Rapid Repair of Bridge Decks in Cold Weather

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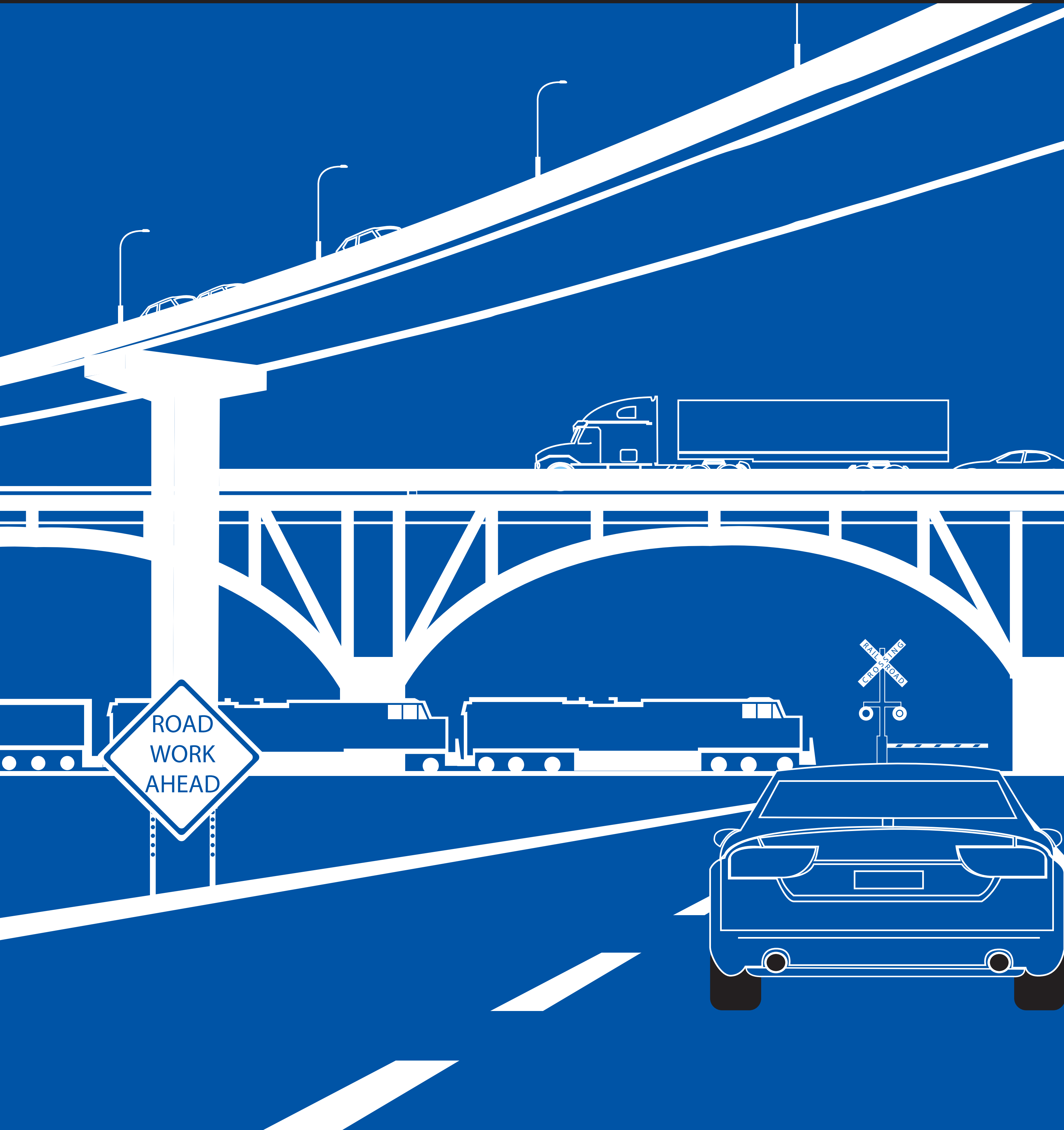

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Research Report
KTC-19-18/SPR12-436-1F

Rapid Repair of Bridge Decks in Cold Weather

Abheetha Peiris, Ph.D.
Research Engineer

and

Issam E. Harik, Ph.D.
Professor of Civil Engineering

Kentucky Transportation Center
College of Engineering
University of Kentucky
Lexington, Kentucky

In Cooperation With
Kentucky Transportation Cabinet
Commonwealth of Kentucky

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16. Abstract
Using regular concrete or mortar to repair potholes in concrete bridge decks is typically infeasible in cold weather due to extended set and curing times. However, several commercially available rapid-set repair materials can be used at temperatures near or below freezing. This study evaluated five such materials to assess their properties and determine which are most suited to executing pothole repairs in cold weather. For each material, laboratory testing evaluated set times, compressive strength gains, and bond strength to existing concrete at three temperatures: 35°F, 15°F, and 0°F (1.7°C, -9.4°C, and -17.8°C, respectively). Testing identified Phoscrete as the repair material best suited to cold weather partial-depth deck patching. It consistently had the highest compressive strength (more than 2,500 psi within three hours at all three test temperatures), while its bond strength with existing concrete was adequate (between 250 psi and 760 psi at 28 days). Phoscrete, aided by its fast-set accelerant, set up within 40 minutes at all three test temperatures. Subsequent field testing evaluated the use of Phoscrete to repair a pothole on the deck of the US 27 Bridge over the Kentucky River (040B00028L). As expected, the material set up rapidly and the lane was reopened to traffic within two hours. Maintenance personnel found the low workability of Phoscrete, compared to a typical cement-based repair mortar, to be an issue. Before maintenance crews repair bridge decks in the field using Phoscrete they should perform a trial pothole repair in order to ensure their familiarity with Phoscrete's workability. Field inspections conducted one year after the US 27 Bridge was mended found no distress on the Phoscrete-repaired patch.

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Executive Summary

When temperatures are at or below freezing, the repair of partial-depth spalls in reinforced concrete (RC) bridge decks with traditional repair materials (e.g., mortar or concrete) is time-consuming and generally unsuccessful because of extended curing and set times. This report details work performed by Kentucky Transportation Center (KTC) researchers to identify an optimal repair material for patching concrete surfaces in cold weather.

Researchers first identified commercially available products that can cure at low temperatures. More specifically, they sought out products that can bond to existing concrete walls in a pot hole, set up rapidly and, when deployed, allow the resumption of vehicle travel within 1 or 2 hours of placement. Five candidate materials were selected for initial laboratory testing. For each material, researchers evaluated set times, compressive strength gain, and the bond strength to concrete at three different temperatures. Testing was conducted in a climate-controlled room at KTC, which maintained test temperatures of 35 °F, 15 °F and 0 °F (1.7 °C, -9.4 °C and -17.8 °C, respectively). Thirty-nine (39) specimens were fabricated for the set-time tests, 264 specimens for the concrete strength tests, and 39 specimens for the shear strength tests, for a total of 342 specimens.

Laboratory testing found that Phoscrete is the repair material best suited for cold weather partial-depth deck patching. It consistently had the highest compressive strength at all three tests temperatures (greater than 2,500 psi within three hours) while establishing an adequately strong bond with existing concrete (between 250 psi and 760 psi at 28 days). Phoscrete, aided by its fast-set accelerant, set up within 40 minutes at all three test temperatures.

Phoscrete was then tested in the field on the US 27 Bridge (040B00028L), which traverses the Kentucky River. While Phoscrete set up quite rapidly and the lane opened to traffic within 2 hours, the workability of the material was quite low compared to cement-based repair mortar. Based on these observations, the following recommendations should guide future use of the material in field applications:

1. A construction crew should have hands-on training before repairing a bridge deck to ensure they are familiar with the Phoscrete's workability properties and how they vary depending on the amount of fast-set admixture used and ambient temperature.

2. The fast-set admixture should be reduced or omitted from the mix to increase available work time. This would entail longer lane closure(s), which may be acceptable depending on the traffic volume and/or patterns on the bridge.

Follow-up inspections detected no distress on the repaired patch one year after construction. Additional field applications of Phoscrete during cold weather conditions should be attempted to evaluate the utility of these recommendations as well as to understand more about its performance and durability.

Cold Weather Pothole Repair With Phoscrete [1]

(Apply when Surface Temperatures are above -5 °F)

Phoscrete Activator
(9 lbs. JUG)

Fast-Set Admix
(8 oz. POUCH)

Phoscrete Dry Mix (HC, HF)
(50 lbs. BAG)

Urethane Mixing Auger

Magnesium Float

Margin Trowel

Step 1:	Wear proper safety gear (goggles, gloves, mask, etc.)
Step 2:	Concrete surface in pothole must be dry (use hot or warm air blower), clean, and sound (no dirt, loose aggregates, oil contamination, etc.). Exposed steel bars in the pothole, if any, must be clean.
Step 3:	Pour entire content of the **Phoscrete Activator (9 lbs. JUG)** into a clean bucket. **Note: The freezing point of the Liquid Activator is -20°F**
Step 4:	Add the **Fast-Set Admix** to Activator when temperatures are at or below 50 °F. **Note 1: For temperatures between -5 °F and 30 °F, use one pouch (8 oz.)** **Note 2: For temperatures between 30 °F and 50 °F, use half a pouch (4 oz.)**
Step 5:	Add the **Phoscrete Dry Mix (50 lbs. BAG)** to the bucket. **Note 1: DO NOT use water when mixing Phoscrete** **Note 2: DO NOT extend with sand or gravel.**
Step 6:	Mix for 45 seconds or until no dry powder remains. Use a heavy duty **Mixing Auger** with a minimum 7 amp drill with side handle. Dual or variable speed drill is recommended.
Step 7:	Quickly Place Phoscrete mix onto to dry and sound concrete, and around clean rebars. Work fast to finish surface of each pour. Phoscrete sets up within 15 minutes, so form up large repairs in smaller segments and work across a repair. For potholes deeper than 3 inches, place Phoscrete in 3 inch layers. **Note 1: DO NOT use water when placing Phoscrete**
Step 8:	Finish Phoscrete using a **Magnesium Float**, **Margin Trowel**, or screed. Rinse tools with water and wipe off excess water before contact with Phoscrete. Once material develops a "skin," leave it alone for the best finish. **Note 1: DO NOT use water when finishing Phoscrete**
Step 9:	Clean hands, tools and buckets with water when finished.

[1] **Visit *http://www.phoscrete.com/* for additional information**

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1. Introduction

1.1 Background

Being able to quickly and efficiently repair damage and deterioration in concrete bridge decks during winter weather is critical for maintaining public safety. Damage typically results from traffic impacting a bridge deck, which in turn causes cracking, freeze-thaw effects on concrete, and corrosion of reinforcing steel. To minimize traffic disruptions, damage must be repaired and lanes reopened as quickly as possible. In the past it was common to execute a temporary patch using asphalt or a similar material until the ambient temperatures favored concrete usage. Due to the colder conditions, during winter months (which limits curing and extends set times) it has usually been unfeasible to repair bridge deck using regular concrete or mortar. When repairs are carried out during the winter months, new material tends to fail prematurely under traffic loads, and deck patches are prone to debond from the existing deck concrete.

Many rapid-setting repair products are capable of curing near or below freezing temperatures. While these products may reduce the lane closure times when bridge decks undergo repairs, their performance requires investigation. Research is needed to identify laboratory testing to evaluate whether use of these materials in the winter is feasible. Such research could also determine which repair materials are best suited to address different types of damage. Based on performance in laboratory tests, the most suitable materials can be selected to repair bridge decks when ambient temperatures are near or below freezing.

1.2 Literature Review and Material Selection

This research study focused on small-scale partial-depth patches on bridge decks. Results are also applicable to other types of structures requiring partial-depth patches (e.g., concrete pavement). Deterioration around cracks, scaling, pop outs, and blow-ups damage concrete but can be addressed through patching (NCHRP 463, 2014). As seen in several locations in Fig. 1, patching may also be required around earlier patches that did not inhibit bridge deck deterioration.

Figure 1 Damage Observed on Bridge Decks

This study also focused on products that can be used as permanent patches during cold weather, when ambient temperatures are near or below freezing. Accordingly, asphalt-based patching material was not considered in this research. The following patching materials were examined as part of this study: cementitious, polymer modified, and epoxy-type mixtures. Special types of proprietary products were also considered, as they can be applied when temperatures fall below the freezing point while still conferring high strength.

Kentucky Transportation Cabinet (KYTC) bridge maintenance crews are responsible for most bridge deck patching in the state of Kentucky. Therefore, products requiring special application equipment for surface preparation or application were not considered. Nor was cost considered as part of this study. This study also assumes the adoption of standard patching techniques in the construction process, including damage identification, concrete removal, cleaning, and material placement (e.g., FHWA, 2005; ACPA, 1998).

One goal of the study was to identify, from a broad list of commercially available products, a small yet representative group of materials that can be used for bridge deck repair in cold weather. All concrete patch repair materials listed in KYTC's list of approved materials were considered. A list of products currently used by the Cabinet for cold weather applications was collected and a broader search for other products conducted. The primary drawback of many concrete patching products is the recommended application temperatures are well above freezing. To assemble the literature review, researchers identified representative materials to evaluate as well as suitable laboratory tests to conduct on the selected materials.

For laboratory experiments, the properties of the selected material were tested at the following temperatures: 35 °F, 15 °F, and 0 °F (1.7 °C, -9.4 °C, and -17.8 °C, respectively). Because rapid setting was of primary importance, initial set time determination was selected as one of the test phases. While fast setting is important, it is also imperative that a material withstand the traffic loads soon after setting. This allows the repair to be carried out quickly so vehicles can travel the repaired lane. Therefore, compressive strength gain with time was included as a test criterion. To measure the durability of a patching material, the bond shear strength between a new material and the typical concrete in bridge decks was also evaluated to assess a material's ability to bond well with the existing concrete substrate and not pop out under service loads.

While additional properties such as drying shrinkage, freeze-thaw resistance, chloride attack resistance, and thermal expansion are also important, they were not evaluated as part of this study.

1.3 Materials

Table 1 lists the materials selected for laboratory testing. Materials were selected following a literature review and based on their ability to cure at low temperatures, gain strength during a short period of time, and bond to existing concrete in a bridge deck. The table provides the manufacturer name, manufacturer-recommended minimum application temperature, and a description of the material. Materials were obtained either directly through the manufacturer or via their authorized vendors.

Table 1 List of Selected Materials

Product	Manufacturer	Recommended Minimum Temperature	Description
Roadware	Roadware Incorporated	-30°F	Two-part (proprietary) hybrid urethane mix that combines with sand to form a polymer concrete
MG-Krete	Imco Technologies Inc.	14°F	Two-part (proprietary) high early strength structural repair material
Phoscrete 601-Q	Phoscrete Cooperation	-5°F	Two-part (proprietary) magnesium-alumino-liquid-phosphate based repair material
Duracal[1,2]	USG Corporation	32°F	Specially formulated (proprietary) cement based concrete patching material
Tekcrete Fast[2]	Minova Corporation	50°F	Specially designed (proprietary) highly adhesive and extremely rapid hardening, high performance gunite

[1]Material on KYTC list of approved materials
[2]Materials mixed with water

Of the selected materials, MG-Krete, Phoscrete, and Duracal had been used previously for deck repairs in cold temperatures by the Cabinet's bridge maintenance crews. Duracal is also found on KYTC's list of approved materials.

While not manufactured for bridge deck patching, Roadware was selected for testing because it can be applied at extremely low temperatures. Roadware is composed of a two-part liquid hybrid urethane, with sand added to create a polymer concrete. This was primarily studied to evaluate its effectiveness in filling large cracks and smaller pot holes that may be not possible with the other products.

Although not recommended for use below 50 °F, Tekcrete Fast was evaluated because the product is manufactured in Kentucky and had not yet been evaluated at low temperatures. Both MG-Krete and Phoscrete are packaged as two components: a bag of powder mix and a jug of liquid activator. An accelerator can be added to both materials to reduce the set time. Both Duracal and MG-Krete allow aggregate extension, while Phoscrete does not recommend the use of aggregate.

2. Laboratory Testing

2.1 Introduction

Specimen preparation and curing were conducted in a climate-controlled room at the Kentucky Transportation Center (KTC) in which temperatures can be set between -20 °F and 60 °F. The three laboratory tests conducted to evaluate the performance of each repair material were carried out at three temperatures: 35 °F, 15 °F, and 0 °F (1.7°C, -9.4°C, and -17.8°C, respectively). These tests are listed below:

Test #1: Set Time
Test #2: Rate of Compressive Strength Gain
Test #3: Bond Shear Strength with Concrete

Further details on each test type and the test matrix considered for each test are provided in the following sections. Researchers adhered to instructions provided by manufacturers when mixing and placing materials. The amount of cold temperature accelerator used with Phoscrete and MG-Krete was adjusted to ensure specimens achieved initial set up within 30 minutes of mixing. To reach the test temperature, all materials and equipment for specimen preparation were placed in the climate-controlled room 30 minutes prior to mixing. Duracal and Tekcrete are cementitious materials that are mixed with water. As such, room-temperature water (72°F) was used when mixing both materials, while the respective material was kept at the test temperature. Following preparation, all specimens cured at the respective temperatures until removal for testing. The set time testing was carried out in the climate-controlled room.

2.2 Set Time

For each material, three specimens (9” × 9” × 2”), each from a new mix, were prepared at each temperature. Set times were evaluated according to ASTM C403/AASHTO T 197-11 specifications using a concrete penetrometer (ASTM C403-16, 2016; AASHTO T 197-11, 2011). The test matrix is shown in Table 2.

Table 2 Test Matrix for Calculations of Set Time

Material	**Number of Specimens**		
	0 ^{0}F	**15 ^{0}F**	**35 ^{0}F**
Roadware (+ Sand)	3	3	3
MG-Krete	3	3	3
Phoscrete 601-Q	3	3	3
Duracal	N/A	N/A	3
Tekcrete	3	3	3
Total	**12**	**12**	**15**
Total number of specimens = 39			

The penetrometer provided analog readings up to 640 psi. The penetrometer's plunger was inserted to the marker on the penetrometer (1" depth) and the corresponding resistance read from the spring-reaction scale. The penetration resistance was measured at 5-minute intervals until the material set (at which point the plunger would not penetrate the mix). Penetrations were made at least 1" away from the sides of the container, with each penetration made at least an 1" away from previous test spots.

For set time tests, only the repair material was used — aggregate was not added. There was one exception. For Roadware, the set time was evaluated when it was mixed with sand. For materials with accelerants (Phoscrete and MG-Krete), initial pan tests were conducted to determine the accelerant ratio needed to achieve initial set within 30 minutes. Based on the results obtained at 35 °F, (see Chapter 3) Duracal was not tested at 0°F or 15°F. Figure 2 illustrates the penetrometer being used on a mix.

Figure 2 Penetrometer used to evaluate set time

2.3 Rate of Compressive Strength Gain

Concrete cylinders (3” diameter × 6” height) were prepared according to ASTM C192 guidelines (ASTM C192, 2018). Researchers opted for smaller 3” diameter cylinders instead of traditional 6” diameter cylinders in light of the expected high strengths of the cylinders (based on manufacturer specifications), and the capacity limits of testing equipment. To evaluate gains in strength, compressive strength was evaluated according to ASTM C39 (ASTM C39, 2018) standards 1 hour, 3 hours, 24 hours, and 672 hours (28 days) after specimen preparation. Three batches of each product were prepared at each test temperature. From each batch of repair material mix, four cylinders were prepared, cured, and then tested after 1 hour, 3 hours, 24 hours, and 672 hours (28 days). Except for Roadware, repair materials were tested with and without extending by using 50% aggregate in the mix (size 1/4” or less pea gravel). Roadware is a high-penetration, two-part urethane that can be combined with sand to form an instant polymer concrete. Thus, Roadware was tested only with sand added as fine aggregate. Table 3 provides the test matrix for compressive strength gain assessments.

Table 3 Test Matrix for Calculation of Material Strength Gains

Material	**Time**	**Number of Specimens**		
		0^0F	**15^0F**	**35^0F**
Roadware (+ sand)	1 hr	3	3	3
	3 hr	3	3	3
	24 hr	3	3	3
	28 day	3	3	3
MG-Krete	1 hr	3	3	3
	3 hr	3	3	3
	24 hr	3	3	3
	28 day	3	3	3
MG-Krete (+ 50% Pea gravel)	1 hr	3	3	3
	3 hr	3	3	3
	24 hr	3	3	3
	28 day	3	3	3
Phoscrete 601-Q	1 hr	3	3	3
	3 hr	3	3	3
	24 hr	3	3	3
	28 day	3	3	3
Phoscrete 601-Q (+ 50% Pea gravel)	1 hr	N/A	3	3
	3 hr	N/A	3	3
	24 hr	N/A	3	3
	28 day	N/A	3	3
Duracal	1 hr	N/A	N/A	3
	3 hr	N/A	N/A	3
	24 hr	N/A	N/A	3
	28 day	N/A	N/A	3
Duracal (+ 50% Pea gravel)	1 hr	N/A	N/A	3
	3 hr	N/A	N/A	3
	24 hr	N/A	N/A	3
	28 day	N/A	N/A	3
Tekcrete	1 hr	3	3	3
	3 hr	3	3	3
	24 hr	3	3	3
	28 day	3	3	3
Tekcrete (+ 50% Pea gravel)	1 hr	3	3	3
	3 hr	3	3	3
	24 hr	3	3	3
	28 day	3	3	3
Total		**72**	**84**	**108**
Total Number of Specimens = 264				

Figure 3 Mixing of MG-Krete at 35 °F for Cylinder Preparation

When products without aggregate were mixed (except Roadware), components were measured and placed in a mixing container (the liquid activator or water followed by the dry mix). If an accelerant was used, it was added to the liquid activator and mixed for a few seconds before it was added to the dry mix (Figure 3). Once the mix was ready, it was scooped into the cylinders using a trowel; cylinders were filled to the half-way point. Half-filled cylinders were rodded with a metal rod (3/8 in. diameter). The sides of the cylinders were then tapped with a mallet as per ASTM C192 (ASTM C192, 2018). Cylinders were then filled the rest of the way and the rodding and tapping repeated. A trowel was used to strike off the top surface, and then the cylinders were left in the cold room to cure until testing.

Figure 4 Preparation of Roadware Compression Cylinder Specimens at 35°F

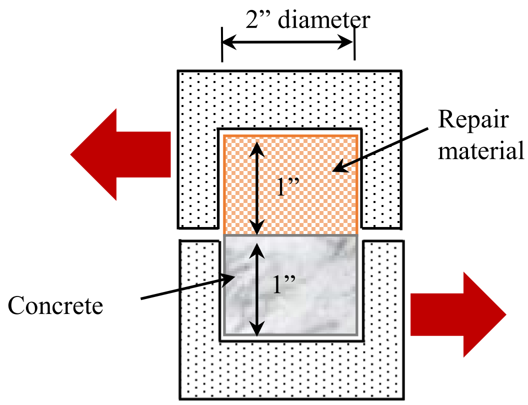
For mixes with aggregate, the same basic mixing process was used. However, after mixing the accelerator aggregate was added and the two thoroughly combined. Cylinder preparation occurred in the same manner as for mixes without aggregate. The only exception was Roadware — as per manufacturer instructions the two liquid parts were mixed and then sand was added into the mixture (Figure 4). Once fully mixed, test cylinders were prepared using the same steps described above. For each product, proportions of each mixture component were determined based on manufacturer specifications. The amount of accelerant used for Phoscrete and MG-Krete was based on the values used in the set-time tests.

Prepared cylinders were tested in compressions at the four specified time intervals (Figure 5). Based on the set-time results at 35 °F, Duracal was excluded from testing at 15 °F and 0 °F. While the manufacturer does not recommend using aggregate with Phoscrete, this was carried out to evaluate the performance of the material at 35 °F and 15 °F. Due to the large difference observed in the strength results between cylinders with and without aggregate, cylinders of Phoscrete with aggregate were tested at 0 °F.

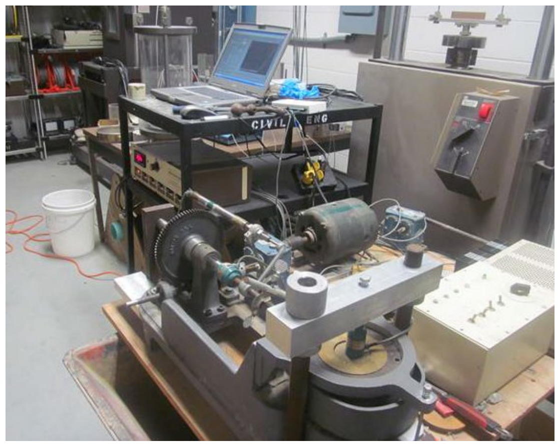
Figure 5 Phoscrete compression test 1 hour after mixing at 0 °F

2.4 Bond Shear Strength Test

The bond between existing concrete and the repair material was tested using a direct shear testing equipment. The equipment tests shear capacity of a cylinder 2” in diameter and 2” deep by applying a shear force at mid-height of the cylinder. Preparing the cylinder was a two-step process: (1) 1” thick concrete cylinders with a 2” diameter were cast using 4,000 psi concrete and cured for a minimum of 28 days and used as the base; (2) An additional 1” layer of the repair material was cast onto the 4,000 psi concrete cylinders at temperatures of 0 °F, 15 °F, and 35 °F. Following another 28-day curing period, the material was tested in direct shear to evaluate bond strength. A schematic of the direct shear test setup is shown in Figure 6(a). The test machine and data acquisition system are shown in Figure 6(b).



(a) Schematic of Direct shear cylinder specimen



(b) Direct shear machine and data acquisition system

Figure 6 Direct Shear Test Set Up

Table 4 is a test matrix showing the sample count for the bond test. The material for each bond shear test specimen was part of the mix for the four concrete cylinders cast as a batch for the compressive strength gain testing. Repair material extended with aggregate was excluded from the bond shear test matrix. Specimens cured for a minimum of 28 days and were then tested in direct shear. The failure of two of the Tekcrete bond shear specimens mixed and cured at 15 °F is shown in Figure 7.

Table 4 Test Matrix for Material Shear Strengths

Material	**Number of samples**		
	0 ^{0}F	**15 ^{0}F**	**35 ^{0}F**
Roadware (+ Sand)	3	3	3
MG-Krete	3	3	3
Phoscrete 601-Q	3	3	3
Duracal	N/A	N/A	3
Tekcrete	3	3	3
Total	**12**	**12**	**15**
Total number of samples = 39			

Figure 7 Tekcrete Bond Shear Specimens After Failure

3. Laboratory Test Results

3.1 Set Time Test Results

Test results for set times at 35 °F, 15 °F, and 0 °F are presented in Figures 8, 9, and 10, respectively. Each data point represents the average of three test specimens. As noted previously, the accelerants for both Phoscrete and MG-Krete were based on additional testing carried out prior to the set-time tests, where the quantity of accelerant was varied to achieve a set time of approximately 30 minutes. While the amount of accelerant was sufficient for the quantities mixed for laboratory testing, these values may not be viable when mixing large batches of material in the field. Typical repair materials, such as epoxy or polymer-modified mortars, tend to set up faster when the volume of the mix is greater. Water for both Tekcrete and Duracal was kept at room temperature (approximately 72 °F) outside the climate-controlled room prior to mixing.

As Figure 8 demonstrates, for the specimens mixed and cured at 35 °F, all material except Duracal set up within 30 minutes following placement. Initial set was almost instantaneous with Tekcrete and Roadware. Both showed penetration resistance at 5 minutes; both MG-Krete and Phoscrete took 10 minutes. Duracal did not begin to set up until after 20 minutes and did not fully set up until the 80-minute mark. Due to the delay in set time, Duracal was not tested at 15 °F and 0 °F. It was also dropped from the compressive strength gain and bond shear tests at those temperatures.

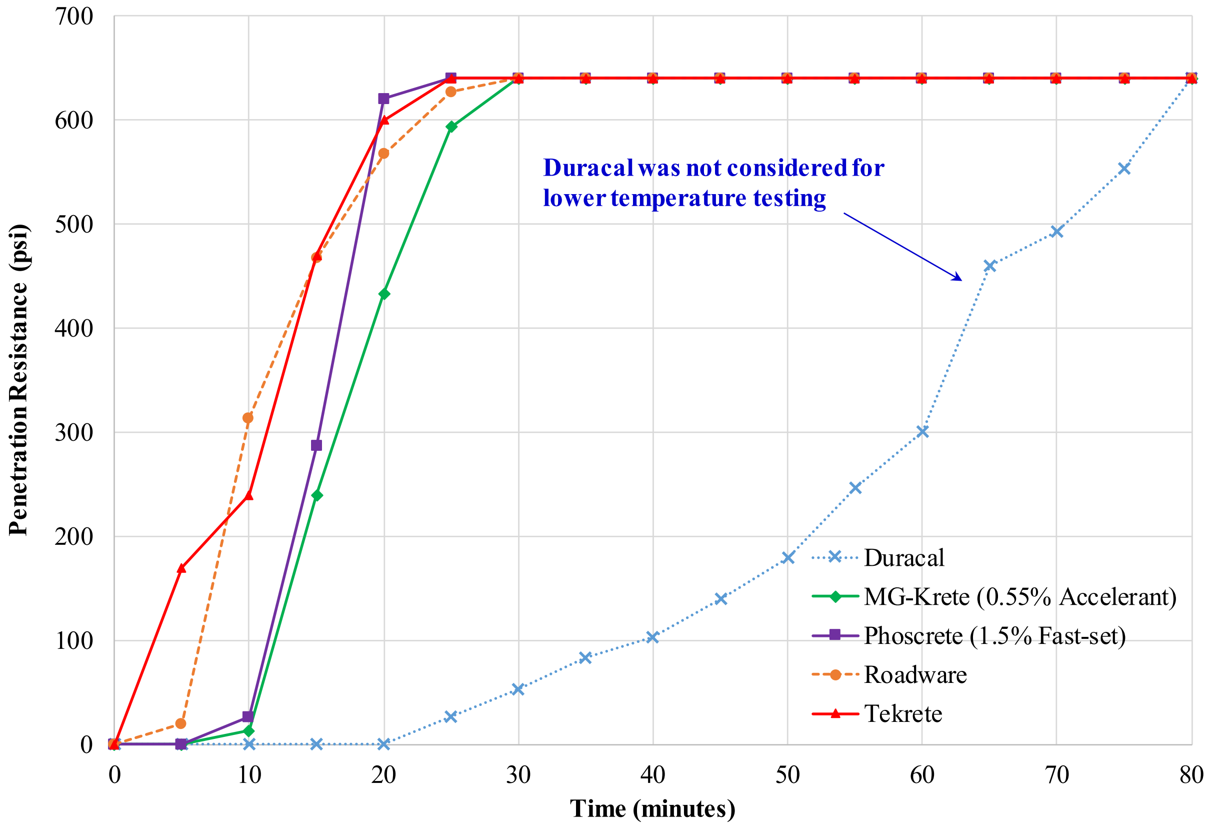


Figure 8 35 °F Set Time Results

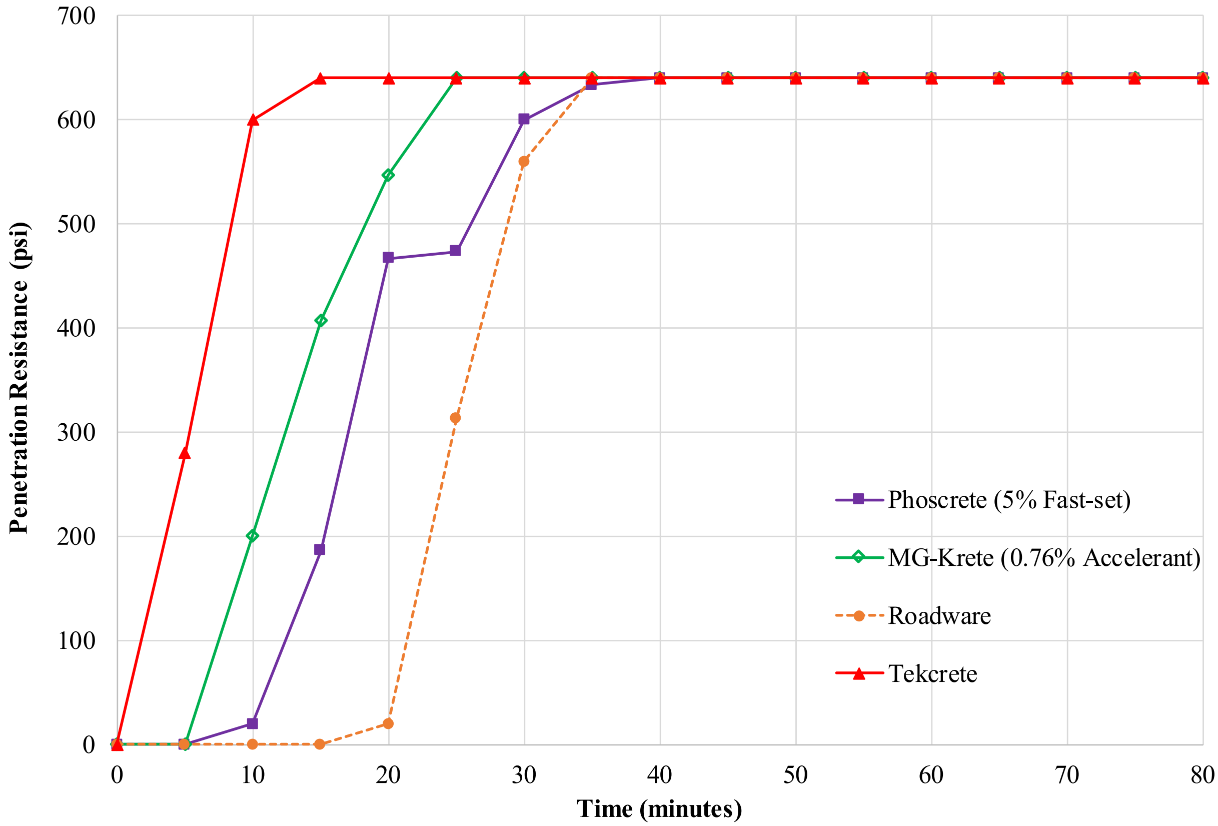


Figure 9 15 °F Set Time Results

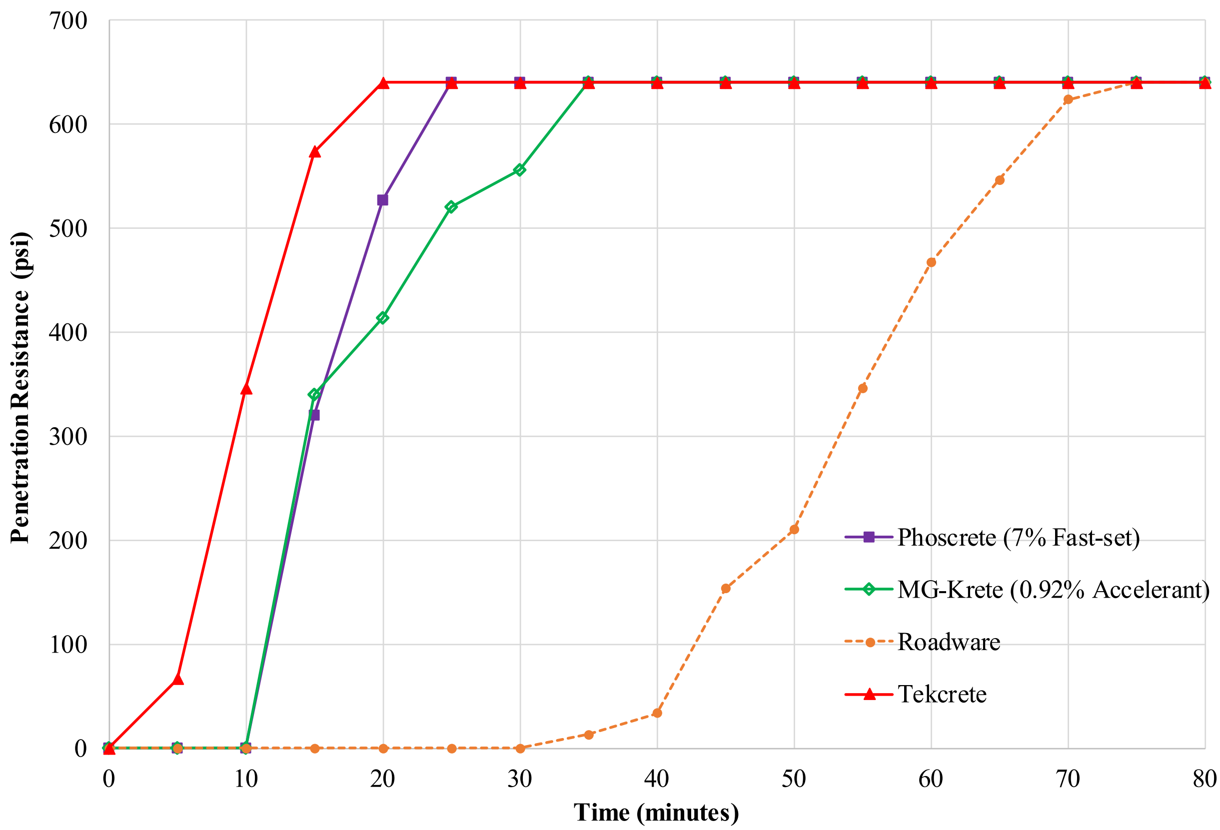


Figure 10 0 °F Set Time Results

At 15 °F, all four tested products set up within 40 minutes of placement (Figure 9). Initial set was at 5 minutes for Tekcrete, 10 minutes for Phoscrete and MG-Krete, and 20 minutes for Roadware. Tekcrete was fully set 15 minutes after placement. Results at 0 °F (Figure 10) show the materials, except for Roadware, set up within 35 minutes of placement. Roadware set up in 75 minutes, with initial set occurring at 35 minutes. Tekcrete exhibited the quickest set up — 20 minutes. Phoscrete and MG-Krete set up in 25 minutes and 35 minutes, respectively.

Test results indicated the set time for Tekcrete is unrelated to ambient temperature. This may partly be due to the room-temperature water used to mix the material. Both Phoscrete and MG-Krete set up within the desired 30-minute window by increasing the amount of accelerant as ambient temperature was lowered. Roadware, which does not have an accelerant, took longer to set up as the ambient temperature dropped.

3.2 Rate of Compressive Strength Gain Test Results

For the three test temperatures, the rate of compressive strength gain was evaluated according to ASTM C39 (ASTM C39, 2018) at 1 hour, 3 hours, 24 hour, and 672 hours (28 days). Results from compressive strength test are presented in Figures 11, 12, and 13. Each data point in the figures represents the average of the tests for three cylinders. Individual compressive cylinder test data are tabulated in Appendix A. Due to the widening time intervals between the four tests at each temperature from 1 hour to 672 hours [(5^4 + 47) hours or 28 days], the time axes in Figures 11–13 are plotted in a base 5 log scale.

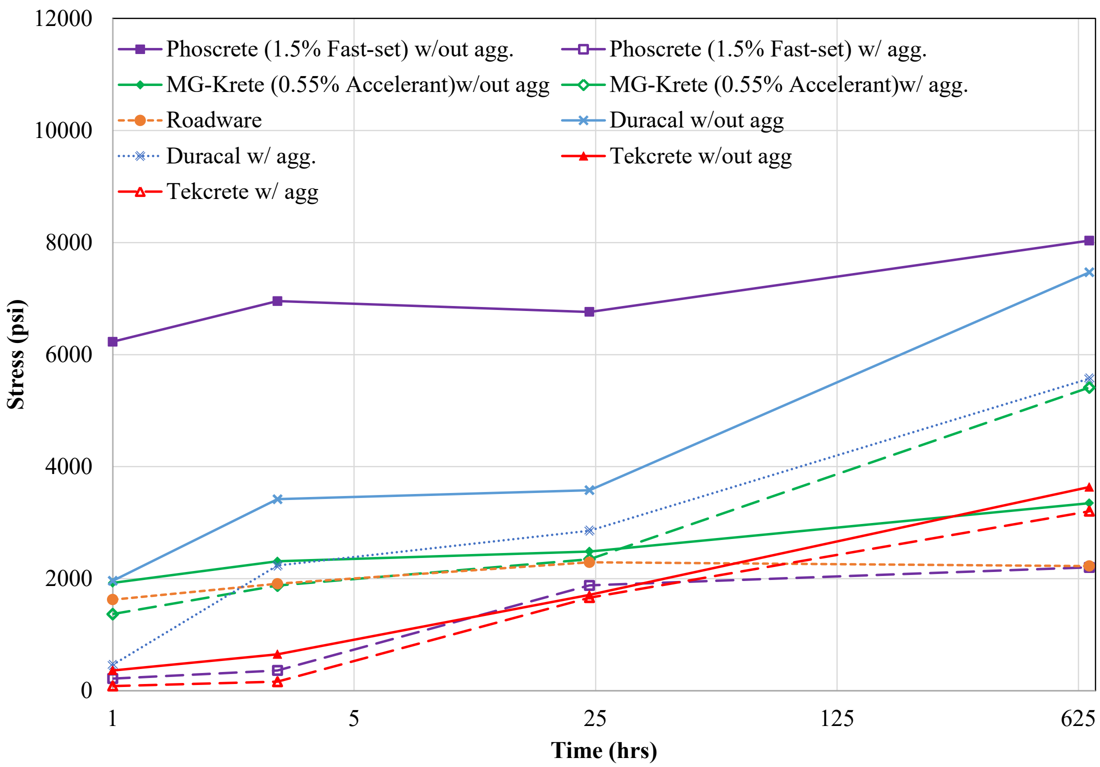


Figure 11 Compressive Strength Gain at 35 °F

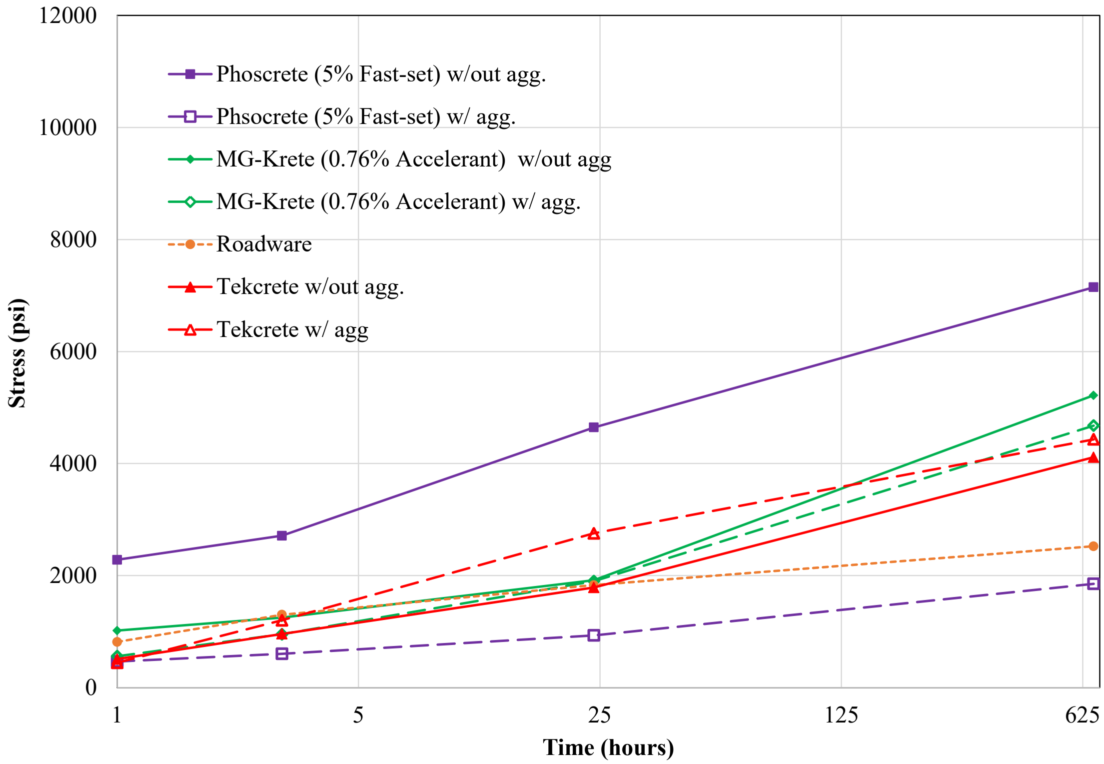


Figure 12 Compressive Strength Gain at 15 °F

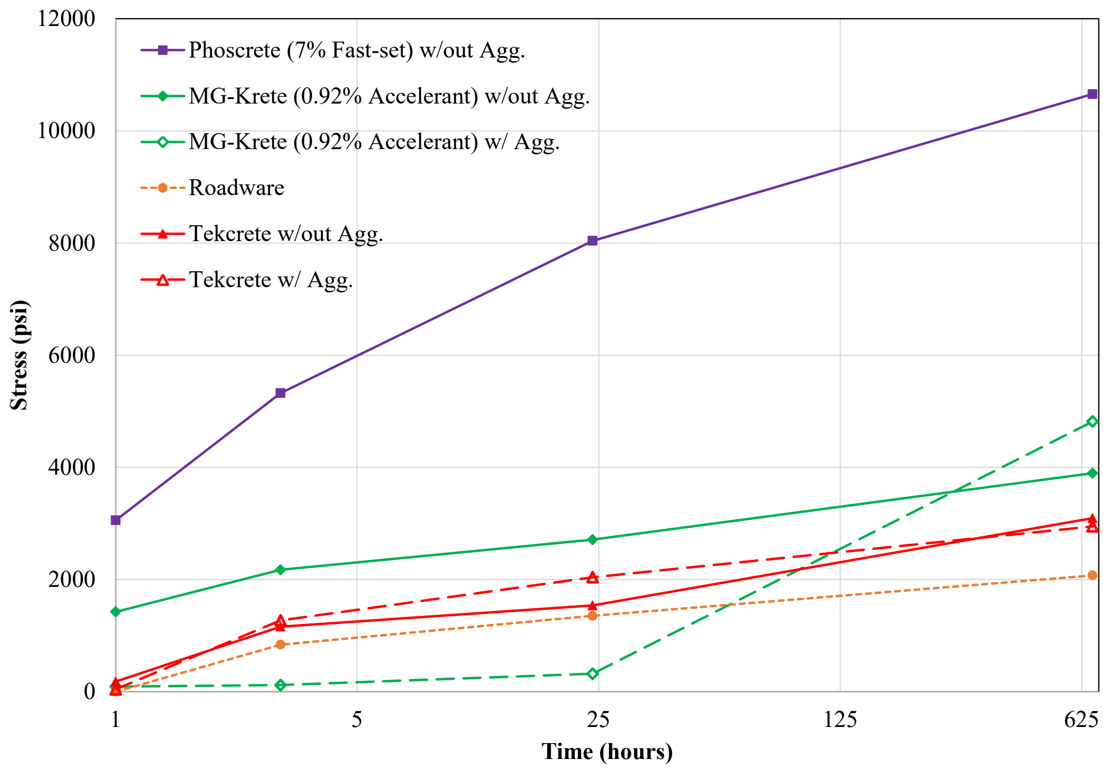


Figure 13 Compressive Strength Gain at 0 °F

At the three test temperatures, all specimens reached a compressive strength of at least 1,800 psi. Incorporating aggregate reduced the compressive strength of Phoscrete at both 35 °F and 15 °F. For this reason, Phoscrete with aggregate extension was not tested at 0 °F. As the manufacturer does not recommend using aggregate with Phoscrete, the results of Phoscrete with aggregate extension were not considered a viable material. The compressive strength of Tekcrete was unaffected by aggregate extension. Aggregate extension increased the 28-day strength of MG-Krete at both 35 °F and 0 °F, while the 15°F strength was slightly higher for cylinders without the aggregate. At the three temperatures, the MG-Krete without aggregate had a higher strength when compared to MG-Krete with aggregate extension up to 24 hours after placement. Phoscrete without aggregate extension was the strongest material at all temperatures at every test period.

For the three test temperatures, Roadware consistently had a compressive strength of slightly over 2,000 psi at 28 days It would be the weakest material if Phoscrete with aggregate extension is discounted. However, Roadware was considered for the test matrix primarily as a material for filling large cracks and openings in temperatures near or below freezing — not primarily as a deck patching material.

Phoscrete and MG-Krete used different amounts of accelerant based on the set time tests at the three different test temperatures. The percentage of accelerant is based on the total weight of the mix (excluding aggregate). To carry traffic, the compressive strength of repair materials used for full-depth repair is typically over 3,000 psi; for partial-depth repairs, strengths between 1,600 psi and 1,800 psi are sufficient. This is due to the patch being confined and supported by the existing concrete (FHWA, 2014). Only Phoscrete consistently exhibited compressive strength greater than 2,000 psi 3 hours after placement at all three temperatures. Duracal and MG-Krete (with and without aggregate), along with Roadware, had compressive strengths above 1,900 psi at 3 hours only for the tests at 35 °F. Duracal without aggregate had a compressive strength over 3,300 psi at 3 hours at 35°F. Tekcrete, both with and without aggregate, had low compressive strength values at all three test temperatures at 3 hours after placement.

3.3 Bond Shear Strength Test Results

Bond shear strength results, based on the direct shear between existing concrete and the repair material, are shown in Figure 14. Each column in the figure represents the average of three direct shear cylinder tests. Individual shear test result data are in Appendix A. Except for Roadware, the bond shear of all materials declined as temperature was lowered. Note that Duracal was only tested at 35°F. The bond shear strength of Roadware above 500 psi at all three test temperatures, with the lowest at 35 °F. All test materials, with the exception of Tekcrete, had bond strengths above 200 psi at all three test temperatures. Considering the typical shear strength of concrete, 200 psi is likely a conservative value for bond strength in direct shear.

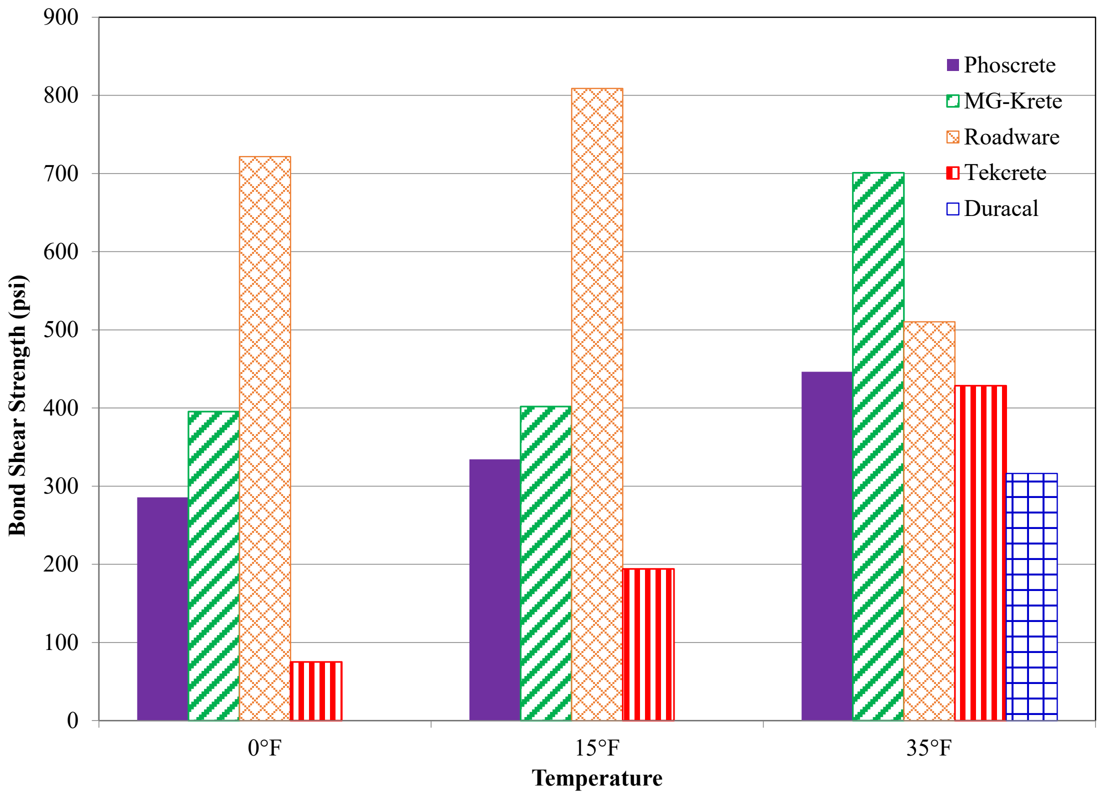


Figure 14 Average Bond Shear Strength Test Results

3.4 Conclusions from Laboratory Testing

Laboratory testing failed to demonstrate that one material consistently outperforms all others. Phoscrete without aggregate was the repair material best suited for partial-depth patching in cold weather. It consistently had the highest compressive strength at all three tests temperatures while retaining an adequately strong bond with existing concrete. It could potentially be used for full-depth repairs due to the high compressive strength achieved just 3 hours after placement. Phoscrete, with the aid of its fast-set accelerant, set up within 40 minutes at all test temperatures.

Provided sufficient time is available for set up, Duracal (with and without aggregate) may be a viable alternative when temperatures are above 35 °F. MG-Krete (with and without aggregate) is also acceptable at temperatures above 35 °F. Although its set time was rapid, Tekcrete had low compressive strengths 3 hours after placement at all three test temperatures while also exhibiting the lowest bond shear strength at 15 °F and 0 °F. Thus, Tekcrete is not recommended for cold weather bridge deck repairs. Roadware manifested high bond shear strengths but low compressive strengths at all three test temperatures. While set time increased from 30 minutes at 35 °F to 75 minutes at 0 °F, the material's compressive strength and bond strength values were consistent at the three temperatures. When combined with the material's liquid-like consistency, it may be an option for repairing cracks and/or areas around joints where bond strength may be more critical than compressive strength.

4. Field Application

4.1 Introduction

Based on laboratory testing, Phoscrete was chosen for the field application phase of the study. The field test evaluated its workability and material properties in field conditions. Because the laboratory testing was conducted using small amounts of material, properties such as set time were expected to vary when working with larger volumes. Readers should note that the manufacturer discontinued the Phoscrete 601-Q product, which was a special winter mix, and now produces a four-season mix that was used for the field application.

Field trials were carried out on the US 27 Bridge over the Kentucky River (040B00028L) in Gerrard County, Kentucky. A previously repaired partial-depth patch on the southbound slow lane cracked, resulting in spalling concrete. The damaged area with crumbling concrete was approximately 18” × 18”, but sounding around the damaged area indicated the delaminated area was much larger. A KYTC District 07 bridge crew undertook the repair on February 4, 2016. The ambient temperature was 34°F, the humidity 63%. The deck concrete surface temperature was 39°F (measured using an infrared thermometer).

4.2 Partial-Depth Patch Repair

Concrete sounding around the crumbling patch identified a rectangular 54” × 48” repair area. The area extended a minimum of 4” beyond the delaminated areas. A concrete saw was used to cut 2” deep vertical edges around the repair area (Figure 15). Using pneumatic hammers, all deteriorated concrete was removed from the repair area to a depth of approximately 6.5”, exposing the top layer of rebar. Workers used compressed air to remove debris and clear the surface for Phoscrete application.

(a) Saw cutting repair edge (b) Chipping Concrete

Figure 15 Preparing Repair Area

One unit of the liquid Phoscrete activator was added to a 5-gallon bucket. One bag of the fast-set admixture was then added — as recommended by the manufacturer — for a surface temperature of 40°F. One bag of the Phoscrete dry mix was then poured into the bucket. The mixture was blended for at least 45 seconds using a drill-powered spiral auger. The repair area was filled in two layers; the first layer was approximately 3” deep. Total application time was roughly 20 minutes. Finishing was done using magnesium floats — as recommended by the manufacturer — to prevent Phoscrete from sticking to the float. Figure 16 depicts the placement and finishing of Phoscrete.

(a) Placing Phoscrete

(b) Finishing Phoscrete

Figure 16 Phoscrete Repair

4.3 Material Tests

Three concrete cylinders (3” diameter × 6” height) were prepared with three batches of the mix used to repair the patch. Only two cylinders were tested in compression; one cylinder could not be capped because the Phoscrete set up before the top surface was leveled. After 28 days, average compressive strength of the two cylinders was 9,450 psi. Cylinders remained at the bridge site for approximately 3 hours at temperatures between 34 °F and 40 °F. Once removed from the site, they were stored indoors at a temperature of 72°F prior to testing.

Part of the Phoscrete mix produced for the deck repair was placed in a pan (9” × 9” × 2”) to measure the set time. The same penetrometer used for laboratory testing was used to measure the penetration resistance. Compared to laboratory testing, the mix was more cohesive, preventing any smoothening of the surface within the pan. Final set was reached within 11 minutes of casting — also faster than what was observed in the laboratory. The cast cylinders and set-time measurement are shown in Figure 17.

(a) Phoscrete test cylinders

(b) Set time measurement

Figure 17 In Situ Material Tests

The surface temperature of Phoscrete on the deck patch measured 140 °F soon after the repair set up. This served as evidence of the exothermic reaction taking place during Phoscrete's curing process, which gives it its chemical bond.

4.4 Conclusion from Field Test

The bridge was reopened to traffic 55 minutes after the repair was complete. Total lane closure time for repairs was about 2 hours. Although quite fast, because the material was rapid setting, its workability was reduced during repair activities. While a preconstruction meeting was held with the KYTC bridge crew to discuss the rapid-set nature of Phoscrete, the lack of workability was unexpected. Finishing the surface of the repair area proved difficult. A few low spots were detected, but as the material could not be applied in lifts less than one inch (per manufacturer specifications) these could not be corrected. The lack of workability affected the set-time test specimen surface finish as well as the surface finish of a compressive strength test cylinder. Based on these observations, the following recommendations should guide future field applications:

1. A construction crew should have a hands-on training before undertaking a repair to ensure they are familiar with the workability properties of Phoscrete and how they vary depending on the amount of fast-set admixture used and the ambient temperature.
2. The fast-set admixture should be reduced or omitted from the mix to increase available work time. This would entail longer lane closure(s), which may be acceptable depending on the traffic volume and/or patterns on the bridge.

Additional field applications of the material during cold weather conditions should also be attempted to evaluate the validity of these recommendations as well as to understand more about the material and its performance.

4.5 Long-Term Inspection

The Phoscrete deck patch was inspected during several field visits. As seen in Figure 18, the inspection carried out on Feb. 12, 2017 (one year after construction) revealed no distress to the repair patch. Some small surface cracks were detected, while the previous repair material on one side of the Phoscrete patch was failing (Figure 18). To measure durability, the repaired patch should undergo annual monitoring for several years.

Figure 18 Repaired Patch One Year Later

5. Summary and Conclusions

Repairing partial-depth spalls in reinforced concrete (RC) bridge decks with traditional repair materials during the winter is time-consuming and rarely successful due to cold temperatures. Because cold temperatures limit curing and extend set times, it has generally been unfeasible to repair bridge decks using regular concrete or mortar during the winter. But many rapid-setting repair materials are now available that can cure in temperatures near or below freezing. This study sought to identify newly developed materials that can bond to existing concrete walls, set up rapidly in cold weather, and carry traffic loads a few hours after placement.

This report detailed work done to identify an optimal repair material for patching concrete surfaces in cold weather. A literature review located several commercially available products, from which five candidate materials were selected for laboratory testing. Research consisted of evaluating set times, compressive strength gain, and the bond strength to concrete of the selected repair materials at three different temperatures. Laboratory testing was conducted in a climate-controlled room, which maintained the three test temperatures of 35 °F, 15 °F and 0 °F (1.7 °C, -9.4 °C, and -17.8 °C, respectively). Testing found that Phoscrete is the repair material best suited for cold weather partial-depth deck patching. It consistently had the highest compressive strength at all three tests temperatures while having adequate bond strength with existing concrete. Phoscrete, aided by its fast-set accelerant, set up within 40 minutes at all three test temperatures.

Phoscrete was then tested in the field on the US27 Bridge (040B00028L), which traverses the Kentucky River. While Phoscrete set up quite rapidly and the lane opened to traffic within 2 hours, the workability of the material was low compared to cement-based repair mortar. Based on field observations, the following recommendations should guide its future use in the field:

1. A construction crew should have a hands-on training before undertaking a repair to ensure members are familiar with the material's workability properties and how they vary depending on the amount of fast-set admixture used and the ambient temperature.
2. The fast-set admixture should be reduced or omitted from the mix to increase available work time. This would entail longer lane closure(s), which may be acceptable depending on the traffic volume and/or patterns on the bridge.

Follow-up inspections detected no distress on the repaired patch one year after construction. Additional field applications of Phoscrete during cold weather conditions should be attempted to evaluate these recommendations as well as to understand more about its performance and durability.

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Appendix A

A.1 Set time test results at 0° F

0° F				
Time (min)	Average Penetrometer Resistance (psi)			
	Phoscrete	MG-Krete	Roadware	Tekcrete
0	0	0	0	0
5	0	0	0	66.67
10	0	0	0	346.67
15	320	340	0	573.33
20	526.67	413.33	0	640
25	640	520	0	640
30	640	556.67	0	640
35	640	640	13.33	640
40	640	640	33.33	640
45	640	640	153.33	640
50	640	640	210	640
55	640	640	346.67	640
60	640	640	466.67	640
65	640	640	546.67	640
70	640	640	623.33	640
75	640	640	640	640

A.2 Set time test results at 15° F

15° F				
Time (min)	Average Penetrometer Resistance (psi)			
	Phoscrete	MG-Krete	Roadware	Tekcrete
0	0	0	0	0
5	0	0	0	280
10	20	200	0	600
15	186.67	406.67	0	640
20	466.67	546.67	20	640
25	473.33	640	313.33	640
30	600	640	560	640
35	633.33	640	640	640
40	640	640	640	640
45	640	640	640	640

A.3 Set time test results at 35° F

35° F					
Time (min)	Average Penetrometer Resistance (psi)				
	Phoscrete	MG-Krete	Roadware	Tekcrete	Duracal
0	0	0	0	0	0
5	0	0	20	170	0
10	26.67	13.33	313.33	240	0
15	286.67	240	466.67	470	0
20	620	433.33	566.67	600	0
25	640	593.33	626.67	640	26.67
30	640	640	640	640	53.33
35	640	640	640	640	83.33
40	640	640	640	640	103.33
45	640	640	640	640	140
50	640	640	640	640	080
55	640	640	640	640	246.67
60	640	640	640	640	300
65	640	640	640	640	460
70	640	640	640	640	493.33
75	640	640	640	640	553.33
80	640	640	640	640	640

A.4 Compressive strength gain test results

Material	Time	0^0 F		15^0 F		35^0 F	
		Compressive Strength (psi)	Average Strength (psi)	Compressive Strength (psi)	Average Strength (psi)	Compressive Strength (psi)	Average Strength (psi)
Roadware (+ sand)	1 hr	0	0	580.03	815.82	1895.71	1626.92
		0		919.56		2249.39	
		0		947.86		735.65	
	3 hr	834.68	839.4	1570.33	1301.53	2419.16	1909.86
		806.39		1075.18		2405.01	
		877.12		1259.09		905.41	
	24 hr	1867.42	1353.41	2588.92	1829.69	3140.66	2291.83
		1174.21		1400.56		2843.57	
		1018.59		1499.59		891.27	
	28 day	2999.19	2074.91	3862.16	2522.9	3253.83	2225.81
		1598.62		1725.95		2334.27	
		1626.92		1980.59		1089.33	
MG-Krete	1 hr	990.3	1424.14	452.71	1018.6	2079.63	1924.01
		1570.33		1089.34		1570.33	
		1711.80		1513.76		2122.07	
	3 hr	1725.95	2173.94	1061.05	1249.7	2051.33	2310.70
		2348.42		1244.96		2603.07	
		2447.45		1443.02		2277.69	
	24 hr	2461.6	2711.53	2433.33	1919.3	2277.69	2485.18
		2716.24		1584.49		2037.18	
		2956.75		1740.11		3140.66	
	28 day	3621.66	3895.17	5208.78	5218.21	2645.51	3348.15
		3961.19		5322.01		3098.22	
		4102.66		5123.85		4300.72	
MG-Krete (+ 50% Pea gravel)	1 hr	84.88	61.30	650.77	561.17	1768.39	1367.56
		99.03		565.88		1556.18	
		0		466.85		778.10	
	3 hr	141.47	117.89	905.41	952.57	2970.89	1876.85
		141.47		1160.06		1655.21	
		70.74		792.24		1004.44	
	24 hr	452.71	320.67	1782.54	1900.43	3918.75	2348.42
		353.68		2079.62		1612.77	
		155.62		1839.12		1513.74	
	28 day	4668.54	4819.45	3975.34	4677.98	5064.66	5413.63
		4696.84		5036.37		6224.73	
		5092.96		5022.22		4951.49	

Phoscrete 601-Q	1 hr	4060.22	3055.77	2475.74	2282.4	6889.64	6229.44
		3267.98		2334.27		6253.02	
		1839.12		2037.18		5545.67	
	3 hr	5375.90	5324.03	2645.51	2711.53	7441.38	6955.33
		6564.26		2914.30		6238.87	
		4031.93		2574.77		7186.73	
	24 hr	9153.18	8040.27	3904.60	4644.93	7158.44	6762.32
		8940.97		5602.25		6649.14	
		6026.67		4428.04		6479.37	
	28 day	11331.83	10657.49	5814.46	7149	8148.73	8035.55
		11402.57		8615.59		7752.61	
		9238.06		7016.96		8205.32	
Phoscrete 601-Q (+ 50% Pea gravel)	1 hr	N/A	N/A	410.27	466.86	113.18	216.92
		N/A		551.74		127.32	
		N/A		438.56		410.27	
	3 hr	N/A	N/A	580.03	603.61	367.82	363.07
		N/A		594.18		339.53	
		N/A		636.62		381.87	
	24 hr	N/A	N/A	905.41	933.71	1839.12	1881.56
		N/A		877.12		2362.57	
		N/A		1018.59		1443.00	
	28 day	N/A	N/A	1499.59	1853.27	2263.54	2202.24
		N/A		2136.21		2221.10	
		N/A		1924.01		2122.07	
Duracal	1 hr	N/A	N/A	N/A	N/A	1612.79	1961.76
		N/A		N/A		1853.29	
		N/A		N/A		2419.18	
	3 hr	N/A	N/A	N/A	N/A	3508.52	3418.92
		N/A		N/A		3451.93	
		N/A		N/A		3296.31	
	24 hr	N/A	N/A	N/A	N/A	3678.29	3579.26
		N/A		N/A		3550.97	
		N/A		N/A		3508.52	
	28 day	N/A	N/A	N/A	N/A	7799.01	7468.74
		N/A		N/A		7671.62	
		N/A		N/A		6935.60	
Duracal (+ 50% Pea gravel)	1 hr	N/A	N/A	N/A	N/A	424.41	462.14
		N/A		N/A		410.27	
		N/A		N/A		551.74	
	3 hr	N/A	N/A	N/A	N/A	2588.92	2235.24
		N/A		N/A		1287.39	
		N/A		N/A		2829.42	
	24 hr	N/A	N/A	N/A	N/A	3211.39	2857.71
		N/A		N/A		1994.74	

		N/A		N/A		3367.01	
	28 day	N/A	N/A	N/A	N/A	5432.49	5573.96
		N/A		N/A		4753.43	
		N/A		N/A		6535.96	
Tekcrete	1 hr	42.44	179.2	650.70	509.27	14.15	363.11
		381.97		721.50		679.06	
		113.18		155.62		396.12	
	3 hr	565.88	1160.06	1287.39	957.29	28.29	650.77
		1527.89		1301.53		1244.95	
		1386.42		282.94		679.06	
	24 hr	1174.21	1537.32	1895.12	1787.05	594.18	1711.80
		1952.30		2362.57		2588.92	
		1485.45		1103.47		1952.30	
	28 day	2206.95	3093.5	4357.31	4112.09	2362.57	3635.81
		3494.34		4541.22		4088.52	
		3579.22		3437.75		4456.34	
Tekcrete (+ 50% Pea gravel)	1 hr	42.44	42.44	509.30	443.28	99.03	84.88
		42.44		353.68		70.74	
		42.44		466.85		84.88	
	3 hr	1343.98	1273.24	834.68	1202.5	183.91	162.69
		117.62		1160.06		141.47	
		1358.12		1612.77		169.76	
	24 hr	2079.62	2041.9	2461.60	2753.99	1655.21	1662.29
		2107.92		2688.00		1669.36	
		1938.15		3112.36		1556.18	
	28 day	3239.69	2947.32	4201.69	4432.76	1938.15	3204.32
		2900.16		4470.49		4470.49	
		2702.10		4626.1		3296.28	

A.5 Bond shear test results

Material	0 °F		15 °F		35 °F	
	Shear Stress (psi)	Average Shear Stress (psi)	Shear Stress (psi)	Average Shear Stress (psi)	Shear Stress (psi)	Average Shear Stress (psi)
Raodware (+ Sand)	613.18	721.8	769.3	808.9	570.28	75.4
	709.97		1094.51		630.45	
	842.34		562.95		330.13	
MG-Krete	410.18	395.5	444.71	402.0	855.42	701.1
	368.33		308.16		761.77	
	408.09		453.08		486.04	
Phoscrete 601-Q	301.36	285.7	341.65	334.3	767.12	507.3
	276.77		254.79		482.38	
	278.86		406.52		272.4	
Duracal	N/A	N/A	N/A	N/A	341.3	316.5
	N/A		N/A		332.8	
	N/A		N/A		275.3	
Tekcrete	75.93	75.4	220.26	194.3	405.95	428.7
	77.45		203		497.4	
	72.72		159.57		382.64	