of concrete have spalled loose. This has led to either potholes temporarily filled with asphalt, or locations of loosely attached concrete likely to come out in the near future.

In June 2015, another set of bridge deck repair patches were installed on a bridge deck of I-75 in Cincinnati, just north of exit 2A Western Avenue/Liberty Street in the southbound lanes. The bridge was over Bank St. between Winchell and Dalton. These patches used MG Krete and RepCon 928 for the repair materials.

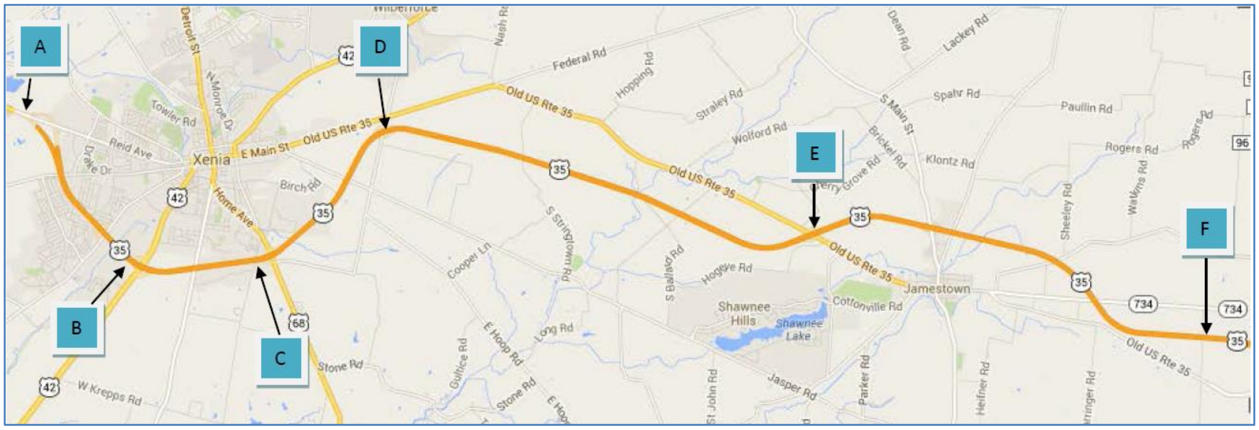


Figure 1: Location of Installation Sites March and June 2014 (Lesak 2014)

Installation of Repair Materials

Installation of repair materials was documented by Lesak (2014) and Susinskas (2016). In order to ensure consistency of installation, the patches in March and June 2014 were installed by the same crew from the Great Lakes Construction Company. It is known that correct patch installation is necessary for satisfactory performance, and using this contractor ensured consistency of installation so that performance differences would be due to material properties.

The bulk of the work in March 2014 was carried out at the bridge deck at location A in figure 1, west of Xenia, Ohio. The patch extended for a full lane width of the bridge deck and nearly half of the deck thickness. It took considerable time to jackhammer out the hole and then to dry out all of the water, and it took several dozen batches of material to fill the patch. This patch is shown in Figure 2. The board separates the two materials used in this patch, FlexSet to the left and MG Krete to the right. During the installation, it was observed that the bridge deck at this location was in poor condition, to the point that there was concern about punching completely through the deck during concrete removal.

Other patches were installed at locations further east along US 35. This was intended to be approximately 20 % of the total number of patches for this project. In all cases, including the June 2015 installation by an ODOT District 8 crew, small mixers of approximately 5 gallon (20 liter) capacity were used to prepare the individual batches. Most batches provided sufficient working time, but in some cases, particularly at higher temperatures, the working time to place and finish the patch was very short. Ice was used to cool mixing water during warmer weather.

The work in June 2014 installed the other approximately 80 % of patches at locations B through E, south and east of Xenia, Ohio. These were all concrete pavement locations. The same tests and monitoring were carried out as in March 2014. A typical patch repair hole is shown in Figure 3.

Figure 2: Bridge deck patch installation (Lesak 2014)

Figure 3: An example of a clean, smooth-cut hole, where patch #14 was installed (Lesak 2014)

During these two installations, Lesak (2014) documented temperatures, times of patch installation, and the location and dimensions of each patch. Because some of the repair materials can generate considerable heat during curing, with a risk of thermal cracking, an infrared camera was used to monitor the highest temperatures reached. An example of an illustration taken of a patch during curing is shown in figure 4. In the later analysis, no correlation was found between the high temperature reached by the patch and its subsequent performance.

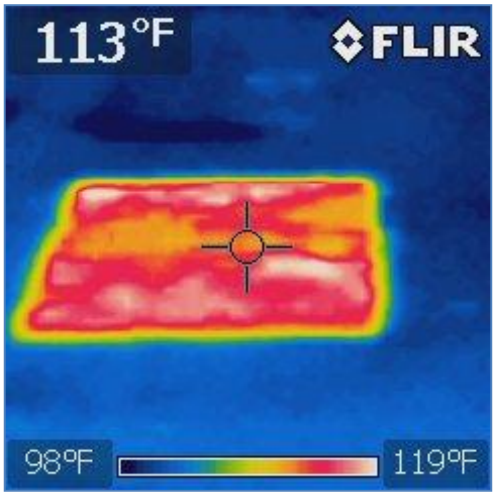


Figure 4: Infrared camera picture of patch temperature and variation (Lesak 2014).

The Delam 2000 tool for detecting and mapping shallow delaminations is shown in figure 5. The figure does not show the extension handle, which allows an operator to roll it along a pavement or bridge deck while standing straight up. This tool was used for monitoring patch performance after installation, but it also proved to be very useful for defining patch limits during installation, making sure that there were no shallow delaminations adjacent to the patch that would cause damage to spread. The research team also used a piece of reinforcing steel to tap to identify delaminated areas, but the Delam 2000 proved to be much more reliable. It is a relatively inexpensive tool, only a few hundred dollars, and would be useful for repair crews to carry and use during patching operations. It is easy to operate while standing up, and it is very easy to hear the difference between the low pitched dull sound of intact concrete and the high pitched ring of a shallow delamination.

Figure 5: Delam 2000 rotary percussion tool for detecting shallow delaminations

On occasion, it may be preferable to have ODOT maintenance crews install patches rather than hire a contractor. Therefore, in 2015, the research team decided to purchase repair material and observe installation by an ODOT crew. MG Krete and RepCon 928 were purchased since they had been performing well at this point in the study. The installation occurred in the southbound lanes of I-75 in Cincinnati near the Western Avenue exit. Due to heavy traffic at the location, these had to be installed at night, on the evening of June 22, 2015. Similar monitoring was carried out as for the 2014 installations. Five patches were installed. Four were relatively small, but one was considerably larger.

For this field test, the first patches were placed using MG Krete. However, due to high ambient temperatures, the MG Krete would not provide enough working time without a retarder. Therefore, the other patches were repaired using the RepCon 928. This went well for all of the bridge deck patches except the last, which was 93 by 68 inches by 3 ½ inches deep (2.4 m by 1.7 m by 90 mm). It took 28 batches of material to fill this patch. The RepCON 928 material had a high flow and tended to spread out when placed, creating large surfaces. It also tended to flow into the lowest part of the patch regardless of where it may have been placed. As a result, when fresh material was placed it often did not completely cover the exposed areas of recently placed material; meaning that it often took several applications of fresh material to completely cover previously placed material. Given that it took a few minutes to mix the material and it could only be prepared in small batches, there is a reasonable probability that cold joints formed in the patch.

In retrospect, rather than using a small bucket size mixer, a larger mobile laboratory type mixer should have been used, and it would also have been a good idea to extend the material with pea gravel for this size patch. Subsequently, the research team consulted with the product manufacturer about the procedures and quantity of pea gravel for extending the material and mixing it in a 9.5 cubic foot (0.3 cubic meter) portable laboratory mixer. This was easy and is recommended for larger patches.

Monitoring of Repair Material Performance

The monitoring of the performance of the repair materials was documented by Lesak (2014) and Susinskas (2016). Field monitoring was divided between Cleveland State University (CSU) and the University of Cincinnati (UC). The intent was for UC to provide more frequent monitoring, primarily visual observation, and for CSU to provide in depth analysis supplemented by nondestructive evaluation. Major investigations were carried out by CSU and UC researchers in August 2014, June 2015, and March 2016, and are documented in detail by Lesak (2014) and Susinskas (2016). UC performed additional visual inspections in May and October 2014 and December 2015.

Various types of nondestructive evaluation equipment have been used to assess the condition of the patches. For the June 2015 and the March 2016, the research team had obtained access to some fairly new equipment, a digital Proceq Silverschmidt rebound hammer and a Pile Dynamics Acoustic Concrete Tester (ACT). This allowed a comparison of this data for that period of exposure, and is documented in detail in Susinskas (2016). The Delam 2000 tool was also used to investigate whether any of the repairs were beginning to separate.

Overall, the patches have been performing very well, with no real differences in performance. Since the low cost Quickcrete FastSet DOT Mix product performed nearly as well as the others, the use of higher cost materials may not be necessary under most conditions.

From the final inspection, which included both visual observation and NDT measurement, a few general conclusions can be drawn:

1) All of the materials appeared to perform quite well. There were a few instances of cracking and full or partial failure, but this was not tied to any particular material.
2) In the cases of excessive cracking or partial failure, the cause appeared to be failure or problems with the substrate material as opposed to failure of the patching material (see discussion below).
3) The Delpatch and the RepCon materials, in general, exhibited little or no cracking (except for cases of substrate failure). The other materials showed some degree of minor cracking that matched cracks in the surrounding pavement, suggesting reflective cracking. Except for cases of substrate failure, none of the cracks were large and none would impair performance. Except for the SR-2000 material, the patches held the tining for surface roughness.
4) The SR-2000 material held up quite well but did not retain the anti-skid surface. This surface was formed by layering a sand like material on top. This anti-skid material was already starting to wear off when the first visual inspections were made and by the final inspection some of the patches had become smooth and slick. This material did not appear to hold a tined surface, either.

Although the patches, in general, performed well, there were three important exceptions. The first was the small number of patches in asphalt pavement repaired using the flexible materials FlexSet and SR-2000. There was considerable cracking of the material, especially around the edges. Over several visual observations, it appeared that failure was mostly caused by failure of surrounding material as opposed to failure of the patch itself. This is shown in figure 6. It also appeared that the problem was an extremely stiff patch in a very flexible material. The patch probably attracted most of the stress leading to failure. Therefore, the materials investigated in this study should not be used to repair asphalt pavements, since other solutions are available at lower cost.

Figure 6: Example of failing patch in asphalt

The other exception was a failure of the bridge deck patch that was installed on the right side of figure 2, using MG Krete. The UC researchers were scheduled to perform a final pre-winter site visit on December 17, 2015. Just prior to the site visit the research team was informed by ODOT that part of the bridge deck patch placed in March 2014 had failed. Looking back at the photos from the June 2015 inspection it is clear that this particular patch was already showing distress at that time. In the center of figure 7, that part of the patch can already be seen to be severely cracked and there are signs of a punching failure.

Figure 7: Condition of bridge deck patch in June 2015

Examination of the photos provided by ODOT of the failed surface, one of which is shown in figure 8, plus the December 17 examination, suggested that the lower part of the bridge deck failed and fell out from under the patch. This would make it more of a substrate failure than a patch material failure. It is interesting that the rebar seems to be clean and in good condition, so rebar corrosion does not appear to be a factor.

Figure 8: Bridge deck patch failure (Photo provided by Brandon Collett, ODOT District 8)

From the beginning there were concerns about the soundness of the bridge deck substrate. When the project team installed these patches in the bridge deck, there was some concern about jackhammering too deep into the bridge deck. This makes it surprising that the patch held together for close to two years. In retrospect, this should probably have been a full depth patch rather than a partial depth patch; pointing out the need to properly assess the substrate conditions for any repair.

This hole has since been repaired with fresh concrete, and the entire bridge deck is scheduled for extensive renovation. This patch is the MG Krete material, which otherwise performed well in both the field and the laboratory, so it will be important to review the other patches made with this material to rule out material performance as a failure mechanism.

The large patch on the I-75 bridge in Cincinnati also failed. Here, the entire patch cracked into pieces and had to be removed for safety reasons prior to the final inspection. Thus, it was not possible to assess if the failure was a patch failure or a substrate failure. However, information from ODOT maintenance personnel suggested that the patch itself failed. This failure was likely due to the fact that this patch was just too big for the material used. As previously stated, it took 28 separate batches to fill the area. It was observed that some portions of the patch were beginning to set before additional material could be mixed and added. This likely caused cold joints in the patch. The issue of large patches will be addressed in the conclusions and recommendations section.

Laboratory Testing of Repair Materials

To supplement the field testing results, samples of the repair materials were brought back to the CSU research laboratories. The testing program and results are reported by Amini (2015). In addition to compressive strength tests, he also carried out testing for shrinkage and freeze-thaw durability.

The research team also developed a new test using composite freeze-thaw beams of ODOT Class S base concrete and bonded repair material. A typical specimen is shown in figure 9. This test evaluates the overall performance of the repair system, rather than just the material. This is important because a patch can fail in the existing patch concrete, in the new repair material, or in the bond between the two materials. The specimens were tested through 300 freeze-thaw cycles over about 2 months, following AASHTO T161 (ASTM C666), with resonant frequency testing by ASTM C215 (no comparable AASHTO specification) approximately every 30 cycles.

Figure 9: Two layer bonded specimen and ASTM C215 resonance testing (Amini 2015)

The purpose of the resonant frequency test is to determine whether freeze-thaw damage has occurred within a specimen. The concrete specimen is struck with a small hammer and vibrates at a specific frequency, which is a function of the geometry of the specimen, its mass, and its modulus of elasticity. As concrete is damaged by freezing and thawing, the compressive strength and modulus of elasticity both decrease. As a result, the concrete becomes weaker and less stiff and vibrates more slowly. The vibration frequency is measured before the specimen is subject to freezing and thawing, and then measured again after every 30 or so cycles of freezing and thawing, until 300 cycles are reached, generally at about 10 weeks of testing. The relative dynamic modulus (P_c), or durability factor, is the frequency after exposure divided by the original frequency squared, expressed as a percent (ASTM C 215):

$$P_c = (n_1^2/n^2) \times 100\ \%$$

The material is considered to fail the test if P_c falls below 60 % within 300 cycles. It is well known that AASHTO T161 (ASTM C666) is a harsh test method, and it is not uncommon for materials to fail the test in the laboratory but to have satisfactory field performance. Figure 10 shows the results of this testing. Three of the materials, FlexSet, MG Krete, and RepCon, showed excellent performance. Two others, the SR-2000 and the Quickcrete, showed some minor deterioration. This has not yet been observed in the field after two years of exposure, but the AASHTO T161 (ASTM C666) test is designed to predict long term performance.

One material, the Delpatch, showed a separation between the base material and the repair. This, however, contradicts the field observations, because this material remains well bonded and actually has continued to show some of the best visual appearance in the field. Delpatch requires the use of a bonding agent. It is possible that the bonding agent used in the lab was either contaminated or not applied correctly. Therefore, this result should be considered inconclusive, but the field performance of Delpatch should continue to be observed to see if this separation occurs in the future. Lesak (2014) provided the specific locations of all patches including those installed with Delpatch.

Once the materials had completed 300 cycles of freeze-thaw testing, pull-off testing was used to determine if the bond between the two materials was still intact. A 2 inch (50 mm) diameter coring drill was used to core down through the overlay into the substrate material, and then a steel pull off disk was bonded to the overlay material using epoxy. Specimens are shown in figure 11. Generally the materials remained well bonded following the freeze-thaw cycles.

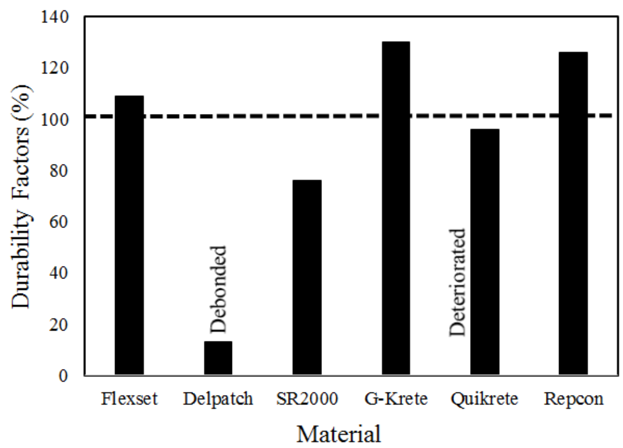
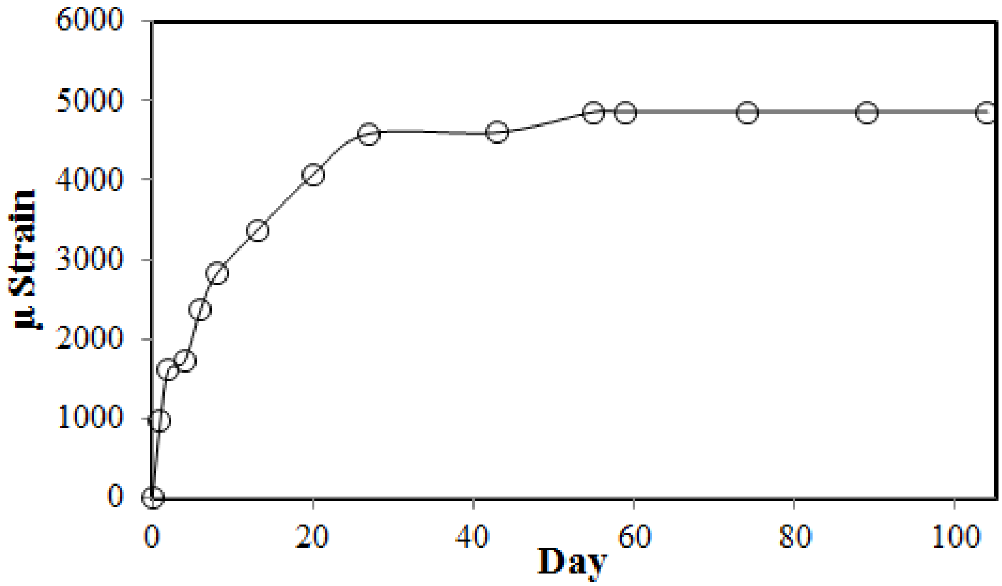


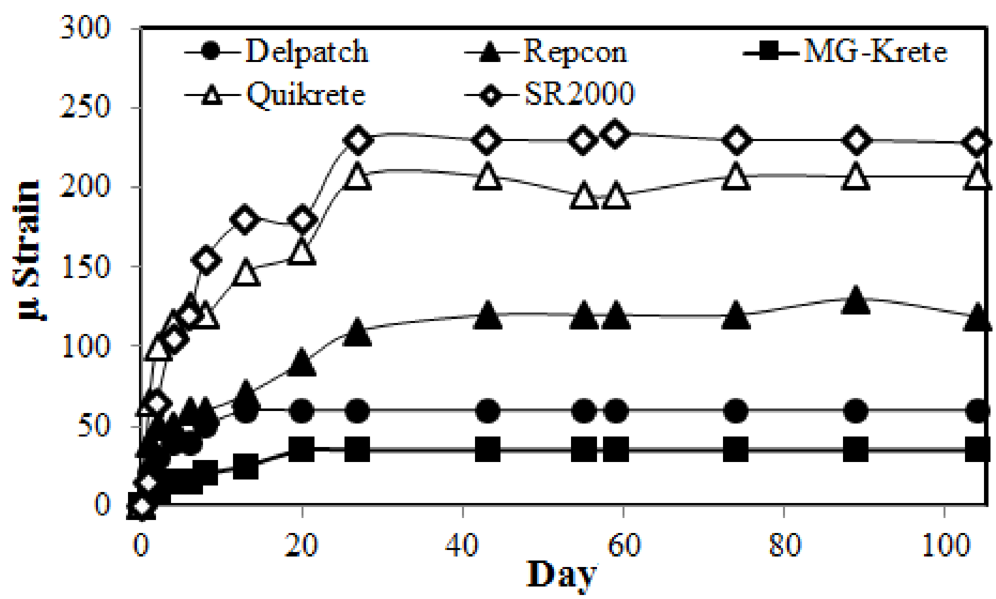
Figure 10: Durability factor of the repair materials after 300 cycles (Amini 2015)

Figure 11: Bond testing of two layer specimens following freeze thaw testing (Amini 2015)

Shrinkage prisms were also made in 3 by 3 by 11 inch (75 by 75 by 275 mm) molds, with embedded metal inserts (AASHTO T160/ASTM C157). Results are shown in figure 12. Five of the six materials showed shrinkage less than 250 microstrain (με), within limits in typical repair material specifications. The FlexSet had much greater shrinkage, approximately 5,000 microstrain (με) or millionths. This would normally suggest a material likely to crack and debond, due to high shrinkage stress development.



(a)



(b)

Figure 12: Shrinkage evolution of the repair materials (a) FlexSet, (b) Other repair materials (Amini 2015)

However, the FlexSet material has continued to perform well in the field. The compression test on this material shown in figure 13 suggests why. Whereas conventional concrete shatters in compression, the FlexSet is very flexible, deforms considerably and really does not fail in compression.

Therefore, since stress is proportional to strain times elastic modulus ($\sigma = \varepsilon E$), the high strain of the FlexSet is offset by the very low modulus, and the material does not fail. This illustrates the challenge of attempting to develop a specification that can address widely differing material types and properties.

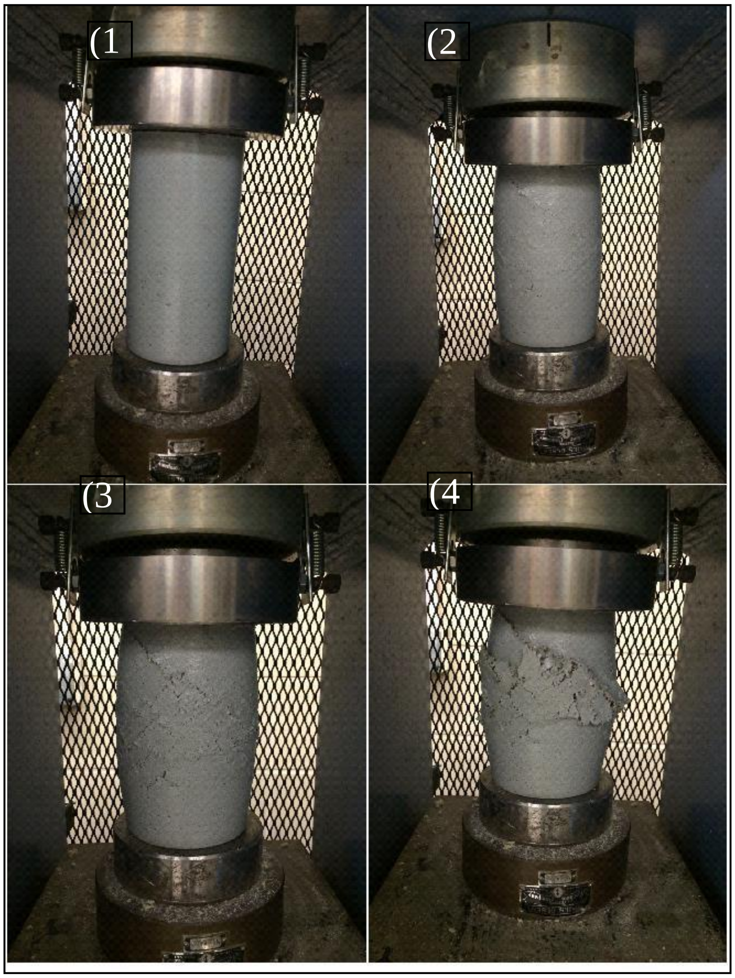


Figure 13: FlexSet cylinders under compression (Amini 2015)

Updated Field Performance Criteria

On the basis of the field and laboratory testing, the field performance criteria have been updated.

- High early strength – the materials should provide sufficient strength to support traffic within 1 to 2 hours after placement. All of the tested materials performed well in this regard.
- High durability – materials should be resistant to freezing and thawing. Through two winters, the materials tested did not show any obvious damage due to freezing and thawing cycles.
- Installation efficiency – two factors influence installation efficiency. One is whether a bonding agent is needed – applying a bonding agent and then allowing it to cure can add about half an hour to the road closure. The other factor is the efficiency of filling large patches. For larger patches, making small 5 gallon bucket mixtures requires too many batches, leading to delays in reopening the road and possibilities of cold joints within the patch. Materials that can be mixed with larger field mixers and extended with pea gravel are more appropriate for larger patches.
- No surface damage – patches should show no large scale surface damage. With the exception of some minor chipping, the materials tested did not have surface damage.
- No internal cracking – patches should not form internal cracks, which can lead to patches breaking up and disintegrating. There are two important exceptions – reflective cracks and sympathy cracks which extend into the patches from the bottom up or from the edges can be formed by the existing cracks in the base

concrete. A small patch cannot be expected to stop such cracks, so they should not be considered a sign of material failure.

- No separation from underlying pavement/ bridge deck (debonding) – the material should remain well bonded to the base concrete material. If it separates, it can be expected to break apart. Whether or not the patch is still bonded can be assessed using the Delam 2000 or a similar device or by tapping with a length of rebar.
- No other indications of distress – this was left as a final category, but the material distress would typically fall into the categories above.

When considering whether a material should be used by ODOT, it is important to understand reasons for any failures. Some patches failed during this study, but generally because they were installed on bridge decks with advanced distress. It appears that those failures should not be attributed to the repair material.

Development of Specification and Decision Matrix

Woods (2016) reviewed specifications and special provisions from nearly all 50 state transportation agencies. The language for removing damaged concrete and preparing to install the repair material was more or less consistent. There was a variety of materials allowed, basically breaking down into the categories of conventional portland cement based repair materials and the high performance repair materials reviewed in this study. Many state transportation agencies use lists of approve materials. The materials that show up on five or more state approved materials lists are shown in Appendix A. The proposed draft specification is provided in the appendix.

Some of the factors that affect the selection of repair materials are presented in the decision matrix in table 2. Examples from the material categories are provided in Table 1. The factors all require the same degree of careful preparation for repair, with removal of unsound concrete, preparation of the patch area, and drying out the patch site. Use of a bonding agent may add a half hour to an hour to the repair process.

Results

At this point, after two winters of exposure, all of the patches appear well bonded and appear to be performing well, with the exception of the issues addressed earlier. In those cases where the patches have not performed well, the issues seem to be mainly with the unsoundness of the base material (e.g. the bridge deck and the worn asphalt pavement) and not due to either the preparation methods or the repair materials used.

While the laboratory testing suggested some potential differences between materials, those have not yet been observed in the field. That may be due to the fact that there have only been two winters of exposure so far. The differences between materials may, however, show up over the next five to ten years.

Conclusions and Recommendations

The preparation techniques used by both the Great Lakes Construction Company and ODOT District 8 were sound and conformed to well accepted concrete repair practices. Specific details are reported by Lesak (2014) and Susinskas (2016). For even a small repair project, the amount of time necessary to establish traffic control and prepare for patching is significant, and thus the difference between a material that can be opened to traffic in one hour versus two hours is not necessarily that great in terms of the total closure, although it some cases such as the closure of the I-75 bridge deck in downtown Cincinnati, that can be important. Materials that require the use of a bonding agent, which typically has an additional cure time before the repair material can be applied, add to the length of the required work zone closure.

In some cases it proved difficult to determine the limits of unsound material when marking the patch areas. A tool such as the Delam 2000, or even a 4 to 5 foot (1.5 m) length of reinforcing steel if the tool is not available, can be very useful for determining appropriate patch limits.

The high performance repair materials investigated in this study did not work well with asphalt pavements, even when recommended for that use by the manufacturer. Conventional asphalt patching techniques are likely to be more reliable and economical.

Table 2: Decision Matrix for Repair Material Selection

Factor	Categories	Recommendation	Example Materials
Traffic interruption	Low traffic, long closure possible	Conventional cement based, lower cost repair material	Conventional concrete, Rapid hardening concrete
	High traffic, short daytime closure	Lower cost repair material, or HP repair material, allow bonding agent, open to traffic in 2 hours	Polymer modified or polyurethane elastomeric concrete
	Very high traffic, short night closure only	HP repair material not requiring bonding agent, rated for traffic opening in 1 hour	Magnesium phosphate, polymer modified, or polymer concrete
Durability requirement	Short term solution, facility replacement within 5 years		Rapid hardening or polymer modified concrete
	Long term solution, 10 to 15 years		Magnesium phosphate or polyurethane elastomeric concrete
Temperature during installation	Low (near or below freezing)	Low temperature rated material	Magnesium phosphate or polymer concrete
	Moderate (40 to 70° F)	Conventional or HP	Rapid hardening, polymer modified, or polyurethane elastomeric concrete
	High (80° F and higher)	Conventional, HP only if high temperature rated or with retarder	Rapid hardening or polymer modified concrete
Patch size	Small, less than about 2 by 2 feet by 3 inches deep (600 by 600 by 75 mm)	Use small batches, do not extent material with pea gravel	Rapid hardening, polymer modified, or polyurethane elastomeric concrete
	Larger than about 2 by 2 feet by 3 inches deep (600 by 600 by 75 mm)	Use a portable higher capacity mixer, extend with pea gravel	Magnesium phosphate or polymer modified concrete w/pea gravel
Bridge deck substrate condition	Distress limited to top third or half	Surface patch	Based on other criteria
	Distress through full thickness	Cut through and form full depth patch	Based on other criteria
Pavement Type	Asphalt pavement	These materials are not recommended	These materials are not recommended
	Concrete pavement	All materials tested are satisfactory	Based on other criteria

In this case, the lowest cost repair material performed nearly as well as the highest price materials that cost more than 20 times as much. Many of these materials were developed for airfield repair, which has much more stringent consequences for poor performance than typical bridges and highways. Thus, it is recommended that the higher cost materials be used only if there is some other parameter which justifies the use (e.g. hot or cold weather application)

For larger patches, the use of small batches is problematic. The time to mix a large number of batches is an issue as is the possible formation of cold joints as the material sets while additional material is mixed. In the cases of large patches, it would be better to extend the material with clean, sound pea gravel and use a larger capacity field mixer. This has a number of potential benefits: It will reduce the cost of the patch by about half, will reduce the heat generated by the patch, which can be a problem with large volume patches in hot weather and will also help to prevent cold joints in the patch. The pea gravel is dimensionally stable and will also reduce the shrinkage of the patch, reducing the risk of cracking and debonding.

It should be noted that at this point the patches have only been observed for two winters. Each winter will be different in terms of cold, freeze thaw, snowfall and salt application. All of the patch locations and dimensions are documented in Lesak (2014) and Susinskas (2016) and ODOT District 8 maintenance personnel are aware of both the existence and the general locations of the patches. If any of those patches fail in the future, the information is readily available to identify what material was used. It is recommended that District 8 personnel continue to monitor the patches and refer to these documents in case performance problems are observed.

Recommendations for Implementation of Research Findings

The draft specification provided in the appendix represents the research team's implementation recommendation. This, of course, would require thorough review before ODOT adoption.

- The steps needed for implementation would be the usual steps for ODOT specification adoption and revision.
- The expected benefits would be longer lasting repairs of concrete.

- Recommendations for implementation: It is recommended that a specification be adopted to allow for pre-qualification of materials by either laboratory testing or by field performance from a documented, controlled study. A proposed specification is included as Appendix B. It is also recommended that ODOT maintain a pre-qualified material list. It is further recommended that ODOT use the lowest cost material whose properties are appropriate for the job site conditions as this study did not show any appreciable difference between high and low cost materials. Use of higher cost materials may be justified in certain conditions such as hot or cold weather, need for very rapid set/strength gain, application in wet conditions, etc.
- Steps needed to implement: Adoption of a proposed specification and a pre-qualified material list.
- Expected benefits from implementation: Adoption of the proposed specification and pre-qualified materials list will result in higher quality, lower cost repairs capable of being done with minimal disruption of traffic.
- Potential risks and obstacles to implementation:
  - Because products are added to the market, removed from the market and reformulated, the need to keep the pre-qualified list up-to-date will be challenge.
  - ODOT will need to determine how, when and by who the prequalification testing is done. In – house testing will add a cost to ODOT but may assure more consistent results.
- Strategies to overcome potential risks and obstacles: It is recommended that the Office of Materials Management maintain a data base of prequalified materials which is then reviewed periodically. It is recommended that pre-qualification testing be done by the manufacturer and/or contactor and that ODOT conduct such testing only if there is some question about the validity of the results.
- Potential users and other organizations that may be affected. The largest potential impact is on maintenance personnel and contractors. Delays and costs are possible if a material must be qualified or if prequalified materials are in short supply or otherwise not available
- Suggested time frame for implementation: As soon as possible.
- Estimated costs: Differential costs of high performance repair materials, preparation and traffic control costs more or less the same
- Recommendations on how to evaluate the ongoing performance of the implemented result (if appropriate). ODOT maintenance personnel should be polled on a regular basis for their assessment of patching material performance. It is recommended that the Office of Materials Management provide a means to enter performance issues into a data base which is then reviewed periodically. If a particular material exhibits performance issues, that material should be reviewed and either requalified or removed from the pre-qualified list.

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Appendix A: Most Common Materials on State Approved Product Lists

Table 3: Products and Number of States Listing (Woods 2016)

BRAND NAME	COMPANY NAME	DOTs
RepCon 928	SpecChem LLC	25
MasterEmaco T1060	BASF	24
HD50	Dayton Superior	23
Sika Quick 2500	Sika Corp	23
Quikrete Commercial Grade Fast Set DOT Mix	The Quikrete Companies	22
Quikrete Rapid Road Repair With or Without Fibers	The Quikrete Companies	18
Rapid Set Concrete Mix	CTS Cement Mfg. Corp.	17
Five Star Highway Patch	Five Star Products, Inc.	16
Rapid Set DOT Repair Mix	CTS Cement Mfg. Corp.	15
Rapid Set Cement - All	CTS Cement Mfg. Corp.	12
Speed Crete 2028	Euclid Chemical Company	12
Pave Patch 3000	Dayton Superior	11
Eucospeed MP	Euclid Chemical Company	11
Five Star Structural Concrete	Five Star Products, Inc.	11
Futura 15	W.R. Meadows, Inc.	11
ChemSpeed 65	ChemMasters	10
Speed Crete Green Line	Euclid Chemical Company	10
Phoscrete Four-Seasons	Phoscrete Corporation	10
Duracal	U.S. Gypsum Co.	10
DOTLine	CeraTech, Inc.	9
Rapid Set Mortar Mix	CTS Cement Mfg. Corp.	9
Express Repair Mortar	Euclid Chemical Company	9
VeraSpeed	Euclid Chemical Company	9
Durapatch Hiway	L&M Construction Chemical	9
Planitop 18	Mapei Corp	9
DOT Patch HD	Symons Corporation	9
High Power DOT Grade Repair Concrete	US Concrete Products	9
US Spec Transpatch Concrete	US Mix Co.	9
MasterEmaco T1061	BASF	8
MasterEmaco T545	BASF	8
Pavemend SLQ	CeraTech, Inc.	8
Phoscrete VO-Plus	Phoscrete Corporation	8
Sikacrete 321 FS	Sika Corp	8
Sika Quick 1000	Sika Corp	8
PolyPatch FR	US Mix Co.	8

MasterEmaco T415	BASF	7
Pavemend TR	CeraTech, Inc.	7
Pavemend 15.0	CeraTech, Inc.	7
Pavemend SL	CeraTech, Inc.	7
Duracrete II	Kaufman Products	7
Eucospeed	Euclid Chemical Company	6
Fastset Concrete Mix	The Quikrete Companies	6
Fastset Repair Mortar	The Quikrete Companies	6
Prospec Rapid Patch VR	Bonsal American	5
Mainline	CeraTech, Inc.	5
Pave Patch 3000	Conspec Marketing & Mfg. Co., Inc.	5
Perma Patch	Dayton Superior	5
Re-Crete 20-Minute	Dayton Superior	5
Speed Crete Red Line	Euclid Chemical Company	5
Flexkrete 102	Flexkrete Technologies	5
Planitop X	Mapei Corp	5
RepCon V/O	SpecChem LLC	5
Transpo T-17	Transpo Industries, Inc.	5
Futura 45	W.R. Meadows, Inc.	5
FasTrac 246 Concrete	Western Material & Design, LLC.	5
FasTrac 220 FQ	Western Material & Design, LLC.	5

Appendix B: Draft Specification

1. Description.

This work will consist of furnishing the necessary labor, materials and equipment to repair pavement and concrete bridge decks in accordance with current specifications and in close conformity with the grades, thickness, and cross sections shown on the plans or as directed by the Engineer. This work shall include the removal of all loose and unsound concrete; preparation of existing concrete surface; removal and concrete for partial-depth repairs; blast cleaning or high pressure water cleaning; furnishing, placing, finishing, texturing and curing of high performance, rapid setting repair material for partial-depth repair, as specified, and all operations necessary to complete this work according to these specifications and to the satisfaction of the Engineer.

2. High Performance Rapid Setting Repair Materials.

All materials shall be prepackaged, stored and incorporated in the work as recommended by the manufacturer. The Engineer or Owner may require a manufacturer's representative to be present at the beginning of the work to advise the contractor on the recommended practice for the material.

3. Test Requirements and Prequalification.

All materials shall be qualified in the proportions to be used on the job. If a material has options for different proportions, such adding admixtures or aggregates, the material need only be qualified for the proportion used on the job, not for all options.

High performance repair material will meet the following test requirements:

Table 4: Recommended Test Methods and Requirements

Test	Minimum Requirements
Compressive Strength ASTM C109, psi (MPa)[1]	
@ 1 hour	2000 (14)
@ 24 hours	5000 (34)
@ 7 days	7000 (48)
Compressive Strength ASTM C39, psi (MPa)[1]	
@ 1 hour	2000 (14)
@ 24 hours	3500 (24)
@ 7 days	6000 (41)
Initial Set Time ASTM C266, min	10
Flexural Strength ASTM C78, psi (MPa)	
@ 4 hours	200 (1.4)
@ 3 days	500 (3.4)
Freeze and Thaw ASTM C666	
Procedure B (350 Cycles)	80%
Procedure A (300 Cycles)	79%
Modulus of Elasticity ASTM C469, ksi (GPa)	
@ 28 days	3500-4000 (24.2-27.6)

[1] Use C109 for cement or mortar type materials containing no aggregate or only fine aggregate (largest particle less than or equal to #4 sieve) and C39 for any material containing coarse aggregates.

Freeze-thaw testing shall be done using at least two repetitions of two specimens. Specimen 1 shall be the repair material. Specimen 2 shall be a composite specimen. A standard mold shall be filled half way with ODOT Class S concrete or a concrete specified by the Engineer. The surface shall be roughed to a broom finish. After curing for 28 days, the remainder of the mold shall be filled with the repair material after removing any loose material or laitance from the concrete surface. The test shall begin when the repair material has cured for 48 hours.

As an alternative, ODOT may, at its option, prequalify a material without testing if there is evidence from a controlled field study of at least 2 years in length of the satisfactory performance of that material.

High performance repair materials must be prequalified for use. In order to be contained on the Qualified Product's List,

1. Manufacturer's technical data sheet
2. Material safety data sheet
3. All components for testing or 50-lb (20 kg) sample
4. Mixing instructions

The Contractor shall furnish the Engineer with a copy of the manufacturer's comprehensive job specific preparation, mixing and application instructions. Any significant changes to these instructions which are recommended by the manufacturer for a specific job or an unanticipated situation shall be approved by the Engineer prior to the adoption of such changes.

4. Mixers.

Concrete shall be mixed according to manufacturer's recommendations.

Patching material may be mixed on site in small mobile drums or paddle mixers. Mixers at the site of construction shall be capable of combining all specified materials, aggregates, cement/product components and water into a thoroughly mixed and uniform mass within the specified mixing period. They shall have sufficient capacity to comply with minimum production requirements. Mixers will be kept clean, free of partially dried or hardened materials, and properly operating at all times.

5. Tools

Provide edgers, trowels, hand floats, brushes, and other small tools necessary to produce the results required. Milling machines, concrete saws, jackhammers, or other approved machinery to include pneumatic or hand tools must be approved by the Engineer.

6. Size of Patches

The Contractor shall follow all of the manufacturer's specifications concerning the maximum or minimum thickness of application and/or absolute size of a patch for the patching material. The contractor shall provide enough mixers with sufficient mixing to assure the material can be placed without the presence of cold joints. If the maximum allowable application thickness of a material is such that it would be necessary to place the material in two or more lifts with the formation of a cold joint, this shall be permitted only if the manufacturer's specifications allow this and with permission of the Engineer. If material is placed in multiple lifts, the manufacturer's specifications shall be followed.

7. Removal of Concrete.

The Engineer shall sound the structure and outline the areas to be removed. All loose, soft, honey-combed, disintegrated and unsound concrete, and ¼ inch (6mm) depth of sound concrete shall be removed. Where the bond between the concrete and a reinforcing bar has been destroyed, or where more than one-half of the periphery of such a bar has been exposed, the adjacent concrete shall be removed to a depth that will provide a minimum ½ inch (13mm) clearance around the bar except where other reinforcing bars make this impractical. After completion of the secondary removal operation, the Engineer will resound the areas to ensure that only sound concrete remains. All work shall be done in a manner that will not damage or shatter the concrete that is to remain, and will not cut, elongate or damage the reinforcing steel in any way.

Unless the manufacturer's specifications state otherwise, the area around the unsound concrete will be saw cut with straight lines to a minimum depth of 1 ½ inches (38 mm) in the shape of a square or rectangle.

8. Surface Preparation

Cleaning shall precede application of the patching material by not more than 24 hours. Surface preparation shall be according to the manufacturer's specifications. Exposed reinforcing and structural steel shall be cleaned to remove all loose and built-up rust, asphalt residue, and all other contaminants detrimental to achieving an adequate bond. It may be necessary to use hand tools to remove scale from the reinforcing steel or anchor bolts. The surface shall be free of spalls, laitance and all traces of foreign material. All un-chipped surfaces that will receive new material shall be mechanically roughened.

9. Patching.

The mixing, proportioning, placing and curing procedures, as well as, tools, equipment, labor and materials used shall be in accordance with the manufacturer's specifications and recommendations. Apply a thin coat of mortar or other recommended material to the concrete when necessary. Mix only the amount of concrete that can be placed within the setting period. Place concrete mixtures when the ambient temperature is between 50 and 70 degrees F (10-20 degrees C) or within the temperature limits set by the manufacturer. If necessary and allowed by manufacturer, add an accelerator or retarder to the mixture or prepare the area for temperatures outside of the range. For larger repair areas, over 2 inches (51 mm), adding 3/8 inch (9.5 mm) to ½ inch (13 mm) aggregate may be necessary to extend the mixture, but may be used only if allowed by the manufacturer's specifications. Trowel or screed patching material into the prepared area ensuring contact with the outer surfaces of the patch. The finished surface of the repair area shall be flush with the surrounding area and conform to the original concrete surface.

10. Finishing/Curing.

Finish the patched area to match the texture of the surrounding concrete. Patches shall be cured in accordance with the manufacturer's recommendations.

11. Inspection and Sounding of Concrete Patches.

After curing and before final acceptance, all patches shall be sounded. All unsound or cracked patch areas shall be removed and re-patched according to this specification at the Contractor's expense. Aerosol paint for outlining shall be provided by the Contractor. All sounding and replacement of rejected areas will be the responsibility of the contractor and included in the unit bid price for this item. Sounding and re-patching shall continue until only sound, un-cracked patches remain.

12. Method of Measurement.

The quantity shall be the actual area of the exposed surface of all accepted patches, irrespective of depth or thickness of the patch. If the patch includes corners or edges of members, all of the exposed surfaces shall be included. The cost of all labor, equipment, incidentals and materials for sounding and patching shall be included in the unit price bid for this item.

13. Basis of Payment.

Payment will be made at the contract price for patching concrete structures with high performance rapid set repair material by square foot (square meter).