FHWA-NJ-2024-002

Innovative Pothole Repair Materials and Techniques Volume II: Concrete Structures

Final Report

January 2024

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In cooperation with

New Jersey
Department of Transportation
Bureau of Research
And
U. S. Department of Transportation
Federal Highway Administration

DISCLAIMER STATEMENT

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. **FHWA-NJ-2024-002**	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Innovative Pothole Repair Materials and Techniques Volume II: Concrete Structure		**5. Report Date** January 2024 **6. Performing Organization Code** CAIT/Rutgers
7. Author(s) Husam Najm, Bala Balaguru, Hao Wang, Hardik Yagnik, Alissa Persad.		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Center for Advanced Infrastructure and Transportation Rutgers, The State University of New Jersey 100 Brett Road Piscataway, NJ 08854		**10. Work Unit No.** **11. Contract or Grant No.** NJDOT TO 362
12. Sponsoring Agency Name and Address Federal Highway Administration (SPR) 1200 New Jersey Avenue, SE Washington, DC 20590 New Jersey Department of Transportation (SPR) 1035 Parkway Avenue, P.O. Box 600 Trenton, NJ 08625.0600		**13. Type of Report and Period Covered** Final Report, September 2021 – September 2023 **14. Sponsoring Agency Code** FHWA, NJDOT

15. Supplementary Notes
Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract
Long lasting and durable repair materials are necessary for maintaining concrete pavements, concrete bridge decks, and substructure to prevent deterioration and ensure longer service life. Rapid setting cementitious patch repair materials are popular for repairing small concrete damages and providing a functional repair within few hours. Based on extensive literature search and several DOT practices, three formulations were chosen as the best performing candidates. All three formulations are listed on the NJDOT QPL. The three formulations were further improved to increase workability especially for pumping, better toughness, and better adhesion to eliminate the need for the bedding compound. The workability was improved using the polymer whereas the toughness using nonmetallic fibers. One formulation has a stronger adhesion which could be used where adhesion is a primary requirement. Typically the repair mortar has a lower shrinkage strains. An attempt was made to further decrease the shrinkage strains by adding fine aggregates. Workability, strength, and restrained shrinkage cracking of the formulations were investigated The restraint shrinkage test protocol simulated upper and lower limits of restraint that a repair material undergoes in real applications. The repairs were also cast and placed in external environmental conditions to expose them to natural weathering actions. The cracking behavior was evaluated including cracking spacing and maximum crack width. The investigation led to the identification of three formulations that did not crack for a period of 10 months in filed exposure to NJ climate conditions. Typically rapid set formulations do not shrink after 6 months. The formulations that did crack revealed that addition of 1 percent of PVA fibers could significantly reduce the maximum crack width. The maximum crack widths observed in all the formulations were an order of magnitude less than the maximum allowable crack width specified by NJDOT which is 1/32 in. Use of Schmidt hammer for non-destructive compression testing of rapid setting class of materials was evaluated so it can be used as quality assurance tool before openings lanes to traffic. The research effort did lead to the identifications of the formulations for horizontal, vertical, and overhead rapid repairs and elimination of the bedding compound. The Schmidt hammer can be used to ascertain that the needed compressive strength was achieved.

17. Key Words Potholes, rapid repair, crack width, fibers, polymer, cements		**18. Distribution Statement** No restrictions.	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 70	**22. Price** Leave blank

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGEMENTS

The authors wish to acknowledge the efforts of the New Jersey Department of Transportation (NJDOT) Bureau of Research under the direction of the Project Manager, Dr. Giri Venkiteela and Ms. Amanda Gendek, Manager of the Bureau of Research. The authors would also like to thank the selection and implementation panel members: Dr. Giri Venkiteela, Yong Zeng and Emanuel Bassey from NJDOT and Mr. Robert Clark of the Federal Highway Administration (FHWA) Division Administrator. The authors also would like to acknowledge Luca Ondris, Derek Shum, Aneesh Kakirde, Ruofan Chen, Brian Jacoppo, Masoma Paiman, Aabir Rashid, Jack Zaccaro and Mathew Chen for their help and assistance working on this project.

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EXECUTIVE SUMMARY

Concrete structures are prone to deterioration over long periods of time due to vehicular loadings and external weathering actions. Microcracks can develop in concrete that can lead to further deterioration due to chloride infiltration. Infiltration of chlorides into concrete bridge decks can accelerate the corrosion of the reinforcing steel or steel girders underneath. Since the volume of corroded products is generally higher than parent metal, corroded reinforcement can further accelerate the cracking of concrete and cause delamination which will eventually lead to spalling and potholes. The exponential nature of the material degradation may eventually require replacement of the bridge deck. Moreover, potholes on the concrete pavements over bridge decks can cause additional safety concerns for the riders. Hence, long lasting repair of damaged pavements is a primary concern for the owner of the roadway or bridge.

A good repair material thus becomes necessary for maintaining the concrete bridge decks and pavements. Additionally, since the repair of such damage on the pavements requires a temporary lane closure, it is desired to have the repair material functional within a few hours of application. This is especially necessary for cementitious patching materials. An ideal repair material should thus have the following characteristics: constructible – the material should be easy to work with and apply under different weather conditions; fast setting – the cementitious patching materials should be able to develop the necessary strength within a few hours of application to minimize lane closure.; long-lasting – the repair material shall possess good durability to serve the purpose of preventing further deterioration of the pavement. For cementitious patch repair materials, the durability is ensured by preventing the shrinkage cracks, and enhancing the flexural behavior and toughness; and compatibility with the parent concrete – the repair material shall stay adhered to the parent concrete in the presence of environmental stressors and vehicular loads.

In this research, three patch repair materials were developed for three repair applications: over-head, horizontal, and vertical repair. The patch repair material consists of cement-water matrix, fibers, aggregates, and admixtures. In this project, the cement products needed for developing patch repair material were selected from the Qualified Products List (QPL) of New Jersey Department of Transportation (NJDOT). The three cements are designated as C1, C2, and C3 in the order of CSA cement, Portland cement with proprietary admixtures, and Portland cement with quartz respectively. Other materials used in the formulation of repair mixes were selected based on literature review and their availability in the market. These include Polyvinyl alcohol (PVA) fibers, latex polymer, coarse and fine aggregates, and water reducer. The repair mix formulations were first experimented with different compositions in laboratory setting to study their ease of application (workability), compressive, and flexural strength gain in 24 hours. The selected formulations were then cast into 3-ft long x 2-inch-wide x 1-inch thick beam samples over existing concrete surfaces of varying roughness to study their shrinkage characteristics under external weathering conditions over long term. The concrete surfaces consisted of porous concrete surface and the plain cement board surface. The shrinkage crack occurrence and their growth in these samples were monitored over a period of six months.

A total of 12 formulations were experimented on each of the two existing concrete surfaces for studying the restrained shrinkage cracking. These included four types of mix formulations using each of the cements: no fibers and no gravel, with fibers but no gravel, with gravel but no fibers, and with fibers and gravel. Since each of these formulations was repeated for both the porous concrete and plain cement surfaces, a total of 24 mixes were performed. Once cast, the shrinkage crack widths were recorded using digital microscope. Number of cracks, total crack width and maximum crack width were analyzed.

Observations from workability showed that there were noticeable differences between the consistency and working time of mix formulations from the three different cements. For the same cement matrices, formulations without gravel were relatively simpler to work with than the formulations with gravel. The placement and setting of the formulations also depended on the external temperature and humidity. Addition of fibers helped in achieving the strain hardening in the load-deflection responses, especially for the cement types 2 and 3. Three formulations were able to resist the shrinkage cracks completely over either of the tested surfaces. A higher number of cracks were observed over surface with higher restraint than over the surface with relatively lower restraint for the formulations without gravel. The total crack widths were observed to be stabilizing after six months. The maximum crack width among all the samples was less than half of the allowable maximum crack width by New Jersey Department of Transportation (NJDOT). With the addition of fibers, the formulations were able to either resist the crack width completely or to control the maximum crack width to less than a quarter of the allowable maximum crack width by NJDOT. Three formulations were recommended for patching repair for horizontal, vertical, and overhead repair application.

Additionally, tests were performed to evaluate the feasibility of using Schmidt Hammer for compressive strength evaluation of rapid setting repair materials. Preliminary results showed that compressive strength verses rebound number curves specific to rapid repair materials can be developed for accurate prediction of compressive strength through non-destructive testing. The Schmidt hammer could thus be used for deciding the opening of repaired section to the traffic.

BACKGROUND AND LITERATURE SEARCH

Rapid repair of concrete structures is an integral part of maintenance of transportation infrastructures. Quick patching rapid set repairs are the most common type of concrete repairs for bridge decks, barriers, joints, and sign haunches. They are also the most common repairs for concrete pavements. Repairs of other bridge elements such as piers and abutments are also common as well as repairs to retaining walls and other infrastructure elements. It is estimated that highways agencies spent approximately 21.4 billion annually on road repair between 2009 and 2014. [(1)] Spending on road repairs was approximately 30% of the total state DOTs' highway capital spending. Figure 1 shows annual DOT's expenditure on road repair and road expansions for two 5-yr periods (2004-2008) and (2009-2014). In New Jersey, the average annual expenditure on road repairs between 2009 and 2014 was approximately 1.4 billion accounting for 57% of the annual highway capital spending. [(1)]

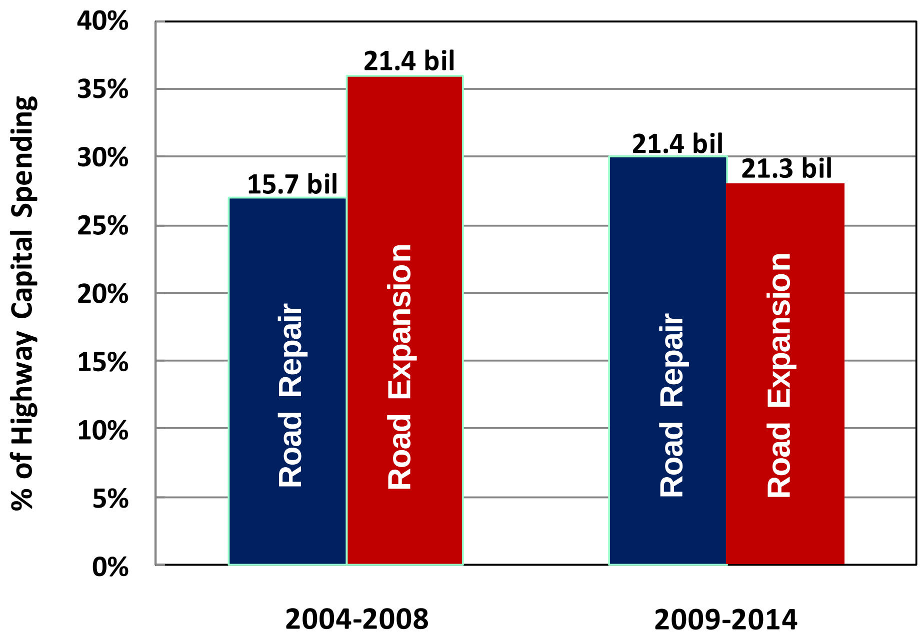


Figure 1. Average annual state DOT's spending on road repair and road expansion (adapted from [(1)])

Rapid concrete repairs are critical to extending the service life of roads and bridges and hence to reduce the expenditure on transportation infrastructure. NJDOT has established procedures and approved material formulations for rapid repairs. However, there is always room for improvement and the team responsible for repairs identified the following areas for enhancing the existing capabilities. Their vision is to develop repair materials with following characteristics:

- Workable and suitable patching material for: (1) overhead, (2) vertical and (3) horizontal repair areas with narrow voids.

Typical cases for overhead, vertical, and narrow horizontal repairs are shown in Figure 2. New repair materials for overhead and vertical applications should have low flowability (stiff) so that they can be applied without the need of formwork in the field. On the other hand, for horizontal repairs (similar to the one shown on the right in Figure 2), to fill a very small size void in concrete, the material composition with very high flowability and low viscosity is needed so that the void can be fully filled. The ideal workability can be especially meaningful at the construction level.

Figure 2. Overhead repair (left), vertical repair (middle), horizontal repair (right)

2. Requirement of bedding compound

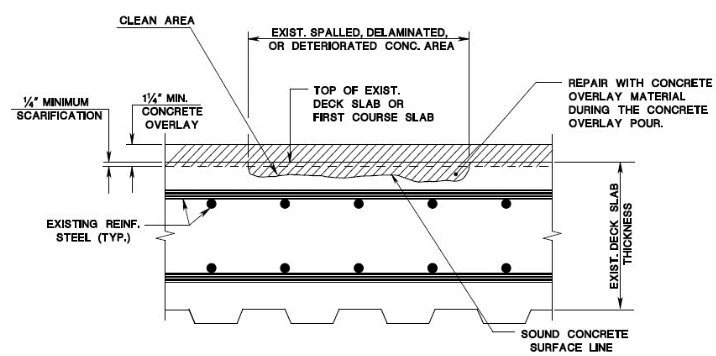
The current quick setting patch material listed on NJDOT QPL requires the bedding compound applied first to increase the bonding. If there is only one component for the patch material, that would be more convenient for the field performance to save time and labor.

The development of patching materials was centered around the requirements of their primary users: NJDOT and the contractors involved in performing the concrete repairs for NJDOT. Hence, it is also necessary that the patching materials qualify the basic strength requirements pertaining to NJDOT standards. NJDOT specifications, classify the quick setting patch repair materials as Type 1, 1A, 1B, and Type 2. (2) The definitions of each class of patch repair material can be found in NJDOT Specifications. (2)

Table 1 lists these requirements for quick setting patch repair materials according to NJDOT specifications. (2) Additionally, the construction details of typical minor spalled areas on bridge deck as obtained from NJDOT Bridge Construction Details – 551.1 are shown in Figure 3. (3) This figure (Figure 3) clearly shows the scope of patch repair materials for horizontal applications, as defined by NJDOT standards.

Table 1 - NJDOT requirements for quick setting patch repair materials

	Type 1, 1A, 1B	Type 2
Bond Strength		
7 day (minimum)	1000 psi	1000 psi
28 day (minimum)	2000 psi	2000 psi
Expansion/Shrinkage		
Cured in Water (maximum)	+0.20%	+0.20%
Cured in Air (maximum)	-0.20%	-0.20%
ifference (maximum)	0.30%	0.30%
Durability		
Retained strength at 50 cycles (minimum)	90%	90%
Visual condition rating at 50 cycles (maximum)	3	3
Permeability (maximum chloride content at 2 inches)	2.5 lbs/yd^3	2.5 lbs/yd^3
Compressive strength		
3 hour (minimum)	2000 psi	-
1 day (minimum)	3000 psi	1000 psi
7 day (minimum)	4000 psi	2000 psi
28 day (minimum)	4500 psi	3000 psi
Time of set in minutes (minimum)	15	15



TYPICAL REPAIR DETAIL FOR MINOR SPALLED AREAS
(SEE NOTE 1)

Figure 3. Typical Repair Details for Minor Spalled Areas, NJDOT Bridge Construction Details (BCD) – 551.1 [3]

OBJECTIVES

The research investigation was carried out to identify material compositions for rapid repair of concrete structures pertaining to the requirements of NJDOT. The primary requirements are ease of application, rapid strength gain, long-term durability, and compatibility with parent concrete surface. The three focus areas of application are: over-head repair of damaged bridge girders, vertical repair of columns and piers, and horizontal repair applications on bridge decks and slabs. Thus, three formulations are proposed for the three repair applications. A flowable mix formulation is proposed for horizontal applications in concrete pavements for early opening to traffic. The flowable mix formulation is also recommended for thin, narrow repairs. In contrary, a thick mix formulation is proposed for the overhead repair application. For vertical repair applications, a mix formulation that has a lower setting time is required to prevent accumulation of the repair material at the bottom of the repair area. In all three cases, the formulations are required to have sufficient bond strength without the requirement of an additional bonding layer.

The primary objectives of the investigation are the following:

- Developing rapid setting patch repair materials for overhead, vertical, and horizontal concrete repair pertaining to the requirements of NJDOT.
- Evaluating the developed mix formulations based on workability, compressive strength, and flexural strength gain in 3 and 24 hours.
- Evaluating the load-deflection response of the flexural specimens.
- Evaluating the developed patch repair materials for long-term durability by monitoring cracking formation and crack width from restrained shrinkage tests

SUMMARY OF THE LITERATURE REVIEW

A wide range of products are being used for concrete rapid set patch repair for vertical, overhead, and horizontal application. These products include modified Portland cement concrete with silica fume and chemical accelerators (admixtures), polymer concrete, calcium sulfo-aluminate cement, geopolymer cement, magnesium phosphate cement, non-shrink cement and others. Fast setting pumpable self-consolidating concrete (SCC FAST) has also been used for repairs especially in vertical applications and hard to access areas such as condensed reinforcement. A review of the inventory of current rapid set patch repair products approved by several state DOT's is given in APPENDIX

Table 21.

Current Practices, Challenges and Limitations

There are several existing as well as ongoing studies on the effectiveness and performance of rapid-repair mortar and concrete. These studies looked at the types of products being used by state DOT's and their technical data, their acceptance criteria, performance, and potential future technologies for enhancing their durability. The majority of state DOT's use commercially available rapid repair mortar and concrete products and list them on their approved material list after the product satisfies the agency's minimum required acceptance criteria (see Table 21 in Appendix).

A review of the approved products listed in APPENDIX

Table 21 shows that many of these products are listed on the approved QPL of multiple states while other products are only approved by only one or two states. The review also showed that some of the products listed no longer exist or their names have changed. While these products are produced by different manufacturers, a majority of them have similar performance in terms of early strength, working time, shrinkage, and curing needs. The differences lie in their pre-construction preparation, mixing requirements, finishing, and curing. According to Sprinkel, a successful rapid repair is durable, has minimum congestion, and reduced user cost. [4] Depending on lane closure requirements (short term, long term, or permanent lane closure or detours), the use of rapid repair materials may or may not be needed. The patch geometry and placement temperature affect the strength development rate. [4] The U.S. Army Corps of Engineers evaluated the performance of some rapid setting repair materials and their appropriate acceptance criteria for airfield repairs. Other studies evaluated these products in terms of compatibility with base material, in terms of longevity and in terms of the experience of field personnel. [5, 6, 7] Reviewing these studies indicate that the selection of an appropriate repair material for a particular project can be challenging and that there are many variables that need to be considered for each application. These factors include the time available before opening the repaired location to service; project (patch) size, the working time (gel time), mechanical and thermal compatibility of the repair material with the base material, environmental conditions, proper curing, ease of application, and long-term service life of the repaired section. ASTM C928 provides the requirements for rapid concrete repair systems. (8)

A national survey of fast setting patching materials of state highway agencies (DOT's) was conducted by the National Concrete Consortium in 2021. (9) The survey had several questions for agency officials and had collected data from thirty-five states. Results from this survey showed that the majority of the 35 responding states require a minimum of 3000 psi compressive strength before bridges are open to traffic and five states require a minimum strength of 4000 psi. For pavements, many of the states require 2500 psi to 3000 psi before the pavement is open to traffic. Of the 35 states, 11 states allow calcium chloride to be used as accelerator while 24 states prohibit the presence of chlorides in the repair materials. Very few states reported data on performance and longevity of the repairs. A few states mentioned life spans ranging from 5 to15 years for the repairs but were not confident of these estimates.

The US Army Corps of Engineers conducted a study to determine whether existing requirements for evaluating rapid-repair products were sufficient or further refinement and modifications were needed.(10) The study was intended to aid airfield managers and repair teams in the selection of optimal spall repair materials by maintaining a database of approved tested products. The report presented the test methods and results of 26 rapid-setting repair compounds tested at the U.S. Army Engineer Research and Development Center in Vicksburg, MS, from 2013 to 2017. Figure 4, Figure 5, and Figure 6 show the 2-hour, 3-hour, and 1-day compressive strength results for various rapid set products respectively. Figure 4 shows that most of the tested products exceeded 2500 psi of compressive strength after 2 hours. Figure 5 shows that most of the tested products exceeded 3000 psi of compressive strength after 3 hours. And Figure 6 shows that most products gained more than 4000 psi after 1-day. Based on the results of their tests, the US Army Corps of Engineers developed an updated testing protocol for assessing a material's suitability for airfield spall repairs. Table 2 shows a summary of the updated test protocols.

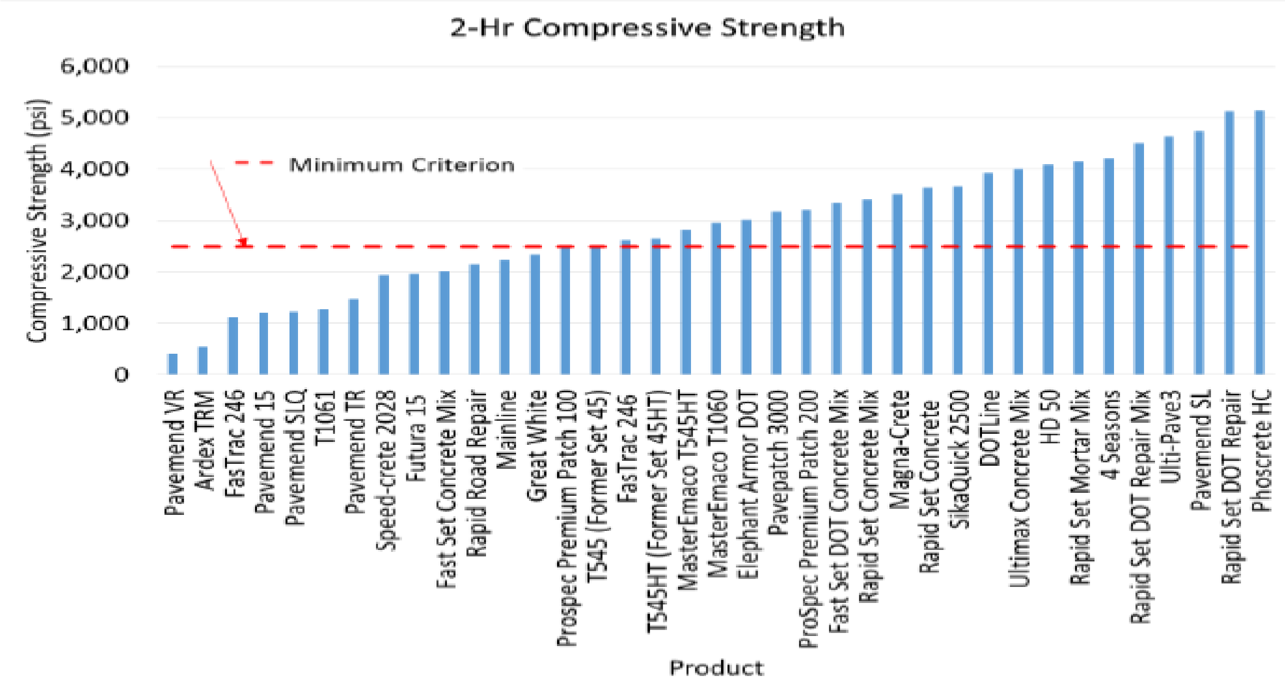


Figure 4. Summary of 2-Hr compressive strength of various products (10)

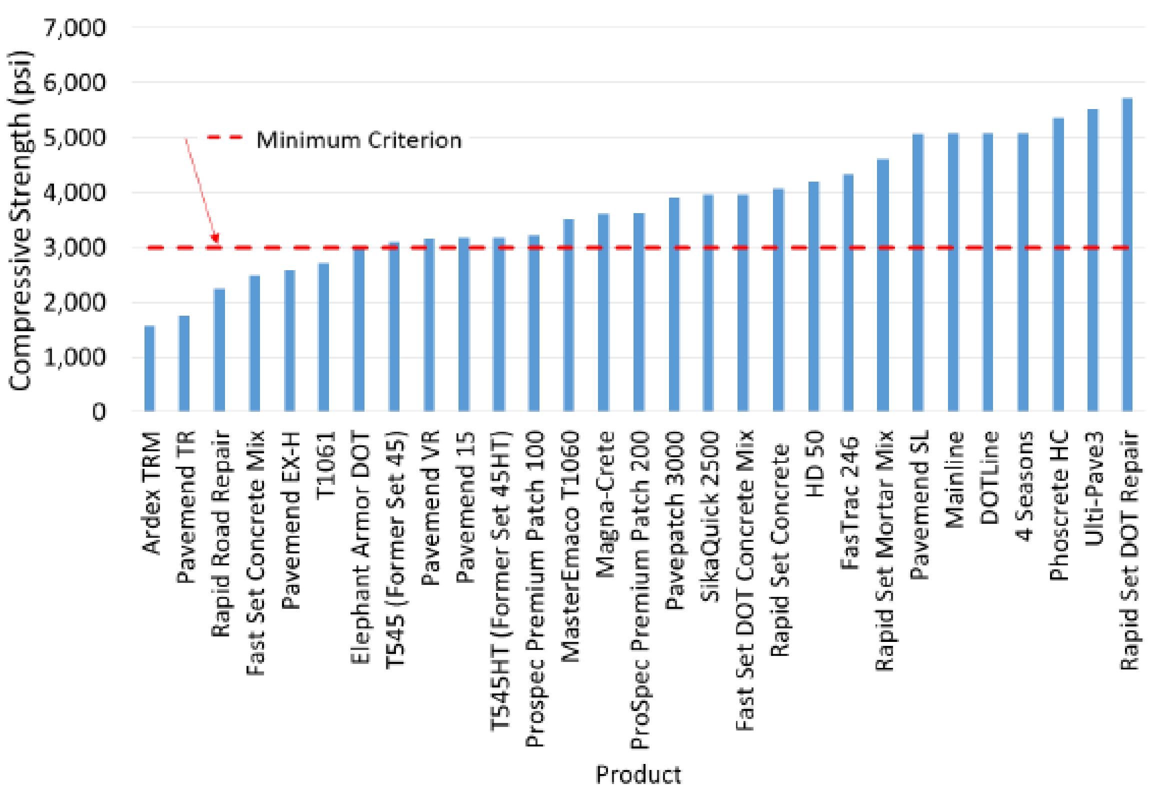


Figure 5. Summary of 3-Hr compressive strength of various products (10)

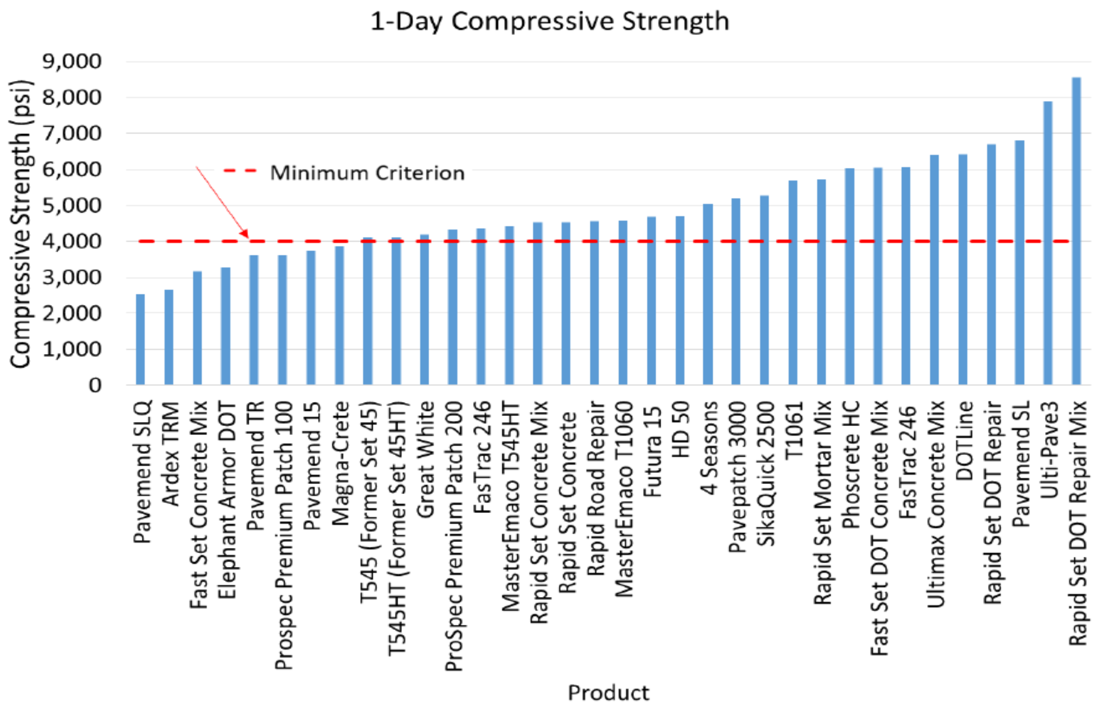


Figure 6. Summary of 1-day compressive strength of various products (10)

Table 2 - Summary of updated test protocols for various rapid repair products [10]

Tier 1 Test Requirements			
Test Property	**Test Method**	**Test Age**	**Test Criteria**
Compressive strength	ASTM C39	2 hr	≥ 2500 psi
		3 hr	≥ 3000 psi
		1 day	≥ 4000 psi
		7 days	≥ 5000 psi
		28 days	≥ 5000 psi
Flexural Strength	ASTM C78	2 hr	≥ 350 psi
		7 day	≥ 500 psi
		28 days	≥ 600 psi
Bond strength (RS/RS)	ASTM C882	1 day	≥ 1000 psi
		7 days	≥ 1500 psi
Bond strength (PCC/RS)		1 day	≥ 1000 psi
		7 days	≥ 1250 psi
Modulus of Elasticity	ASTM C469	2 hrs	2 ≤ x ≤ 6 Mpsi
		28 days	2 ≤ x ≤ 6 Mpsi
Set time penetrometer method	ASTM C403	Initial set	≥ 15 min
		Final set	≥ 15-90 min
Slump	ASTM C143	Within 5 min of added water	3-9 in if > 9 in, perform slump flow
Slump flow	ASTM C1611	Within 5 min of added water	≥ 9 in
Tier 2 Test Requirements			
Test Property	**Test Method**	**Test Age**	**Test Criteria**
Length change	ASTM C157	28 days stored in air	-0.04% ≤x <0.03% at 28 days Continue testing and report length change until 64 weeks
Coefficient of thermal expansion	ASTM C531	-	≤7 (in/in/F $\times 10^{-6}$)
Shrinkage potential	ASTM C1581	14 days	Record microstrain but no pass/fail limits at this time
		28 days	Record microstrain and fail if any ring cracked

At the conclusions of their study, the researchers identified 10 rapid repair products as the most likely to be compatible for partial-depth airfield pavement concrete spall repairs based on the modified test criteria presented above in Table 2.

Table 3 shows the 10 identified products, their manufacturers, and the year they were tested. The Army Corps of Engineers recommended addressing the limitations of ASTM C1581 shrinkage ring test which includes the inability to measure very early age shrinkage and the inability to measure the effects of expansion for future research. [10]

Table 3 - Recommended approved products based on the new test protocols [10]

Product Name	Manufacturer	Year Tested
SikaQuick 2500	Sika Corp.	2013
Ulti-Pave3	Buzzi-Unicem USA Inc.	2014
ProSpec Premium Patch 200	H.B. Fuller Construction Products Inc.	2015
Rapid Set Mortar Mix	CTS Cement Corp.	2015
HD 50	Dayton Superior Corp.	2015
FasTrac 246 Concrete	Western Material and Design, LLC	2016
Rapid Set Concrete Mix	CTS Cement Corp.	2017
Rapid Set DOT Repair Mix	CTS Cement Corp.	2017
MasterEmaco T545HT	BASF	2017
MasterEmaco T545	BASF	2017

In 2021, the National Road Research Alliance (NRRA) administered by the MnDOT published a guide report to agencies on effective joint repairs of concrete pavements. [7] The guide report details installation of rapid repairs and their performance over time. It also provides a rating system for defects in the rapid repairs or *'Patch Condition Rating Scale'*. Michigan DOT estimated that about 8% to 10% of spall repairs fail within a year of patching, and about 50% of all pavement repairs fail within five years of patching. [11] Table 4 shows potential construction problems, typical causes and typical solutions in Partial Depth Repairs, PDR. [7]

Table 4 - Potential construction problems and associated solutions for partial depth repairs [12]

Problem	Typical Causes	Typical Solutions
Deterioration found to extend beyond the original repair	• This is an unforeseen problem because the true amount of deterioration is not known until the concrete is removed	• Extends the limits of the repair area to encompass all of the deterioration. • If the deterioration extends significantly deeper than one-third to one-half of the slab thickness, FDR should be placed.
Repair failures associated with inadequate compression relief provision	• Compression relief is not provided. • Compression relief material is not deep or wide enough to accommodate joint movement below repair. • Compression relief does not extend to end of repair area.	• Replace the repair, making sure to provide adequate compression relief.
Dowel bar exposed during concrete removal	• Concrete deterioration extends deeper. • Improper concrete removal techniques.	• FDR should be used instead of the planned PDR.
Reinforcing steel exposed during concrete removal	• If the steel is located in the upper third of the slab, exposing it is likely unavoidable. • If steel is exposed below the upper third of the slab, either the concrete deterioration extends deeper or improper concrete removal techniques were used.	• If the steel is in the upper third of the slab, the steel should be removed to the edge and the placement of the repair material should continue as planned. • If the exposed steel is below the upper third of the slab, FDR should be used instead of the planned PDR.
Repair material flows into joint or crack	• The joint insert is not extending far enough into the adjacent joint/crack and below repair. • There is an incorrectly selected insert size for the joint/crack width	• Either remove and replace the repair, or mark the joint for sawing as soon as it can support a saw without raveling the mix. • If the repair material is allowed to infiltrate a crack, it should be removed and replaced.
Shrinkage cracking and surface scaling due to improper finishing and/or curing	• These issues are common when the repair material is not cured properly or adequately or if extra water is added to the surface during finishing	• Minor scaling and shrinkage cracking are typically not major issues; the repair must be monitored for additional deterioration. If excessive scaling and cracking is observed, the repair must be replaced.
Repair cracking or debonding of repair material	• Joint insert is not used or used improperly. • Inappropriate joint insert dimensions. • The repair area was not cleaned immediately prior to grouting or concrete placement. • Grout dried out before placing concrete. • Curing compound is not adequate. • Repair material is shrinkage susceptible. • Repair material was placed under adverse environmental conditions.	• If the repair fails prematurely due to one of these causes, replace the repair. • It is important to determine the cause of the premature failure to avoid repetition.

The NRRA also performed patching of artificially created distress in the pavements. The repaired locations were tested for over a year. They tested fifteen (15) rapid repair products and reported on their performance. They used a rating scale of 0-4 with 4 being excellent while 0 rating implies the failure of the patch. These ratings are summarized in Table 5. The photos in Figure 7 shows the visual representation of the typical cases in each rating.

Table 5 - Patch condition rating scale (7)

Rating	**Patch Condition Description**
4	Excellent; 100% of patch is intact, only shrinkage cracks present
3	Good; distresses (cracking and debonding) exist, but 100% original patch is in place
2	Fair; less than 50% of the original patch is gone/ been replaced
1	Poor; over 50%of the original patch is gone/been replaced
0	Failed; Original Patch no longer exists

Figure 7. Photos showing condition ratings (adapted from [7])

Additionally, NRRA estimated the service life for each product based on the annual condition rating system that was established for their research. The terminal serviceability for a patch was set to a rating of 1.5, which based on the rating scale, would mean that the patch had about 50 percent material loss. A patch lasting longer than 3 years was assumed long-lasting in their research. Based on the terminal serviceability criteria and the condition ratings scale from each annual review, an estimated service life was calculated for each product. The maximum service life for their research was taken as 5 years. Table 6 summarizes the long lasting products and their estimated service regenerated from NRRA report. (7)

Table 6 - Summary of the 'long lasting ' products and their estimated service life (7)

Product Name	Estimated Service Live (years)
Crafco, HP Concrete Cold Patch	3.2
Crafcp. Techcrete-TBR	>5
CTS, Rapid Set DOT Repair Mix	>5
CTS Rapid Set DOT Repair Mix with Helix 5-25-SS BA Fibers	>5
CTS Rapid Set DOT Repair Mix with Helix 5-25 Standard BA Fibers	>5
DS Brown, PaveSaver Polymeric Concrete Patch	>5
Five Star Products, Rapid Surface Repair easy Mix	3.4
Spec Chem, RepCon 928	3.8
TCC Materials, 3U18 Modified	>5
TCC Materials, ProSpec Concrete Patching Mix	4.8
USG, Ecofix	5
Western Material and Design, CE 700 HPC	>5
Western Material Design, FasTrac 246	>5
Willamette Valley Company, FastPatch DPR	>5

Bonding Agent

The bond strength between the repair material and concrete substrate is a major factor in the successful application of patching and its durability. Surface preparation, type of bonding agent, strength of the repair material, temperature and curing are all important factors. It is important that the substrate is structurally sound, free of dust, free of grease, release agents, oil traces, debris, curing compounds, or any other surface contaminants that could adversely affect the integrity of the bond. It is common practice to apply a mortar grout to the surface prior to placement of cementitious repair material to achieve better bond even when no bonding agent is required by the patching product.

According to the NRRA Report, a typical grout mix will consist of two-part cement, one-part water and one part sand. (7) Riding and DonJuan evaluated several bonding agents including cementitious grouts, epoxy, acrylic latex, and polyvinyl acetate in the lab and the field. (13) Figure 8 shows the field test slab with long rectangular defects being repaired similar to partial depth repairs. They applied them at intervals ranging from 0 min to 45 min before application of the repair material. Their tests showed that cementitious grouts bonding agents exhibited higher shear and tensile strengths if the repair material was placed before the grout had cured for more than 15 minutes; after 15 minutes, the bond strength started to decrease once curing had exceeded 15 minutes.

For epoxy and acrylic latex, a waiting time less than their setting time did not have significant effect on bond. Polyvinyl acetate had higher bonding strength in the lab, but in the field bond loss was observed with time. Figure 9 shows the pull-off tensile strength of repair material for various bonding agents for different setting times after 5 months. (13) They reported based on laboratory and field studies, that a w/c ratio of 1.0 provided the best balance between workability, bond strength and wait time between grouting and application of the repair material. And they concluded in their report that results showed adequate bond strength for many repairs can be achieved by just applying the repair material directly to the concrete substrate on saturated surface dry condition free of debris, dust, oils, or other surface contaminants. (13)

Figure 8. Field test slab with long rectangular defects being repaired similar to partial depth [13]

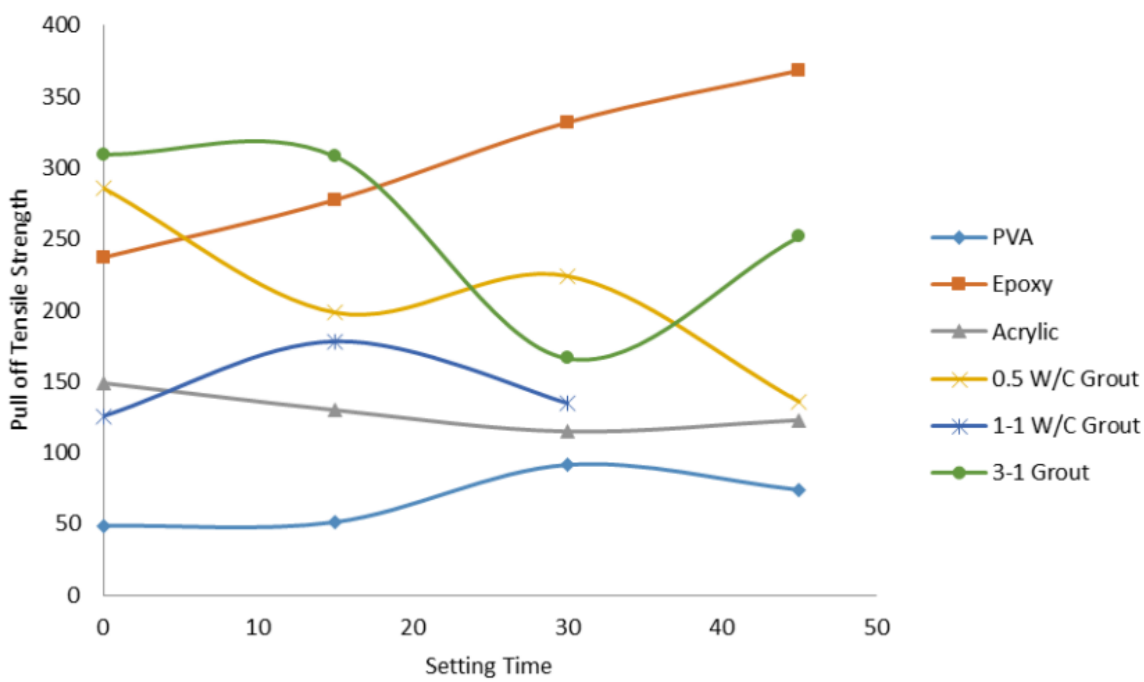


Figure 9. Pull-off tensile strength of repair material for various bonding agents for different setting times after 5 months [13]

Curing

Proper curing is very important for rapid repair concrete to avoid shrinkage cracking. It helps control moisture and temperature and minimizes shrinkage cracks while the repair material achieves required strength. ASTM C309 and AASHTO M148 provide specifications for the majority of curing compounds. [14, 15] NJDOT specifies three groups of curing materials (903.10): Wet burlap cloth, liquid membrane-forming compound (clear or translucent with fugitive dye), and white polyethylene sheeting. White-pigmented curing compounds work by creating a sealing membrane that controls moisture loss and temperature. Its white color helps to control heat from the sun especially in hot weather. Other curing methods such as wet burlap and polyethylene sheets may not be as effective for rapid repair materials because of the rapid loss of moisture and potential for shrinkage cracks.

AASHTO NTPEP Program

The National Transportation Product Evaluation Program (NTPEP) was established to minimize the amount of duplicative testing of transportation materials performed by AASHTO member states by providing a process where manufacturer/suppliers submit their products to NTPEP for laboratory and/or field testing. The results of the testing are then shared with member Departments for their use in product quality verification. All lab and field test data gets collected and test results are made available through the NTPEP DataMine at http://data.ntpep.org. This document is intended to provide guidance in the use of data generated from the "Standard practice for NTPEP Evaluation of Rapid Set Patching Materials for Portland Cement Concrete" which describes the policies and testing protocols for the evaluation of these products. The website: https://data.ntpep.org/RSCP/Products provides information on the product type, manufacturer, year test completed, application (horizontal, vertical or overhead), neat or extended and comments.

State and industry representatives have collaborated in the design of this program with the goal of providing a comprehensive testing regimen that can be used to evaluate concrete patching materials. In addition, AASHTO NTPEP produced a User Guide to assist member departments in the evaluation process. (16) This standard practice has been balloted and accepted by member departments. Access to proprietary data is limited to the submitting manufacturer and registered representatives of member departments of transportation. Non-proprietary data is available to all users. Member departments interested in being represented on this technical committee have to contact a NTPEP representative at www.ntpep.org. Table 7 prepared by AASHTO NTPEP in 2019 summarized the required tests for Rapid Set Construction Products (RSCP). (17) The FHWA Concrete Pavement Preservation Guide also summarizes the typical laboratory test methods used to evaluate the mechanical, durability, and dimensional stability properties associated with cementitious repair materials. These test methods are presented in Table 8. (18)

Table 7 - AASHTO NTPEP Summary of required tests for RSCP [17]

	TEST METHOD		
PROPERTY	**CEMENTITIOUS**	**POLYMER**	**POLYMER-MODIFIED**
Bond Strength by Direct Tension	ASTM C 1583	ASTM C 1583	ASTM C 1583
Bond Strength Using Slant Shear	ASTM 882	ASTM 882	ASTM 882
Chloride Ion Penetration	AASHTO T 277	AASHTO T 277	AASHTO T 277
Surface Resistivity	AASHTO T 358	-	AASHTO T 358
Compressive Strength Neat	AASHTO T 106	ASTM C 579	AASHTO T 106
Compressive Strength Extended	AASHTO T 22	ASTM C 579	AASHTO T 22
Gel Time (Pot Life)	-	ASTM C 881	-
Length Change	AASHTO T 160	-	AASHTO T 160
Linear Shrinkage & Coefficient of Thermal Expansion	-	ASTM C 531	-
Resistance to Freeze/Thaw	AASHTO 161	-	AASHTO 161
Tensile Strength	AASHTO T 198	-	-
Thermal Compatibility	-	ASTM C 884	ASTM C 884
Time of Setting Vicat Needle	AASHTO T 131	-	-
Time of Setting Penetration Resistance	ASTM C 403	ASTM C 403	ASTM C 403
Chloride Ion Content	AASHTO T 260	-	AASHTO T 260

Table 8 - Typical test methods for mechanical, durability, and dimensional stability properties of cementitious repair materials [18]

Property	**Test Method**
Compressive Strength	ASTM C39
Free/Drying shrinkage	ASTM C157
Restrained shrinkage	ASTM C1581
Slant-shear bond strength	ASTM C882 (as specified by ASTM C928)
Tensile bond strength	ASTM C1583
Modulus of elasticity	ASTM C469
Coefficient of thermal expansion	ASTM C581
Freeze-thaw resistance	ASTM C666

None of the reviewed studies provided long-term performance data from repaired locations. The survey from Iowa State and the NCC (National Concrete Consortium) in 2021 to State Highway Agencies provided some limited information on the rapid set repair mortar and concrete products.(9) Results from that survey showed that majority of states require a minimum of 3000 psi compressive strength after 3 hours and more than 1000 psi slanted bond shear strength and +- 0.15% length change. The question on how the repaired location performed overtime or its life span showed that the majority of states did not have enough information or data to report. There is a need to collect performance data either by periodic inspection of selected repaired locations over time or through an implementation pilot project for evaluating the construction practices and short- and long-term performance of common repair material. In addition, agencies need to continue to follow emerging technologies and newly developed commercial products or those developed through research.

According to Cusson and Mailvaganam, there are three modes failures observed in repaired concrete: a) Tensile cracks through the thickness of the patch that can occur due to the lower tensile strength of the repair material compared to bond strength; b) shearing of the substrate concrete below the interface, and c) failure of bond between the repair material and the substrate concrete at the interface.(19) Figure 10 shows these modes of failure.

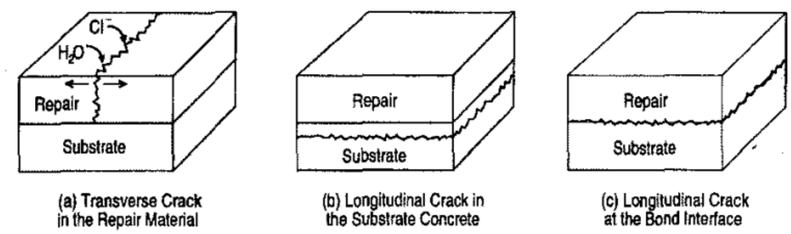


Figure 10. Types of failures in repaired systems [19]

One of the most important factors for the successful application of repair material is to be able to achieve an acceptable level of compatibility between the repair material and the base concrete so that they can act together as a unit in resisting environmental effects such as thermal changes, shrinkage, moisture, permeability. Table 9 shows the desired relationships between the properties of the repair material (R) and base concrete substrate concrete (C) for a successful durable repair. (20)

Table 9 - Properties governing compatibility of concrete patch repair (Adopted from [20])

Physical/ Mechanical Property	**Relationship of Repair material (R) to Concrete substrate (C)**
Strength (Compression, Tension, and Flexure)	R ≥ C
Modulus (Compression, Tension, Flexure)	R ~ C
Poisson's Ratio	Depends on Modulus and Type of
Coefficient of Thermal Expansion	R ~ C
Bond in Shear and Tension	R ≥ C
Curing and Long term Shrinkage	R ≤ C
Strain Capacity	R ≥ C
Creep and Relaxation	Depends on whether creep causes desirable or non-desirable effects
Fatigue Performance	R ≥ C

In 2006, a study conducted by Purdue University for the Indiana DOT (INDOT) to evaluate the performance of rapid setting repair materials that are used in patching concrete pavements and bridge decks, paving of critical intersections and pavements that cannot be closed for extended period of time. [6] The main purpose of the investigation was to provide INDOT with tools for assessment of various repair materials for different application and environmental conditions.

The results from their research showed that a wide range of properties of the repair materials were investigated. They reported that'... *all materials tested had a long-term compressive strength of over 4000 psi, a modulus of 3,000,000 psi, and set between 10 minutes and 2 hours. Results of the bond strength tests demonstrated higher bond strengths in shear than tension.'*. Barde et al also observed large variability in tensile bond strength compared to shear. [6] The tested products also showed a wide range of unrestrained length change. They also reported results from restrained ring tests for cracking potential. Their results showed that *'While several materials exhibited expansion and no residual stress development, other materials demonstrated residual stresses that were nearly 75% of the tensile strength at 7 days.'* [6]

Their recommendations to INDOT were *'…follow up this study with durability tests and field trials of promising materials. The laboratory tests would primarily focus on the freeze thaw durability and the potential for corrosion (where reinforcing steel may be present).'* Their research also included a survey of INDOT field personnel to assess their experience with using these repair materials. From the survey responses, the researchers reported '*It became evident from the survey that different districts have differing experiences regarding which repair practices are most successful. A large portion of the success of any repair is based on the quality of the repair material, the suitability of the repair material for the application, and the quality of the preparation of the parent concrete for the repair as well as the attention to detail during the repair process.'* [6]

A study by Rangaraju and Pattnaik from Clemson University investigated the compatibility between eight repair materials listed on approved list of South Carolina DOT and a typical substrate concrete. [5] Their study was divided into 3 phases: 1) they studied the individual properties of the repair materials such as setting time, flow, compressive strength, flexural strength, split tensile strength, bond strength, drying shrinkage, freeze-thaw resistance, and permeability, were determined using standard ASTM test procedures. Then they studied the compatibility between repair materials and substrate concrete by applying the repair material to a beam whose substrate concrete is patched with repair material and tested in flexure. Lastly, they tried to establish a correlation between the individual repair material properties and the performance of the beam to predict the compatibility of the concrete repair.

Their findings from the study showed that although the mechanical properties of the repair material such as compressive and flexural strength are important to open the patched location to traffic, but these properties did not correlate well with beam results and therefore can't be used to predict compatibility with the parent material. They also reported that, "…to a limited degree the slant-shear bond strength of the repair materials had better correlation coefficient (R^2 = 0.57) with the flexural strength of the composite beam than most other properties of the repair materials''. They also commented that *'the slant-shear bond strength test was found to be inadequate in properly characterizing the compatibility of the repair material with substrate concrete.* Their conclusion was that '*the performance of composite beam under flexural loads (i.e. flexural strength, stress-strain behavior), as proposed in this study, has been found to better characterize the compatibility between repair materials and substrate concrete.'* [5]

Quezada reported tests on rapid set products using with internal curing using lightweight aggregates reduced drying and autogenous shrinkage were reduced by factors up to 20% and 50%.[21] However, detrimentally, creep shrinkage was increased by factors up to 45%. Time to cracking in restrained ring shrinkage tests was increased by factors up to 60%.

In a presentation at the Rapid Bridge Repair Workshop in Virginia, Sprinkle pointed to construction practices as a major factor for a successful application of rapid repair concrete materials in the field. [4] He reported: '*Manpower and equipment are key factors that affect the patching rate*'. He also added: *'Repairs may be less durable because the contractor is rushing to complete the work during the short lane closure time. Repairs maybe less durable because of insufficient lighting and fatigue when the contractor is working at night.*' [4]

Review of NJDOT Approved Rapid Repair Products (QPL)

NJDOT maintains a database of qualified materials and has listed several commercial rapid repair products on the approved Qualified Product List on the NJDOT website.[22] NJDOT also established approval procedures and requirements for quick patching rapid sett repair material as explained in NJDOT specifications 903.07 and in Table 903.07-1 'Requirements for Quick Setting Patch Materials' and NJDOT C-2 'Quick-Setting Patch Materials'. [2] NJDOT specification 903.07 has classified quick setting patching products into four types. These are ready for mixing onsite products following manufacturer recommendations. The products should be concrete gray that does not contain calcium chloride or any other ingredients that could cause corrosion of steel reinforcement. The following paragraph gives the description of the four product types, regenerated from NJDOT Specifications. [2]

Type 1 is suitable for patching above water and can be used as recommended by the producer or the ME can add up to 15 lbs of No. 8 aggregates if the addition does not adversely affect the performance of the product. **Type 1A** is suitable for use above water. These product types have manufacturer specified mix proportions with specified aggregates addition that they cannot be classified as a Type 1. **Type 1B** is suitable for use above water. These product types are those products that have coarse aggregate, sand, or both pre-packaged with the cementitious material. **Type 2** is suitable for vertical and overhead repairs that are not formed or poured.

There is a need to evaluate field performance and durability of selected current products used by NJDOT and identify potential new patch materials or techniques for improved workability and durability. Newly developed commercial products as well as those developed through research may have the potential to provide longer service life of the repairs. In addition to the early strength development, the compatibility properties between repair material and concrete including modulus of elasticity, shrinkage, and coefficient of thermal expansion, as well as construction practices are critical for long-lasting repair. Performance criteria for evaluation and the material approval procedures of rapid repair concrete products needs to be periodically refined and modified based on filed observations and performance.

SUMMARY OF WORK PERFORMED

The project was aimed at developing rapid setting patch repair material for three typical repair applications: thin narrow repair system, typical rapid repair system (large areas), and overhead repair system. The patch repair materials for each of the three repair applications were first evaluated for workability, compressive, and flexural strength in laboratory setting. The selected mix formulations were then cast into 3-ft long beam samples over existing concrete to evaluate their restrained shrinkage characteristics. The materials used in developing the patch repairs and the testing program that followed, are discussed in this section.

Material Selection

The materials used in each patch repair formulation for the project were as follows:

- Cements
- Water
- Polyvinyl alcohol (PVA) fibers
- Latex polymer – Aqueous styrene-acrylate copolymer dispersion
- Sand – Uniformly graded sand
- Pea gravel

Cements

Three commercially available cements were used to develop a patch repair system for each of the target applications: Calcium Sulfoaluminate (CSA) based cement (C1), Portland cement with proprietary admixtures (C2), and Portland cement modified with quartz (C3). The three cement products were chosen from QPL of NJDOT.(22) Each product was targeted for one of the three repair applications. The three products belonged to three different manufacturers and are commonly used by contractors which made them suitable for experimentation and future implementation.

Water

The water-to-cement (w/c) ratios used for the different formulations were 0.11 and 0.14. This water content did not account for water present in the latex polymer, since it can be fairly assumed that amount of water present in the latex polymer is needed for providing the characteristic at fresh and hardened state that latex polymer provides.

Polyvinyl Alcohol (PVA) Fibers

The fibers used were Polyvinyl Alcohol (PVA) fibers. This group of fibers is known to form a hydrogen bond with cement matrix through the hydroxyl groups of ions present in the chemical structure of the PVA fibers.(23) Many fiber types are used in high performance cementitious composites to enhance toughness, increase strain capacity and reduce crack width. These include steel fibers, polypropylene fibers (PP), polyvinyl alcohol fibers (PVA), carbon fibers, basalt fibers, and glass fibers. Based on their availability and advantages offered in presence of latex polymer, the PVA fibers were chosen in this investigation. The dosage of PVA fibers chosen for each mix formulation were 1 percent by weight of cement-water paste. Table 10 shows the physical properties of PVA fibers available from the supplier that provided the fibers.

Table 10 - Properties of PVA Fibers

Filament Diameter	100 µm
Fiber Length	0.5" (13 mm)
Sp. Gravity	1.3
Tensile Strength	180 ksi (1200 Mpa)
Flexural Strength	3600 ksi (25 Gpa)
Melting Point	435^0 F (225^0 C)
Color	White
Water Absorption	< 1% by weight

Latex Polymer

Styrene acrylate based latex polymer was used in formulating the repair mixes. Latex polymers are known to form films that bridge the calcium hydroxide Ca(OH)2 crystalline structures in the cement matrix. (24) The polyacrylate latex produces carboxyl compounds in an alkali-rich environment after cement hydration. This further leads to linking carboxyl groups with the Ca2+ from the Ca(OH)2 that is produced as a byproduct of cement hydration. (25) Moreover, polymers are also known to enhance the hydrogen bonding of PVA fibers with cement mortars.(26) The optimum dosage of the polymer content was found in the existing literature to be about 12 percent (polymer-cement). (27) Hence, the dosage considered in this investigation was 10 percent by weight of cement-water paste (which is equivalent to about 11 percent by cement weight for a w/c ratio of 0.11 used in this study).

Sand

Sand was added in the mix formulations to increase the yield of the mix and to reduce the shrinkage. All the formulations contained oven dried sand to avoid interference of the sand moisture with w/c ratio of the formulations. Figure 11 shows the gradation of the sand utilized in the experiments. It should be noted that commercially available processed sand having majority of particles between the sieve sizes of No. 30 and No. 100 was chosen to avoid compromising the workability with the presence of finer particles. The dosage of sand used in the repair formulations was 15 percent by weight of cement-water paste.

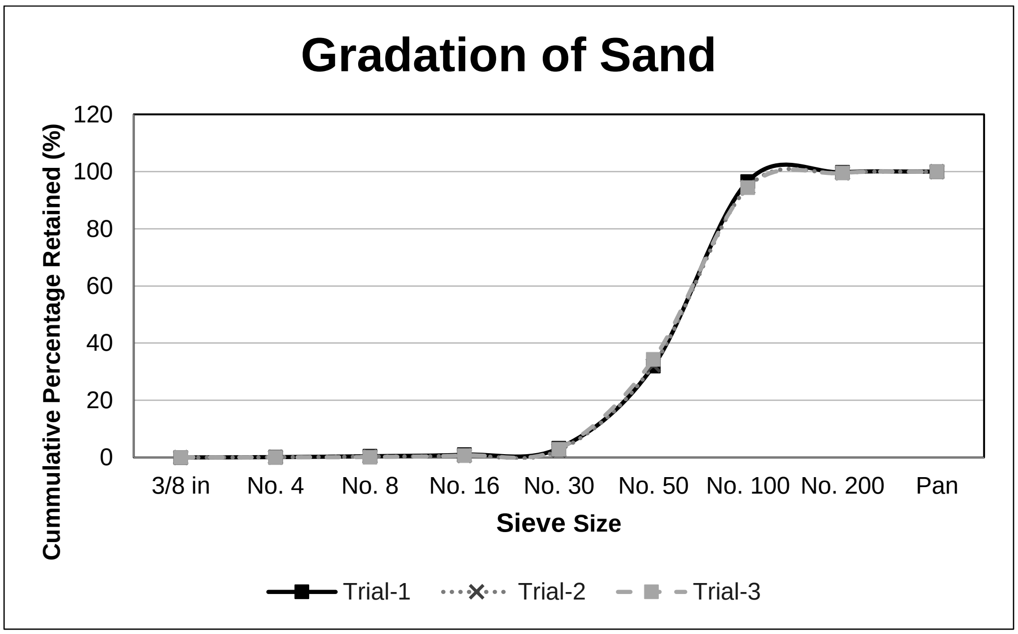


Figure 11. Gradation of sand used in the repair mix formulations

Pea Gravel

Gravel was also considered necessary to extend the mix formulations for larger volume. In addition, pea gravel is well known for its natural internal curing effect through which it can retain moisture during the fresh state and release it later in the hardened state. (28) This helps in reducing the shrinkage of the repair formulations. Figure 12 shows the gradation of the gravel used in the repair mixes. The nominal maximum size of the pea gravel particles used was less than 0.735 in and more than 0.187 in.

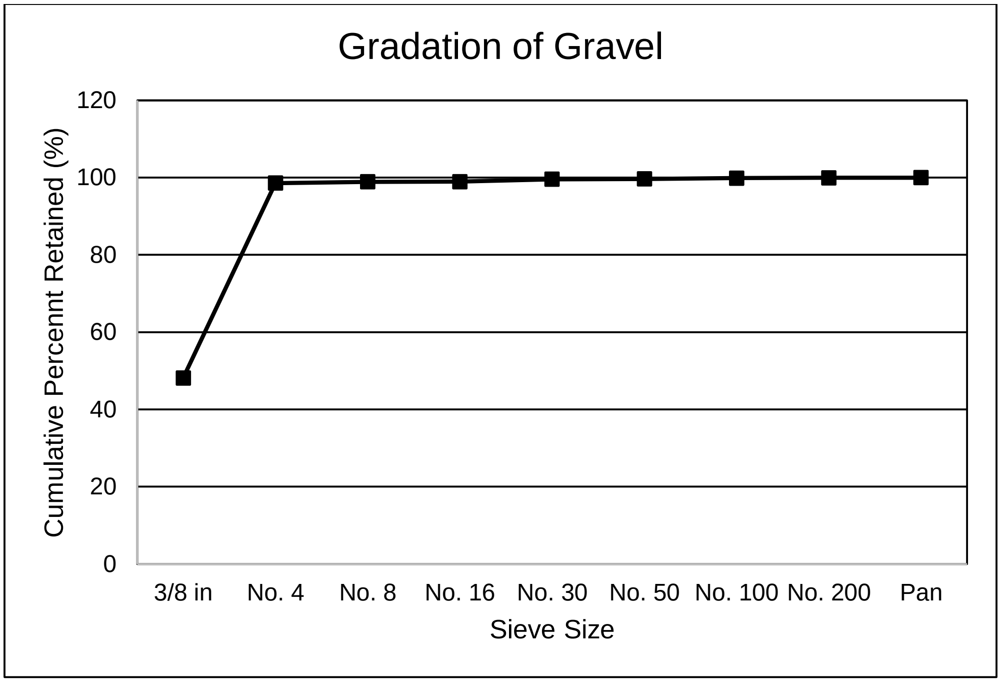


Figure 12. Gradation of gravel used in repair mix formulations

Admixtures

High range water reducing (HRWR) admixture complying to ASTM C 1017 and ASTM C 494 was added in the formulations at the dosage of 3 percent by weight of cement-water paste for all the formulations experimented for restrained shrinkage cracking.(29, 30) For the laboratory samples experimented for strength, the HRWR dosage was kept lower at 2 percent by cement weight.

Equipments

- Hand mixer
- Slump cone
- Vibrator
- MTS testing Machine
- Forney Machine

Experimental Program

The experimental program included evaluating the repair mix formulations for short-term and long-term performance. For the short-term criteria, the workability, compressive strength, flexural strength, and the load-deflection characteristics were evaluated in laboratory setting. For the long-term criteria, the restrained shrinkage cracking of the formulations over two different concrete surfaces representing considerably rough and considerably smooth surfaces (for the civil engineering applications) was evaluated. The rough surface was available from existing porous concrete slabs whereas the smooth surface was incorporated using the commercially available plain cement boards generally used as an underlayment for floors, countertops, and other architectural applications in building systems. (31) The restrained shrinkage samples were cast and placed in external environmental conditions. The samples are then left to undergo any volumetric changes under external weathering conditions.

Preliminary Investigation – Laboratory Setting

The formulations were initially cast in a laboratory setting to evaluate their workability and strength. A total of six mix formulations, two from each of the three selected cement products from NJDOT-QPL were considered for testing. For each cement product, one formulation without gravel and the other with 50 percent of gravel by cement weight was considered. Each mix formulation also contained 1 percent PVA Fibers, 15 percent oven dried sand, 10 percent latex polymer, and 2 percent HRWR, each by weight of cement-water paste. The water-to-cement ratio was 0.14 for the laboratory mix formulations. Table 11 shows the mix composition of these formulations. The L prefix for the mix number indicates that the mix was conducted in a laboratory setting.

Table 11 - Mix composition of formulations for laboratory setting

	C1-F1-G00	C1-F1-G50	C2-F1-G00	C2-F1-G50	C3-F1-G00	C3-F1-G50
Mix No.	L1	L2	L3	L4	L5	L6
Cement	CSA	CSA	Portland & proprietary admixtures	Portland & proprietary admixtures	Portland & Quartz	Portland & Quartz
Fiber (%)	1	1	1	1	1	1
Pea Gravel* (%)	0	50	0	50	0	50
w/c	0.14	0.14	0.14	0.14	0.14	0.14
Sand (%)	15	15	15	15	15	15
Latex Polymer (%)	10	10	10	10	10	10

It should be noted that mix formulations are designated based on their cement type (CSA cement, Portland cement with proprietary admixtures, or Portland cement with quartz), fiber content (0% or 1% of cement paste), and gravel content (0% or 50% of cement weight). For example, a mix containing Portland cement with proprietary admixtures with 1% fiber and 50% gravel will be designated as C2-F1-G50, where C2 stands for Cement-2. The three cements are designated as C1, C2, and C3 in the order of CSA cement, Portland cement with proprietary admixtures, and Portland cement with quartz, respectively. Table 12 provides a summary of the cement labeling convention used for all mixes.

Table 12 - Cement Labeling Convention

Cement Product	Label
Calcium sulfoaluminate (CSA) cement	C1
Portland cement with proprietary admixtures	C2
Portland cement with quartz	C3

After observing the mix consistency, setting time, compressive strength, and load-deflection results, researchers selected the mixes that would be executed to cast Restrained Shrinkage samples over Porous and Plain Concrete slabs outside the Asphalt lab in Livingston Campus. To improve the strength of the samples the water-to-cement ratio of 0.14 was reduced to 0.11 for all restrained shrinkage mix formulations. HRWR was also increased from 2% to 3% in the restrained shrinkage formulations to improve workability after reducing the w/c ratio.

Restrained Shrinkage Investigation – Field Setting

Following the laboratory investigation, the next stage involved mixing and casting the repair formulations in external environmental conditions. The samples primarily included the restrained shrinkage (RS) samples for evaluating the shrinkage cracking behavior of the formulations. Additionally, compressive, and flexural strength samples were also cast along each restrained shrinkage mix formulation. The compressive strength samples were 3-inch diameter x 6-inch height cylinders that were tested 24 hours after casting. Similarly, the flexural samples included 2-inch-wide x 2-inch-thick x 14-inch-long beam samples. The RS samples included 3-ft long x 2-inch-wide x 1-inch-thick beams cast over existing porous concrete and plain mortar slab surfaces. Twelve mix formulations were experimented to study the shrinkage cracking behavior. Each of the twelve formulations were repeated over both the porous concrete and plain mortar slab surfaces.

The mix composition of these formulations cast primarily to study restrained shrinkage cracking contained a lower w/c ratio of 0.11 compared to that of 0.14 in laboratory mix formulations. This was done to improve the compressive strength since the workability of the formulations cast in laboratory was found to be clearly satisfied. The mix design for the samples over porous and plain slabs is shown in Table 13 and Table 14. These restrained shrinkage mixes follow the same nomenclature as the laboratory mixes except the letter "L" is omitted from the designation. For the field application, formulations containing only fibers and only gravel with the remaining cement-polymer matrix were also investigated to compare the impact of fiber and gravel addition on restrained shrinkage, separately. These additional formulations for each cement type contained 1% PVA fibers but no pea gravel, and 50 percent pea gravel but no PVA fibers. Moreover, the control mix formulations containing cement, water, polymer and the HRWR were also added for restrained shrinkage experimentation.

Table 13 - RS mix design without coarse aggregate

Mix Designation	C1-F0-G00	C1-F1-G00	C2-F0-G00	C2-F1-G00	C3-F0-G00	C3-F1-G00
Mix No.	1 and 13	2 and 14	3 and 15	4 and 16	5 and 17	6 and 18
Cement	CSA	CSA	Portland & proprietary admixtures	Portland & proprietary admixtures	Portland & Quartz	Portland & Quartz
Fiber (%)	0	1	0	1	0	1
Pea Gravel* (%)	0	0	0	0	0	0
w/c*	0.11	0.11	0.11	0.11	0.11	0.11
Sand (%)	15	15	15	15	15	15
Latex Polymer (%)	10	10	10	10	10	10
Super P (%)	2	3	3	3	3	3

*w/c – Reduced to 0.11 from 0.14

Table 14 - RS mix design with coarse aggregate

	C1-F0-G50	C1-F1-G50	C2-F0-G50	C2-F1-G50	C3-F0-G50	C3-F1-G50
Mix No.	7 and 19	8 and 20	9 and 21	10 and 22	11 and 23	12 and 24
Cement	CSA	CSA	Portland & proprietary admixtures	Portland & proprietary admixtures	Portland & Quartz	Portland & Quartz
Fiber (%)	0	1	0	1	0	1
Pea Gravel[1] (%)	50	50	50	50	50	50
w/c[2]	0.11	0.11	0.11	0.11	0.11	0.11
Sand (%)	15	15	15	15	15	15
Latex Polymer (%)	10	10	10	10	10	10
Super P (%)	3	3	3	3	3	3

[1]Pea gravel expressed as percentage of cement weight.
[2]W/c reduced to 0.11 from 0.14 in laboratory investigation.

The RS samples were first cast over the porous concrete slab surface using mix formulation no. 1-12. The same mix formulations were then replicated on the plain mortar slabs to compare the development of cracks over each slab surface. Hence, formulation no. 1 to 12 were used to cast RS samples over porous concrete slab surfaces. Whereas the formulations 13 to 24 were repetitions on plain mortar slab surfaces. The strength samples cast from mix formulations 1-12 were tested at 24 hours whereas the ones cast from mix formulation no. 13-24 were tested at 3 hours. Figure 13 shows an overview of the restrained shrinkage testing program.

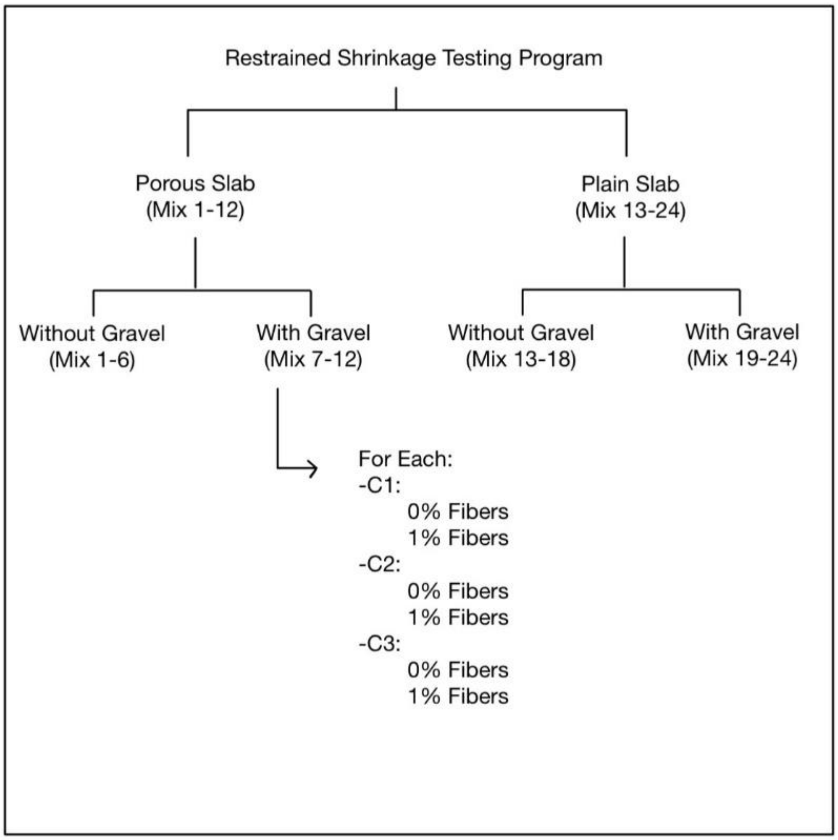


Figure 13. Restrained shrinkage testing program

Each RS sample was 3-ft-long x 2-inch-wide x 1-inch thick. Two porous concrete slabs were required for casting the required number of restrained shrinkage samples. The slabs had a 3-ft edge in plan along which the samples were cast. The slabs were pre-constructed prior to the current investigation and rigidly affixed to the ground. The plain mortar slabs were available commercially having dimensions – 5-ft long x 3-ft wide x 0.5-inch thick. Since the plain mortar slabs were having low thickness, wooden boards were affixed at the bottom of slabs throughout their surface to prevent the slabs from bending. This arrangement of cement boards with wooden planks was placed over thick wooden pallets with a levelled surface. To ensure that the samples are only restrained from bottom through the porous or plain concrete surfaces, the formwork used to cast the samples was covered with packing tape on all sides. This ensured the free movement of samples along the edges in longitudinal direction. Additionally, the inside bottom edge of formwork was sealed with a typical silicone-sealant to ensure no leakage of fresh material. Figure 14 shows the plain mortar slabs used. (31) Figure 15 and Figure 16 shows the form work for the two slabs before the beams were cast.

Figure 14. Plain mortar slab [31]

Figure 15. Formwork for porous slab

Figure 16. Formwork for Plain Slab

Mix Procedure

The following mix procedure was used for all the RS mixes cast on the porous and plain slabs:

1. Cement and fibers were dry mixed with the hand mixer for 1 minute.
2. All the sand was added to the dry mixture and mixed for 1 minute.
3. In a separate bucket water equivalent to 0.11 water-to-cement ratio was combined with all the polymer and 1% of superplasticizer.
4. The dry mix was added to the wet mixture then mixed for 1 minute.
5. The remaining water (equivalent to water-to- cement ratio of 0.03) was combined with 1% of superplasticizer then added to the mix.
6. The concrete was then mixed for 2 more minutes.
7. If pea gravel was required in the design, it was added at the end of 3 minutes and the mixing was carried on for 1 more minute.
8. Slump test was performed, and samples were casted. The test was not carried out for mixes with gravel.

Casting

For each mix, two samples for restrained shrinkage were cast. In addition, one beam sample (2 in. x 2 in. x 14 in.) for flexural strength and 3-cylinder samples (3 in. x 6 in.) were cast for testing. The tests were performed at 24 hours for samples cast over porous slabs and at 3 hours for samples cast over the plain slabs.

Each RS sample was cast in three equal layers. Each layer was first vibrated using a battery-driven needle vibrator and then rolled using the 1-inch-wide roller to orient the PVA fibers along the length of the sample. The use of a roller also helped in reducing the air voids inside the samples. The top layer was rolled using a wider roller that could go over the entire width of the sample.

The beam and cylinder samples for strength testing were also cast in similar fashion as RS samples, except that for cylinders, the sides were tapped according to ASTM C192 to close the voids after vibration. [32] Figure 17 and Figure 18 shows the dry mixing and vibration process being carried out for a typical mix.

Figure 17. Dry mixing

Figure 18. Vibrating the layers of concrete

Curing

The samples were covered with saturated wet burlap approximately 30 minutes after casting when they were visibly losing plasticity. More water was sprinkled over the wet burlaps after the samples were covered. The burlap was sprinkled with water again after 15-20 minutes of placing wet burlap over the samples. However, it was not sprinkled further and repeatedly for the next 24 hours to simulate the real conditions. It should be noted that the burlap stayed wet naturally for 2-3 hours, after which repair can be expected to open to traffic in a real application. Figure 19 and Figure 20 shows the curing of typical samples using burlaps. The burlap was covered with a plastic sheet to prevent evaporation of water.

Figure 19. RS samples curing with burlap

Figure 20. RS flexural and compressive samples curing with burlap

Testing

Inverted Slump Test

Inverted slump cone tests were performed for each non-gravel mix. The test was performed using a hollow plastic cone of 9-inch height, 4.5-inch top diameter and 1-inch bottom diameter. To perform the test, the cone would be kept hanging on a burette stand about 1 to 1.5-ft above the ground. The height of the cone above the ground is not a concern since the time was measured only to empty the cone and not to measure the time it took the mix to fall on ground, see Figure 21. Next, one of the two operators would lock the bottom 1-inch opening of the cone and the second operator would pour the mix from the top 4.5-inch opening to fill up the cone completely. Once filled up, a battery-driven needle vibrator would be inserted from top, and the first operator would let the bottom open at the same time. The time would be measured from the start of vibration (or opening of the bottom hole) until the entire cone gets empty. If the mix is having a thick consistency, it will take more time to empty the cone and vice versa. However, in some cases, the mix would be very thick, and a small chunk of the repair material would get stuck at the bottom. In such cases, comments were made during the slump test. While the needle vibrator was moved vertically during the slump test, it was not used to force any such chunk stuck at the bottom opening. Slump test was not performed for samples with gravel due to the aggregate getting stuck in the cone when slump test would not be valid for a highly fluid mix since in such a case, cone would empty within a few seconds. Being emptied.

Figure 21. Inverted slump test

Compressive Strength

Compressive strength testing was performed in accordance with ASTM C 39 which required the casting of three-3 in x 6in cylinders for each mix. (33) As previously mentioned, the mixes cast on the porous slab were repeated on the plain slab. Therefore, mixes 1 to 12 for the porous slab had compressive strength samples cast and tested at 24 hours. Meanwhile, mixes 13 to 24 on the plain slab had compressive strength samples tested at 3 hours after casting. Testing at 3 hours and 24 hours allowed for the comparison of the strength gained over time for the rapid set mixes.

Flexural Strength

One-2 in x 2 in x 14 in beam was cast and tested in flexure at 24 hours for each mix using an MTS testing machine. The flexural beams were cast, rolled, and vibrated in layers in the same manner as the RS beams. The beams were simply supported with a 1-inch overhang on each side. Effective length was 12 inches with 3rd-point loading according to ASTM C78. (34) Figure 22 shows the test set up for flexural testing.

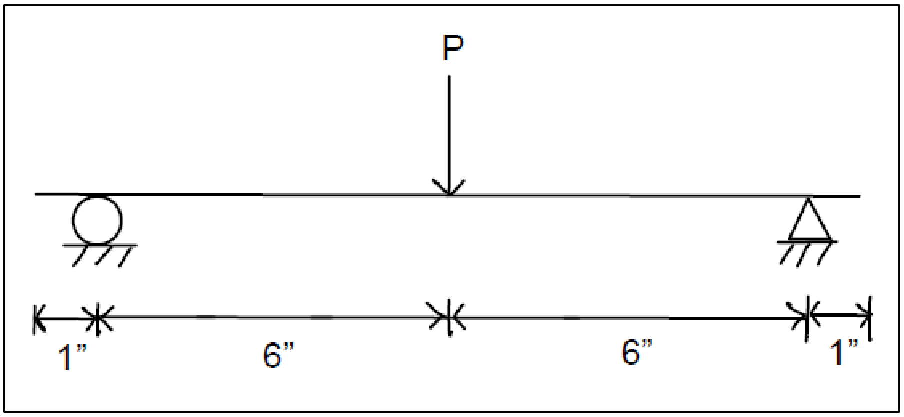


Figure 22. Flexural testing set up

Shrinkage Crack Monitoring

The restrained shrinkage samples cast on top of the porous and plain concrete slabs were monitored for shrinkage cracking. The shrinkage cracks were expected to appear and develop until 6 months after the samples were cast. Porous concrete slabs provide the highest restraint practically possible. Since the formwork was covered with a packing tape and the samples are restrained only from the bottom, the cracks are expected to develop as the samples shrink beyond their tensile strain capacity of the formulation. The important crack data recorded every month for a period of six months was: (1) number of cracks, (2) crack width.

The porous slabs were cast in late June 2022 and were monitored every month starting in July 2022. The plain slabs were completed on November 10, 2022 and the monitoring process started two weeks after on November 23, 2022.

To record the crack widths, a Wifi-Microscope was used to take pictures of cracks at different locations. For each crack, the microscope is placed near both ends and in the middle, to take 3 photos. From each photo, the width is measured at 4 different sections along the crack. Since it is necessary to measure the crack width perpendicular to the crack, the microscope was adjusted and rotated while taking photos. Additionally, any areas of cracks that are not distinctly visible or are not predominantly straight are avoided. The microscope typically requires a magnification of 65x -70x for obtaining a clear picture of crack. To measure the crack width, the microscope needs to be calibrated for each magnification for which the photos need to be taken.

The shrinkage and cracking behavior of a sample can be affected by the type of cement, fiber content, and gravel content. In addition, external factors like temperature and humidity, time of casting, and curing can also affect shrinkage of samples. However, these external factors are mostly similar for different types of samples cast. For example, all the samples were cast in an outside environment during similar temperature and humidity conditions. Additionally, since the cracking behavior of the samples will be observed over a longer term, the small differences in weather at the time they were cast does not carry much weight as far as the samples were exposed to similar conditions of weather in their first week. This mainly includes exposure to rain or snow after the first week of casting. The weather forecast was considered when casting the samples. Any days which were followed by chances of rain were avoided. Since the samples were cast between the months of July to October, the chances of snow are naturally eliminated.

Schmidt Hammer Testing

Schmidt hammer testing is a nondestructive method of obtaining the compressive strength of concrete. This method of non-destructive testing can be useful for the rapid repair operations due to the limited time available for the construction crew to test the strength samples. Additionally, the compressive strength estimated by the hammer can also be useful in deciding the opening of lane to traffic. The Schmidt hammer needs to be pressed against the surface to be tested for measuring the compressive strength. Pressing the hammer completely in a particular orientation makes the spring inside the hammer recoil to a certain distance on the graduated scale along the hammer. This scale reads the rebound number (RN) for the material that corresponds to compressive strength of the material.

The manufacturer of the hammer provides graphs that correlate the RN generated from the hammer test to a specific compressive strength. However, the rebound number from the hammer depends on the elastic modulus of the surface being hit. Thus, the compressive strength from the manufacturer supplied graphs also depends on relationship between compressive strength and elastic modulus for the type of material being hit by the hammer. This relation is not the same for any other type of concrete as normal concrete. Hence, for a different class of materials like rapid setting patch repairs, the relation between the RN and the compressive strength needs to be established if it is desired to use the hammer for compressive strength testing of such materials. The research team performed a preliminary investigation to evaluate the feasibility of using the Schmidt hammer for patch repair materials developed in this investigation.

The procedure for the hammer testing followed ASTM C805 standard. (35) The standard requires the hammer to be hit at a location with minimum of 2-inches of the edge distance. Additionally, each hit should be one inch apart. Abiding by the standard requirements, six- 6in x 6in x 6in cubes were cast for each type of base matrix formulation considered in this study. The cubes were then tested with hammer to obtain their RN values, immediately after which they were tested in compression according to

ASTM C39. (33) In this manner, three cubes were tested at 3-hours and the remaining three were tested at 24 hours.

Moreover, when testing using the Schmidt hammer, the orientation of hammer and the angle at which it hits the concrete surface affects the RN value. Hence, three surfaces of the cube were utilized for obtaining compressive strengths. As shown in Figure 23, considering the cube in upright configuration such that the trowel finished surface is on top, two of the four vertical faces (see surface A and B in Figure 23) directly opposite to each other were used to obtain the RN values for the horizontal orientation of the hammer. The face opposite to the trowel finished top surface was tested for the vertical orientation. Figure 24 shows the nine locations on each face tested where the hammer was hit. The machine compressive strength was obtained by placing the cube samples in the same configuration as they were cast, that is, the trowel finished surface was on top.

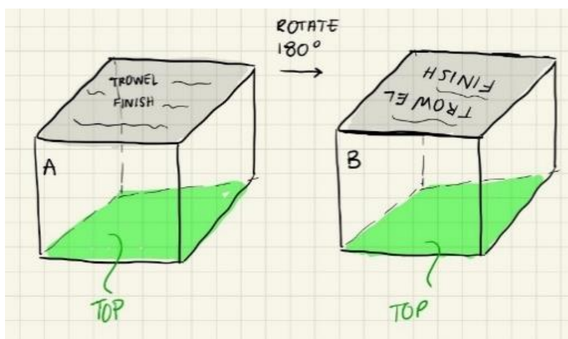


Figure 23. Orientation of the cube faces used for testing

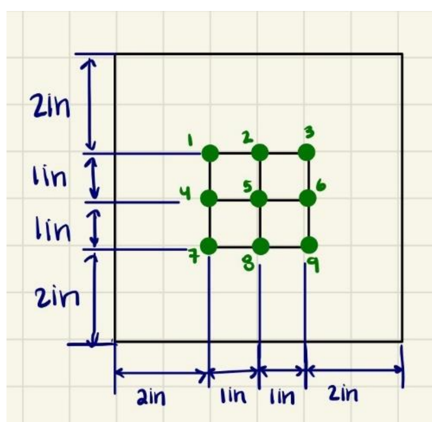


Figure 24. Schematic of the hit locations for the hammer

The Schmidt hammer casting and testing was part of the last experimental phase of the research. The research team cast six cubes using a 0.11 w/c ratio. The cubes were cast following the same procedure and composition as the RS slab mix formulations without fibers or aggregate. Only the base matrices from each type of cement were considered for experimenting with Schmidt hammer. The mix composition is shown in Table 15.

After casting six cubes, three were tested at 3-hours and the remaining three were tested at 24-hours. Figure 25 shows photos of typical cubes that were tested.

Table 15 - Mix Design for cubes to be tested with Schmidt hammer

Mix Design For Cubes			
Mix No.	1	2	3
Cement	CSA Cement	Portland cement with proprietary admixtures	Portland cement with quartz
Fiber (%)	0	0	0
Pea Gravel* (%)	0	0	0
w/c*	0.11	0.11	0.11
Sand (%)	15	15	15
Latex Polymer (%)	10	10	10
Super P (%)	2	2	2

Figure 25. CSA cement cube samples for 3- hour testing

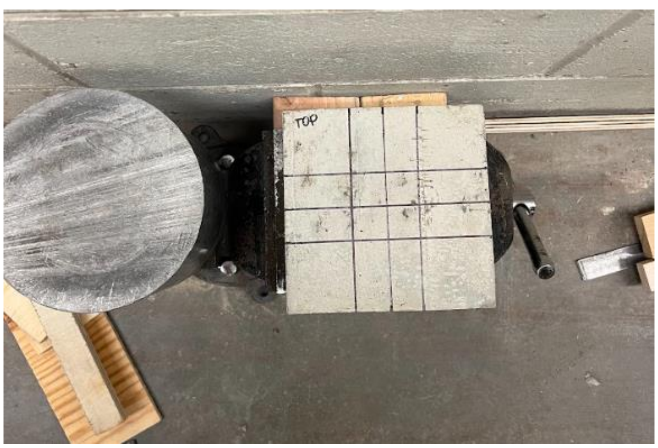
The test set ups were designed differently for hitting the sides of the cube verses hitting the top of the cube. Figure 26 shows the test set up for hammer testing in horizontal orientation. For hitting the sides, the hammer orientation was horizontal to the ground as seen in Figure 26 (b). Simulating the behavior of testing a large slab, the sample was clamped on the sides not being tested and braced against a concrete wall. This was repeated for both sides A and B.

(a)

(b)

Figure 26. Test set up for horizontal orientation of the Schmidt hammer: (a) testing surface, (b) hammer orientation

Figure 27 shows the test set up for orienting the hammer 90 degrees downward to the ground to test the top surface of the cube. Testing the cube samples from top required them to be clamped on the sides to provide a restraint on side. Since the hammer would hit the cube vertically downward the cube was rested on thick pieces of wood so that the readings would not be affected by vibrations at bottom of the steel clamp.



(a)

(b)

Figure 27. Test set up for vertical downward orientation of the hammer: (a) testing surface, (b) hammer orientation

Discussion of Test Results

Workability and Curing

The workability, fluidity, and setting time of the mixes is critical to the feasibility of these RS mix designs for real pothole repair. The researchers recorded their observations after conducting each mix. Table 16, Table 17, and Table 18 report the workability observations for cement types (C1), (C2), and (C3) respectively.

Mix Formulations of CSA Cement (C1)

The base matrix without fibers and aggregates showed very good flowability. The working time was relatively lower at 20-22 minutes. The formulations with fibers but no gravel (C1-F1-G00) showed slightly reduced flowability over the base mixes. Nevertheless, the overall workability of these was better than the base matrix. Their working time was similarly lower at 20-22 minutes. The gravel mixes without fibers (C1-F0-G50) had sufficient working time (more than 30 minutes) since neither of the two mixes started setting during casting. Furthermore, the formulations containing both fibers and gravel (C1-F1-G50) showed a thick consistency. However, these formulations were not difficult to place and required minimal vibration. All the gravel containing formulations had some difficulty when it came to levelling the top surface flat. This is more likely due to the 2 inch width of the RS samples.

Table 16 - Workability observations for CSA cement mixes (C1)

		Porous Slab Mixes		Plain Slab Mixes	
Mix No.	Mix Name	Ambient Temperature (Celsius)	Workability Observations	Ambient Temperature (Celsius)	Workability Observations
1 & 13	C1-F0	27	Mix was very fluid. Took about 20 minutes to start hardening. Only 2% super P was added	20	Setting time was earlier than mix 15. The concrete set very fast but was flowable. The mix became thixotropic
2 & 14	C1-F1	27	Mix was fluid and required minimum vibration during casting.	22.8	Set quickly, initial setting time was approx. 20 minutes
7 & 19	C1-F0-G50	27.8	Mix was very fluid, minimal vibration required	10.6	Mix was thick. The setting time was 30 minutes, and it didn't set during casting
8 & 20	C1-F1-G50	27.8	Mix was very fluid, minimal vibration required	16.7	Not as sticky as mix 19. Mix yielded 4 cylinders and had better workability than mix 19. The mix was thick and difficult to level because of the aggregates.

Mix Formulations of Portland Cement With Proprietary Admixtures (C2)

The C2 base matrix without fibers and aggregates showed a better plasticity than the CSA cement base matrix. One of the two base matrices that was used to cast RS sample over porous concrete slab (Mix 3), started setting earlier and required some vibration while casting. The formulations containing fibers, but no gravel (Mix 4 and 16) naturally showed a thicker consistency than the base matrices. Additionally, these C2 formulations having 1 % fiber showed more flowability than the C1 with 1 % fibers. The two formulations containing gravel, but no fibers (C2-F0-G50) showed significant differences in their setting time, 15 minutes for mix no. 9 compared to 30 minutes for mix no. 21. This was likely due to the difference in temperature at which they were cast, 22.8 °C vs 11.7 °C, respectively. Both the mix formulations containing fibers and gravel (Mix no. 10 and 22 – C2-F1-G50) showed thick and clumpy consistency. While the working time was sufficient for casting the samples, the mixes required significant vibration due to the thick consistency, from the beginning. The use of needle vibrator along the sample left a groove during casting and the mixes did not show any self levelling.

Table 17- Workability observations for Portland cement with proprietary admixture (C2)

		Porous Slab Mixes		Plain Slab Mixes	
Mix No.	Mix Name	Ambient Temperature (Celsius)	Workability Observations	Ambient Temperature (Celsius)	Workability Observations
3 &15	C2-F0	28	The mix set quickly. Researchers required to work fast to cast both RS Beams, cylinders, and flexural samples. Vibration needed while casting samples	20	The mix was more plastic than the CSA mix 13. Flowable
4 &16	C2-F1	28	The concrete paste was very thick and required vibration to keep the mix workable while casting. Surface of samples was rough	22.8	The chunk of concrete stayed in slump cone during test. Mix was workable and had a high yield. Better than CSA mix
9 &21	C2-F0-G50	22.8	Samples with gravel and without fibers had better workability. The mix was more fluid, and the setting time was about 15 minutes	11.7	The setting time was greater than 30 minutes. The mix was fluid and self-leveling. Mix was workable.
10 & 22	C2-F1-G50	22.8	The workability of samples with gravel and fibers was very thick. This mix required additional vibration to the bucket to finish casting. Rolling the samples was also difficulty leading to a rough surface.	11.7	The Mix was clumpy, cement paste was less due to aggregates. The workability was not bad, and the setting time was 30 minutes. No self-leveling and vibrator left a grove.

Mix Formulations of Portland Cement Modified with Quartz (C3)

The base matrix without having fibers and aggregates showed high flowability. However, the working time was much lower than the other two base matrices at 15 minutes. The formulations containing fibers, but no gravel (C3-F1-G00) also set faster and the setting time was comparable to that of the CSA cement mixes with 1 % fibers. Vibration was required after about 10-12 minutes of mixing due to early setting of the mix. Many RS samples of this cement started showing cracks almost as the mix started drying. The formulations containing gravel, but no fibers (C3-F0-G50) showed higher setting times, 20 and 25 minutes for Mix 11 and 23, respectively. These formulations also showed good flowability and self-levelling characteristics. The formulations containing both gravel and fibers (Mix 12 and 24) again showed less working time and required vibration to continue casting the samples.

Table 18 - Workability observations for Portland cement and quartz mixes (C3)

Portland Cement with Quartz Mixes					
		Porous Slab Mixes		Plain Slab Mixes	
Mix No.	Mix Name	Ambient Temperature (Celsius)	Workability Observations	Ambient Temperature (Celsius)	Workability Observations
5 & 17	C3-F0	32	Portland cement with quartz mixes were fluid and workable after mixing but the setting time was only about 15 minutes before it became difficult to cast. RS samples showed cracks immediately after casting.	20	The mix was very soupy and runny. Setting time was slow. Had a higher yield than expected
6 &18	C3-F1	32	The Portland cement with quartz samples with the fibers also required a bit of vibration and showed cracks immediately after casting. Setting time was about 15 minutes before the paste started to harden.	22.8	20-minute setting time. Set fast but not as fast as CSA cement mix with 1%F 0%G.
11 & 23	C3-F0-G50	30.6	The workability of the Portland cement with quartz mixed with gravel and without fibers was very good. Setting time lasted about 20 minutes and there were no difficulties with casting samples	17.8	The set time was about 25 minutes. The mix was self-leveling and fluid. It required minimal rolling. A plastic crack appeared at 25 minutes.
12 & 24	C3-F1-G50	30.6	Portland cement with quartz mixed with fibers required some extra vibration in the bucket after 15 minutes to finish casting compression samples. Overall workability was good.	18.9	Yielded 5 cylinders. The mix was not self-leveling, the setting time was 25 minutes. This mix was like CSA cement with fibers.

Inverted Slump Tests

The inverted slump test timings were recorded for all non-gravel formulations. Table 19 shows the recorded slump times. The ideal timing for a good workable mix for horizontal repair application was observed to be 12-15 seconds. The maximum time recorded was 20 seconds for C1-F1 over plain slab and C3-F0 over porous slab mix. The formulations of the same compositions had consistent slump timings except the base matrix for the C3 cement. The formulations containing 1 percent PVA fibers naturally showed slightly higher slump timing than their base matrix counterparts. The timings of C3 formulations (except C3-F0 over porous slab) were in line with their high flowability observed at the time of casting.

Table 19 - Slump times for RS mixes without gravel

	Porous Slab Mixes	Plain Slab Mixes
Mix Without Gravel	Slump Time (seconds)	Slump Time (seconds)
C1-F0	N/A[1]	15
C1-F1	17	20
C2-F0	13	10
C2-F1	19	17
C3-F0	20	7
C3-F1	11	10

[1]Mix C1-F0 was too fluid to conduct slump test

Compressive Strength Tests

A comparison is shown for improvement in compressive strength due to reduction in w/c ratio from 0.14 to 0.11 (see Figure 28). Minor variabilities were observed between lab samples and field samples. The CSA-cement (C1) based samples showed the highest compressive strength after 3 hours and 24 hours compared to C2 and C3. At 24 hours, the CSA cement (C1) and Portland cement with admixtures (C2) showed strengths above 2000 psi while Portland cement with quartz (C3) showed compressive strengths lower than 2000 psi (approximately 15% lower on the average). Since C3 is mostly used for overhead repairs, compressive strengths lower 2000 psi can still provide sufficient early strength for these applications.

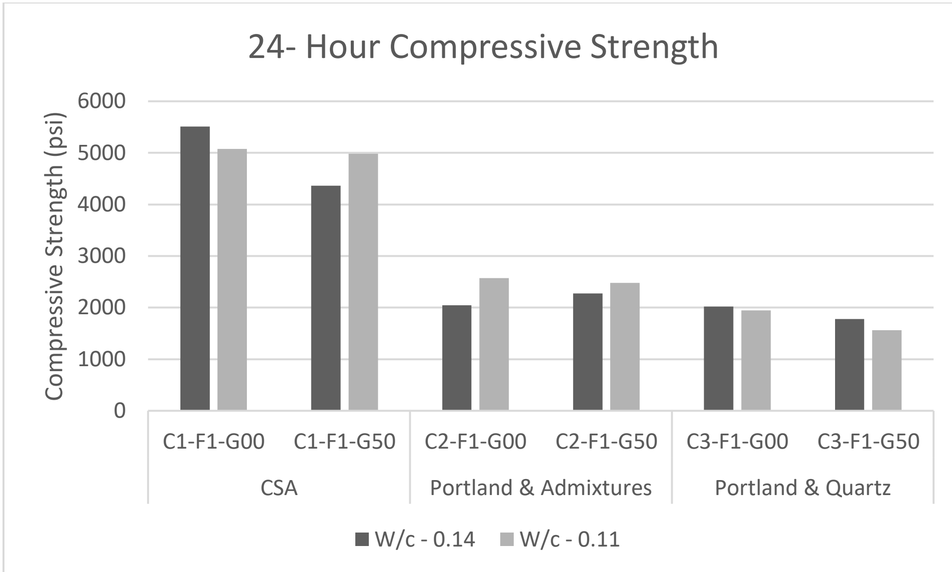


Figure 28. 24-Hr compressive strength comparison for w/c ratio of 0.11 and 0.14

Figure 29 show the average compressive strength of cylinder samples tested after 3 hours and 24 hours. It should be noted again that 3-hour strength data is from plain slab mixes while the 24-hour strength data is from porous slab mixes. The mix proportions for the porous and plain samples were identical.

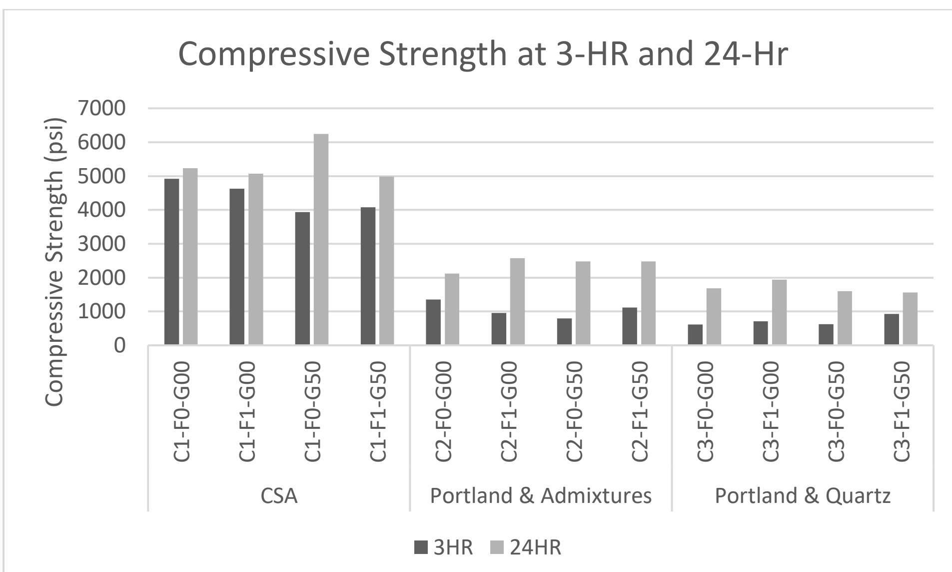


Figure 29. Average compressive strength at 3 and 24 hours

Flexural Tests

Figure 30 shows the modulus of rupture of the mix formulations experimented at 3 hours and 24 hours. Except the C3 mix samples without fibers and gravel, all the other formulations reached modulus of rupture values 400 psi and above at 24 hours. All the C1 mix formulations showed higher rupture modulus than C2 which was followed by C3 formulation samples. Moreover, non-gravel formulations showed on average higher rupture modulus than their gravel counterparts for C1 and C2 cement formulations. C3 mix formulations with 1% fiber and without gravel showed exceptionally higher modulus of rupture compared to the other three C3 formulations.

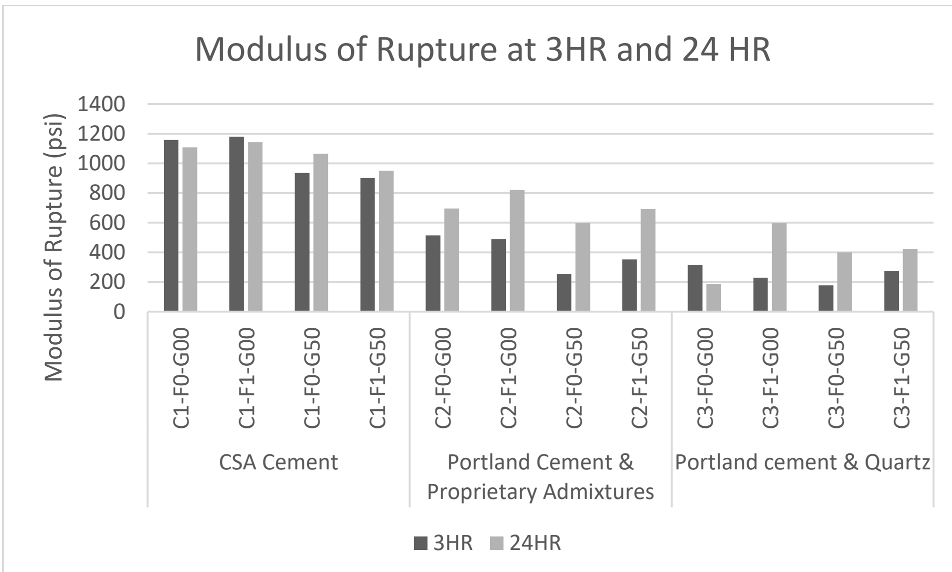


Figure 30. Modulus of rupture at 3 and 24 hours

As can be observed from the load deflection curves (see Figure 31 and Figure 32), the C1 formulations produced similar results for 3-hour and 24-hour tests both for non-gravel and gravel mixes. Whereas the C2 and C3 formulations showed an increase in rupture modulus and thus, toughness from 3-hours to 24-hours. Additionally, for non-gravel mixes, the 24-hour C2 and C3 mix samples showed 2 cracks and better retention of load than at 3-hours. C1 mix samples on the other hand did not show any multiple cracking or did not retain the load post-cracking. Overall, the mixes without gravel did show a better rebound of load resistance than the mixes with gravel. In addition, the non-gravel mixes showed 2 flexural cracks compared to only 1 for their gravel counterparts. This could be due to the weak interfacial transition zone in the gravel formulations which cannot be bridged by a fiber if the crack passes through that zone. Hence, the fiber action may be compromised in gravel mix formulations.

These observations may dictate in future after more testing that the presence of gravel compromises the commonly observed effects of fibers – multiple cracking, toughness, load rebound or load retention post cracking. However, gravel mixes are expected to perform better in terms of shrinkage cracking since the pea gravel is expected to restrain the cement paste from shrinking. Additionally, some researchers also reported that pea gravel provides internal curing effect due to hidden moisture in its pores. This can reduce shrinkage cracking and is investigated in restrained shrinkage experimentation in this research.

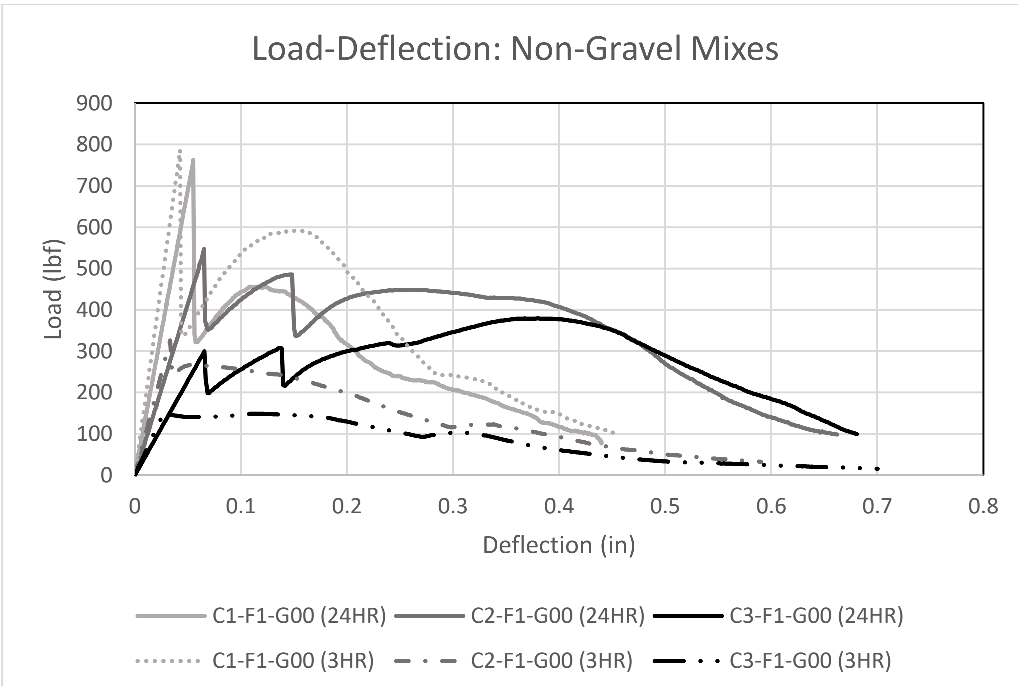


Figure 31. Load deflection curves for mixes without gravel

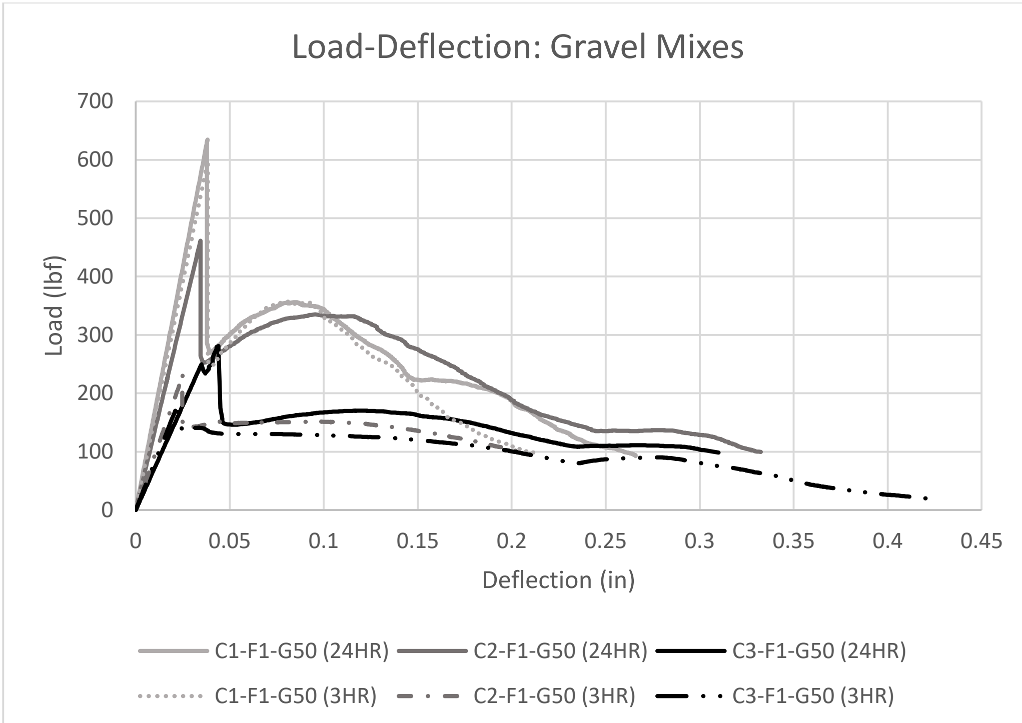


Figure 32. Load deflection curve for mixes with gravel

Restrained Shrinkage Tests

The shrinkage cracking results are analyzed in this section considering the no. of cracks, total, and maximum crack width in each sample. The total crack width is plotted over the duration of crack width monitoring, 6 months. The maximum crack widths are shown at the end of 6 months. Table 20 shows the number of cracks for four different mix formulations of each type of cement. The four formulations for each cement were: 0 % fibers 0 % gravel (F0-G00), 1 % fibers 0 % gravel (F1-G00), 0 % fibers 50 % gravel (F0-G50), and 1 % fibers 50 % gravel (F1-G50). Each of the four formulations were repeated over the two slab surfaces: porous and plain slabs.

Three formulations were successful in preventing the restrained shrinkage cracking entirely on both samples in porous and plain slab surfaces: C1-F1-G00, C2-F1-G00, and C2-F1-G50. Three formulations were successful in preventing shrinkage cracking in either one of the two slab surfaces: C1-F1-G50 (no cracks over porous surface), C2-F0-G50 (no cracks over porous surface), C2-F0-G00 (no cracks over plain surface). At least one sample in each of the C3 mix formulation showed cracking on both porous and plain slab surfaces. More number of cracks were observed over the porous concrete surface than over the plain cement surface, for the non-gravel formulations. For the gravel formulations, overall occurrence of cracks was inconsistent.

Table 20 - Number of restrained shrinkage cracks in each sample after 6 months

Restrained Shrinkage Mix Formulation	Porous Slab Samples[1]		Plain Slab Samples[2]	
	Non-Gravel	Gravel	Non-Gravel	Gravel
C1-F0 (S1)	2	4	1	1
C1-F0 (S2)	1	3	2	2
C1-F1 (S1)	0	0	0	2
C1-F1 (S2)	0	0	0	1
C2-F0 (S1)	1	0	0	5
C2-F0 (S2)	3	0	0	2
C2-F1 (S1)	0	0	0	0
C2-F1 (S2)	0	0	0	0
C3-F0 (S1)	13	1	1	1
C3-F0 (S2)	10	3	0	2
C3-F1 (S1)	9	0	0	2
C3-F1 (S2)	10	0	2	1

[1]Porous slab samples were monitored from July 2022-Decemeber 2022
[2]Plain slab samples were monitored from November 2022-April 2023

Total Crack Width

The total crack widths for each RS sample over the 6-month duration that showed cracking over porous and plain slab surfaces is shown in Figure 33 and Figure 34, respectively. The total crack width can be seen increasing over the 6-month period. Widths observed for the samples over porous slab surface were approximately in the range of 0.0012 – 0.0500 in. On the other hand, the range of total crack widths for the samples over plain slab surface was 0.0010 – 0.0200 in. The maximum value of total crack width was over 50 percent higher for samples over porous slab surface than over the plain slab surface. This shows the effect of restraint created by porous concrete slab and can also be helpful in establishing upper limit of total cracking width for performance evaluation of pothole repair formulations.

Considering the porous slab surface (see Figure 33), the base matrices of C1 and C2 cement showed significantly lower crack widths than that of C3 cement. Addition of 1 percent PVA fibers reduced the average maximum total crack width at 6 months from around 0.049 inch in base matrix of C3 cement (C3-F0-G00) to around 0.031 inch (approximately 36 percent reduction) in C3-F1-G00. It should be noted that none of the other formulations containing fibers showed cracking over porous surface. Both the C1 and C3 cements containing 50 percent gravel but no fibers showed inconsistent total crack widths between the 2 samples. Overall, addition of fibers was more pronounced in reducing and preventing crack widths than the addition of gravel.

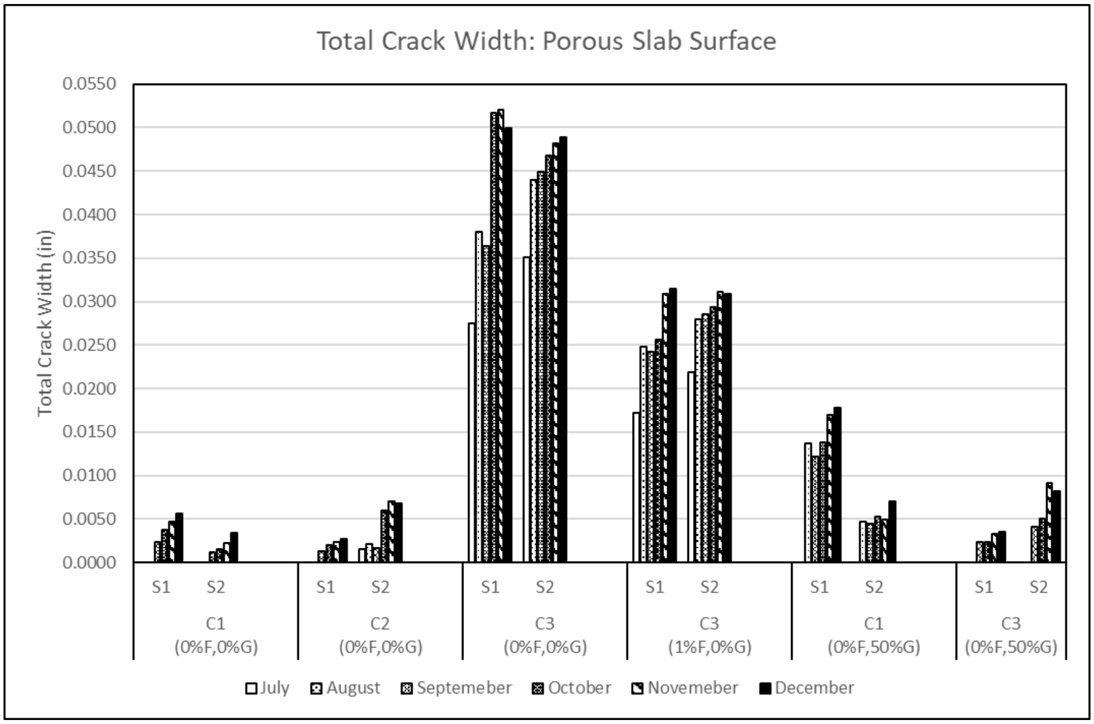


Figure 33. Growth of total crack width over porous slab surface

The total crack widths of the samples over plain slab surface are shown in Figure 34. The widths of the two samples from C1 base matrix showed significant inconsistencies, 0.00875 in vs 0.0175 in. The C2 cement base matrix samples did not show cracking over plain slab surface unlike the samples for the same formulation over the porous slab. The C3 cement without gravel showed a reduction of 66 percent in total crack width at 6 months in the 1 percent fiber formulation (C3-F1-G00) when compared to the base matrix (C3-F0-G00). The gravel counterpart of the C3 cement also showed a reduction in total crack width at 6 months from 0.0135 inch in C3-F0-G50 to 0.00695 inch in C3-F1-G50, a reduction of nearly 49 percent. Similarly, the average total crack width at 6 months for C1 cement with gravel reduced from 0.00725 inch in C1-F0-G50 to 0.004 inch in C1-F1-G50, a reduction of nearly 45 percent.

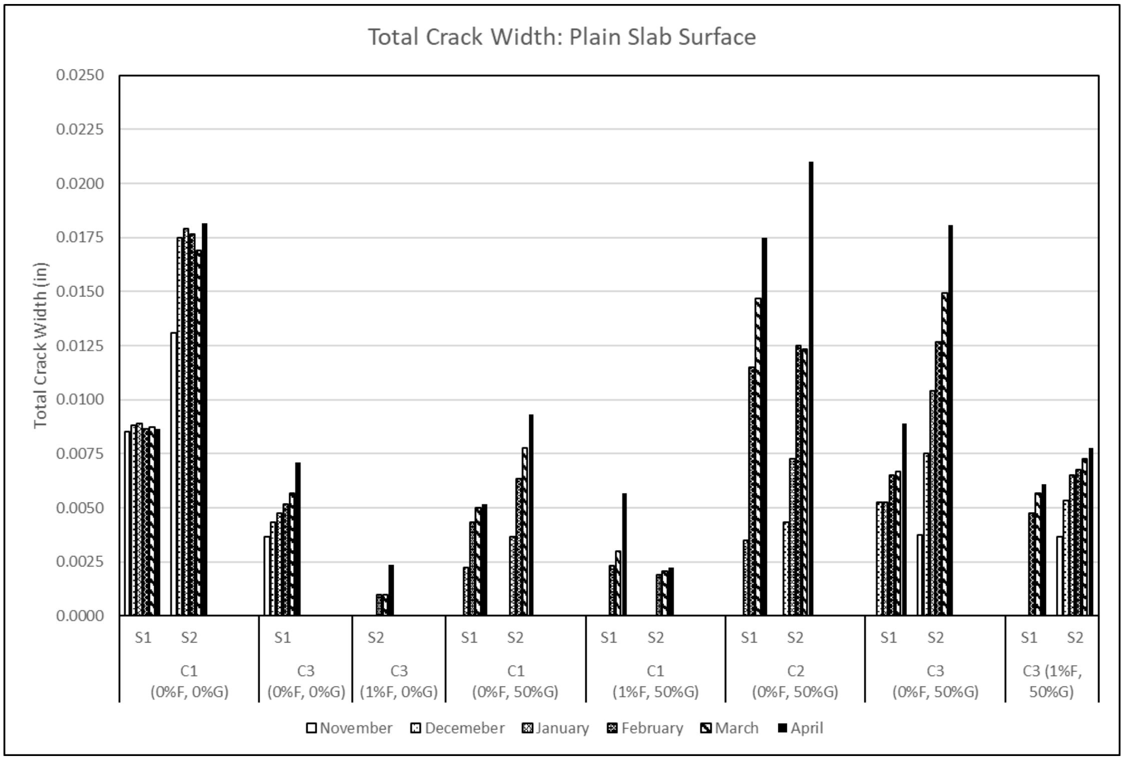
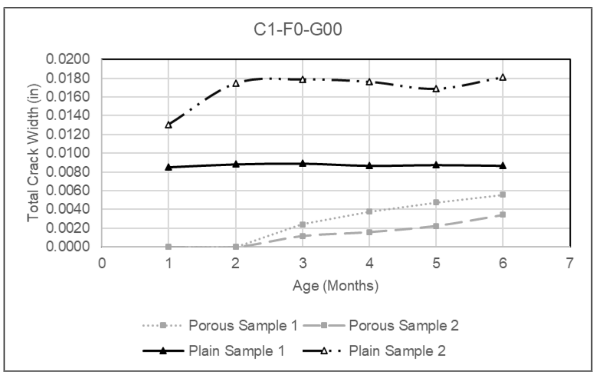


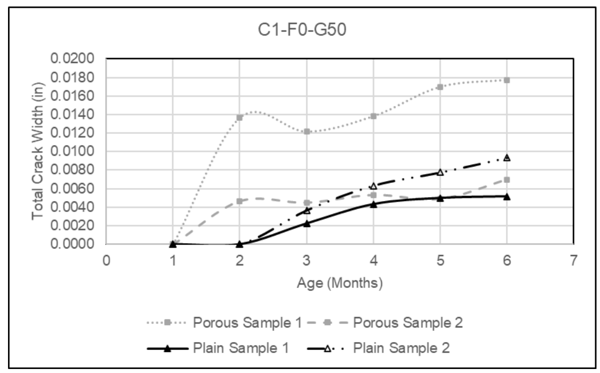
Figure 34. Growth of total crack width over plain slab surface

Overall, the effect of addition of fibers was more consistent in preventing or reducing crack width compared to effect of gravel. For example, in porous slab surface (Figure 33), C1-F0-G00 showed much narrower crack widths than C1-F0-G50 whereas, the widths were reduced significantly for C3-F0-G50 compared to C3-F0-G00. On the other hand, for the samples over plain slab surface, both the C1-F0-G50 showed reduced total crack width than C1-F0-G00 while the opposite was observed for pairs of C3-F0-G50 and C3-F0-G00, and C3-F1-G50 and C3-F1-G00. This could be because formulations with gravel were less workable and difficult to cast into 2-inch sample compared to formulations with fibers but no gravel. Moreover, the C2 cement formulations that showed better performance otherwise, developed total crack widths nearer to the upper limit of the range for the C2-F0-G50 formulation in plain slab surface.

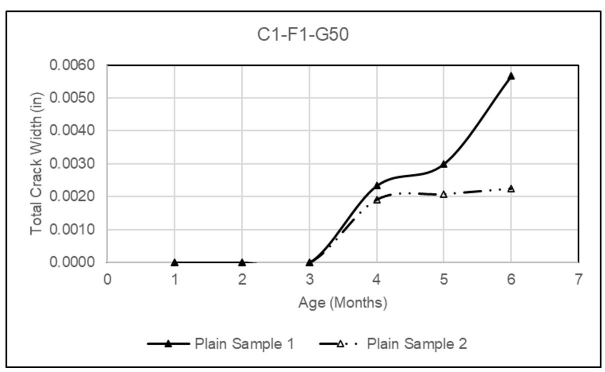
Figure 35 shows the total crack width growth over time for C1 cement samples over both the porous and plain slab surfaces. The crack widths were not controlled by the degree of restraint provided by plain or porous concrete slab surface. For example, the samples over porous slab surface showed narrower crack widths for the C1-F0-G00 formulation than those over the plain slab surface. On the other hand, for the formulation of C1-F0-G50, the plain slab samples showed narrower widths than their porous counterparts. Addition of gravel did not seem to reduce the crack width whereas addition of fibers helped in preventing cracking completely in C1-F1-G00 (both porous and plain surfaces). The total crack widths could be seen to stabilize after 4th and 5th months, except one of the two samples from C1-F1-G50 over plain slab surface.



(a)



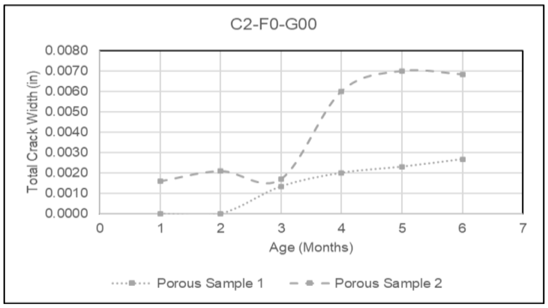
(b)



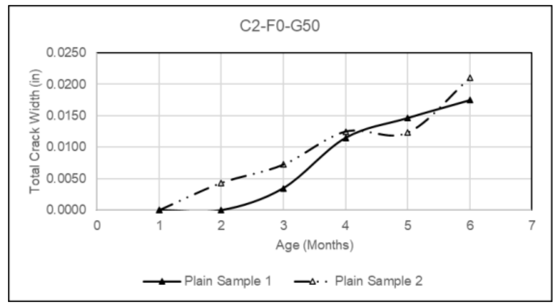
(c)

Figure 35. Growth of total crack width over time for C1 samples: (a) C1-F0-G00; (b) C1-F0-G50; (c) C1-F1-G50

Figure 36 shows the growth of crack width over time for the C2 cement samples. It should be noted again that all the samples of C2 cement with fibers were successful in preventing the occurrence of shrinkage cracks. The C2-F0-G00 samples over porous slab surface showed inconsistency in crack widths, however, the total widths in both the samples started stabilizing after 4 months. The C2-F0-G50 samples developed a total crack width of at least 60 percent of the six-month width at the fourth month.



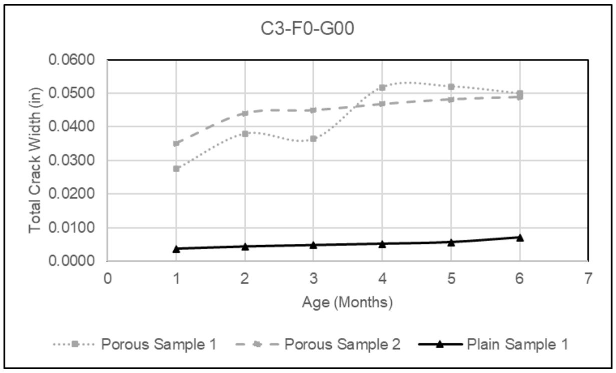
(a)



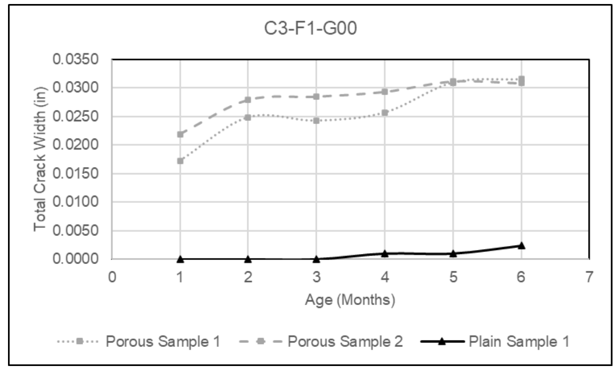
(b)

Figure 36. Growth of total crack width over time for C2 samples: (a) C2-F0-G00; (b) C2-F0-G50

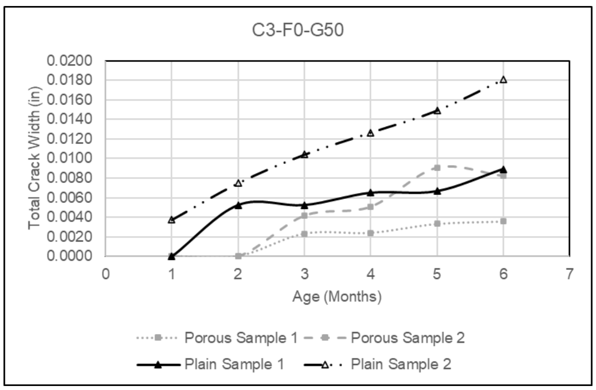
The C3 samples without gravel showed significant growth of total crack width within the first month only. This is also consistent with the visual observation as many of the C3 cement samples started showing cracks during the curing period. The addition of fibers can be seen to reduce crack widths, see Figure 37 (a) and (b). Moreover, only the samples containing both fibers and gravel resisted the cracking completely for the C3 cement samples, implying a higher amount of shrinkage of C3 cement.



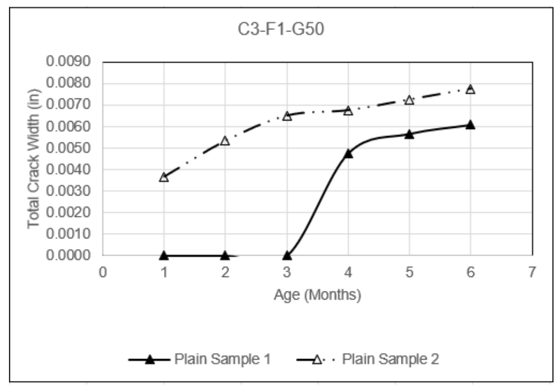
(a)



(b)



(c)



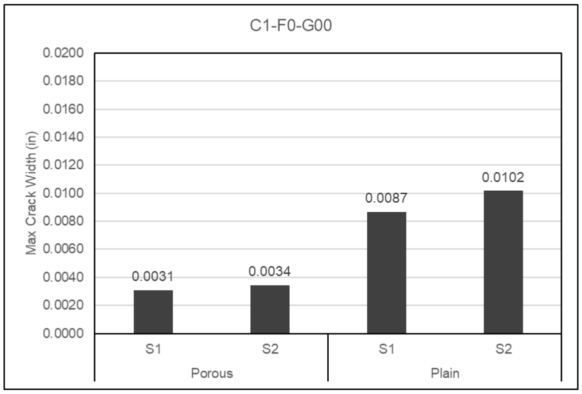
(d)

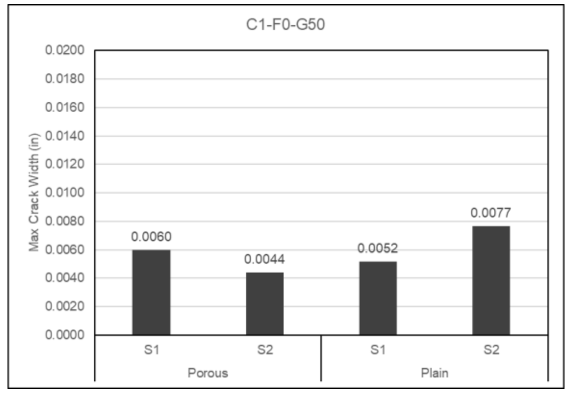
Figure 37. Growth of total crack width over time for C3 samples: (a) C3-F0-G00; (b) C3-F1-G00; (c) C3-F0-G50; (d) C3-F1-G50

Maximum Crack Width

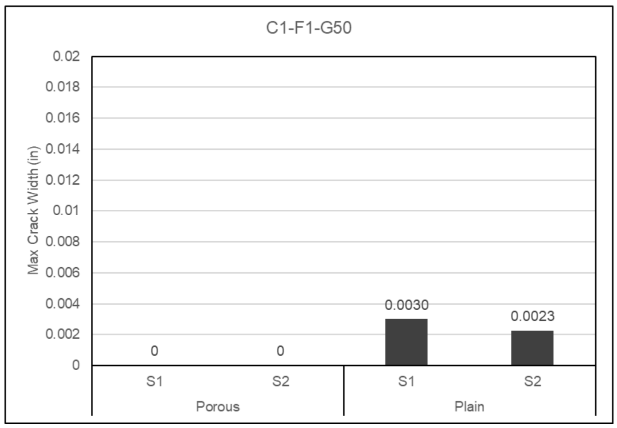
The maximum allowable crack width by NJDOT Bureau of Materials for approval of quick-setting patch materials is 0.03125 inch. [36] All the formulations that showed cracking were well below within the allowable limit. The widest maximum crack width occurred in one of the C2-F0-G50 samples over plain slab surface, 0.0149 inch, which is less than half of the allowable limit.

The maximum crack widths at the end of 6-months period is shown for all the samples that showed cracking in Figure 38, Figure 39, and Figure 40. Addition of gravel to C1-F0-G00 produced inconsistent results for samples over porous and plain slab surface. However, with addition of fibers, the maximum crack widths reduced significantly in C1-F1-G50 over plain slab surface. The average maximum crack width of two samples in C1-F1-G50 was 41 percent of that of samples in C1-F0-G50 over plain slab surface. Furthermore, the C1-F1-G50 samples over porous slabs were able to successfully resist the cracking compared to average maximum crack width of 0.0055 inch in C1-F0-G50 samples.





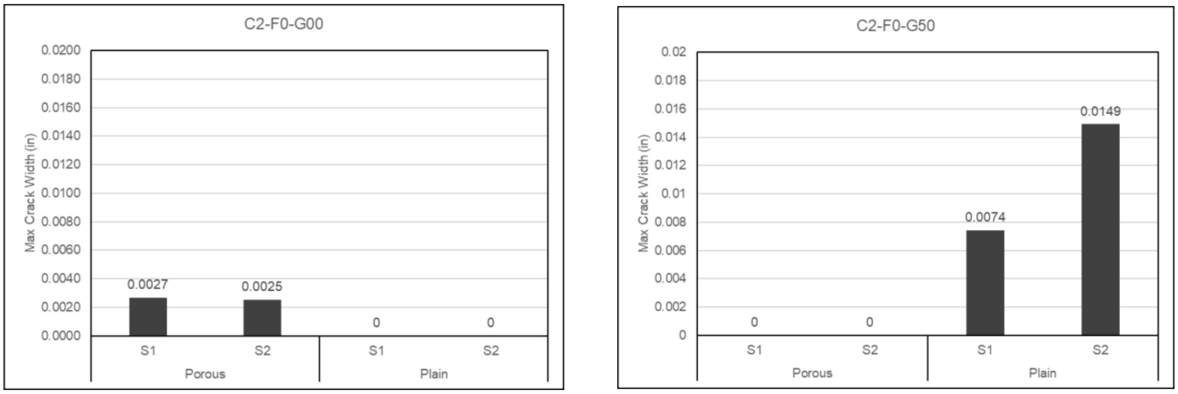
(a) (b)



(c)

Figure 38. Maximum crack widths at 6-months in C1 cement samples: (a) C1-F0-G00; (b) C1-F0-G50; (c) C1-F1-G50

C2 samples with fiber did not show any cracking. The C2 base matrix showed very minimal cracking over the porous slab surface. The maximum crack width of this formulation was much lower than its C1 counterpart. Overall, the C2 formulations showed very low crack widths except one of the samples of C2-F0-G50 that showed exceptionally high crack width of 0.0149 inch, the highest of all the maximum crack widths.



(a) (b)

Figure 39. Maximum crack width at 6-months in C2 cement samples: (a) C2-F0-G00; (b) C2-F0-G50

The average maximum crack width in C3 base matrix was over two times higher than both the C1 and C2 base matrices. The addition of 1 percent PVA fibers in C3 base matrix led to reduction of average maximum crack width by about 17 percent for porous slab samples while about 80 percent for plain slab samples. Similar behavior was observed upon adding 1 percent PVA fibers to C3-F0-G50 samples. The samples over plain slab showed a 46 percent reduction of maximum crack width from C3-F0-G50 to C3-F1-G50. Samples over porous slab were able to successfully resist the cracks for C3-F1-G50 compared to 0.0035-inch maximum crack width in C3-F0-G50. Moreover, the C3-F1-G00 formulation showed the widest crack width among all the three cement-formulations with fibers but no gravel. This crack width, 0.0071 inch is about 23 percent of allowable maximum crack width in NJDOT specifications.

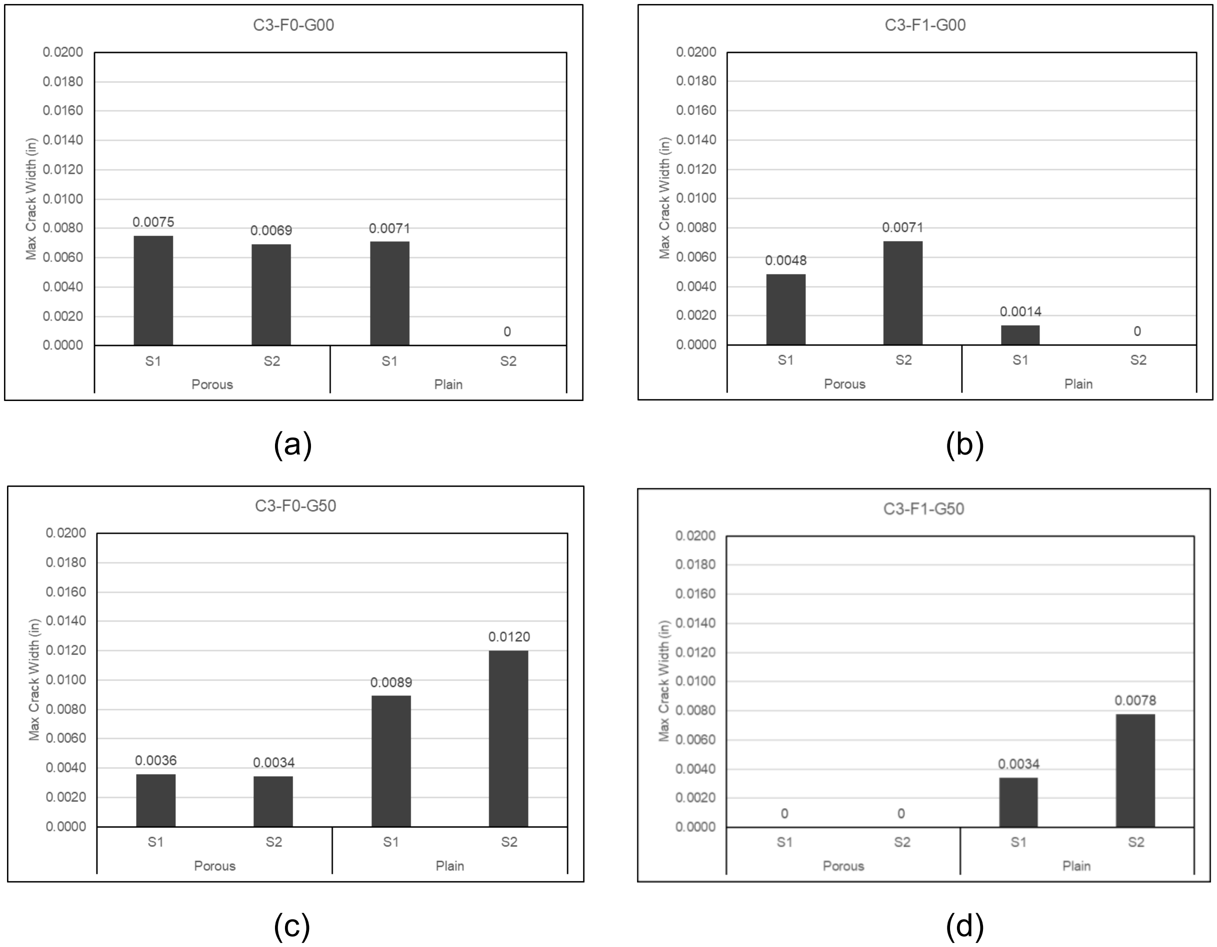


Figure 40. Maximum crack width at 6-months in C3 cement samples: (a) C3-F0-G00; (b) C3-F1-G00; (c) C3-F0-G50; (d) C3-F1-G50

Schmidt Hammer Tests

The Schmidt hammer reports a compressive strength of the material based on the rebound number and the manufacturer provided strength curves. The compressive strength thus obtained from the hammer testing can then be correlated to the actual compressive strength measured by the compression strength testing machine. Figure 41 plots the machine and hammer compressive strength against RN values obtained for all the cube samples.

Figure 41 shows the machine and hammer compressive strength verses the rebound number for all the cube samples together. The hammer compressive strength represents the strength predicted by using available RN vs strength curves. The hammer strength was obtained in both vertical and horizontal orientation and is shown in Figure 41 for comparison. Each data point in the curve corresponds to a single RN value for vertical orientation (average of nine hammer hits). For the horizontal orientation, each data corresponds to average of two RN values obtained by hitting the hammer nine times on each of the two side faces considered for experimentation, see Figure 23. Hence, from each cube sample, two data points were generated corresponding to RN values each in vertical and horizontal direction. Using the available RN vs Strength curves, the hammer compressive strength was obtained corresponding to the two RN values. Additionally, machine compressive strength was also obtained for each cube.

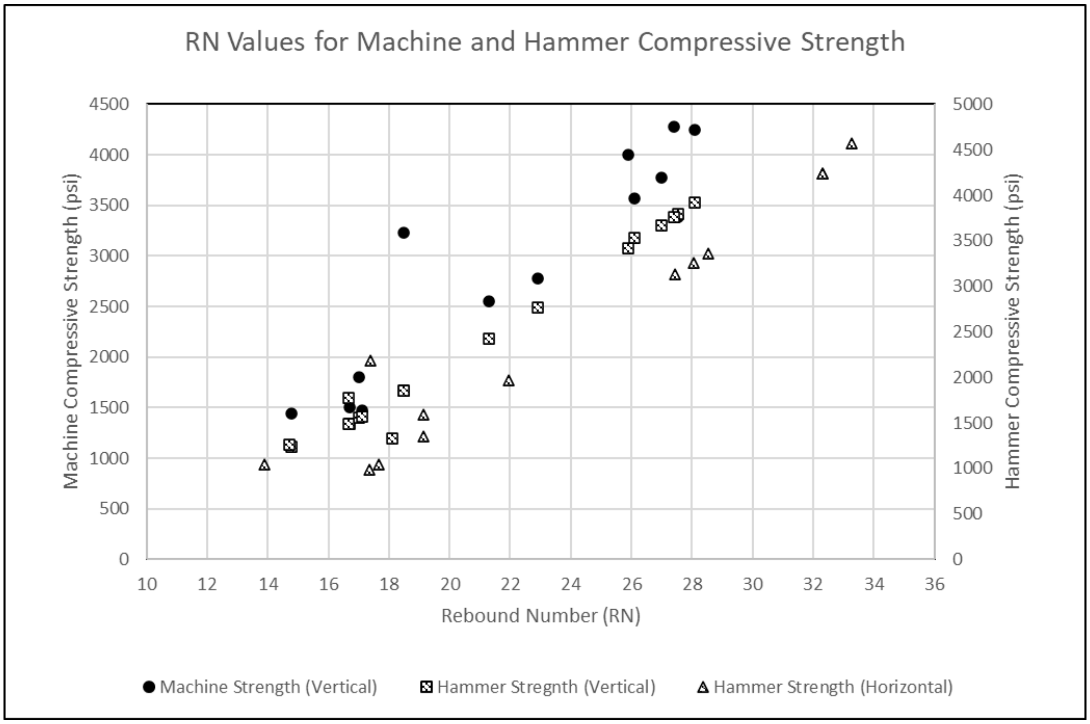


Figure 41. Compressive strength verses rebound number for all three rapid cements.

It can be observed that the same rebound numbers corresponded to higher strengths when the strength was obtained using machine rather than using the available RN vs strength curves. This is likely as the rapid set class of materials may not lie in the same range of compressive strength and elastic modulus as for which the available curves were generated. Additionally, the vertical orientation of hammer predicted the compressive strength more closely to the actual compressive strength in comparison to the horizontal orientation. This can be visualized more clearly from Figure 42. The compressive strength predicted by hammer when in vertical orientation yielded a nearly straight regression line when regressed using a polynomial function. Whereas the horizontal orientation yielded a curve that is visibly deviated from the straight-line behavior. It should be noted that ideally, the hammer predicted strength should be equal to the actual compressive strength, with a straight-line equation.

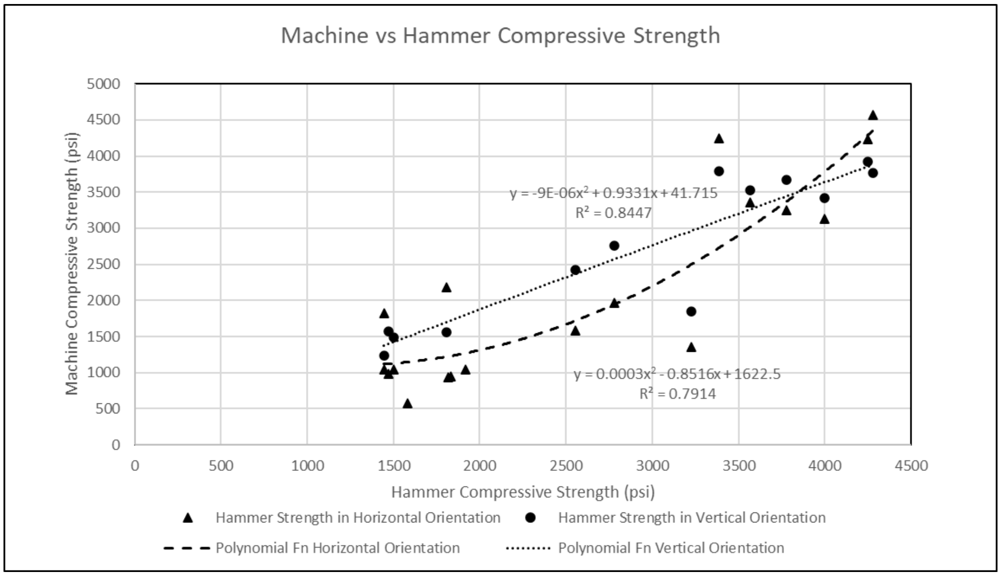


Figure 42. Comparison of machine and hammer compressive strengths

The statistical R2 value indicates the degree of correlation between the machine and hammer compressive strengths. An R2 value can range between zero and one. A value closer to 1 indicates high correlation while a value close to zero indicates no correlation. However, to obtain a valid correlation, a large number of data points should be incorporated in the experimentation, a minimum of 30 from a statistical point of view. Hence, the correlation attempted in the current experimentation is a preliminary investigation to evaluate the potential of using Schmidt hammer for the compression strength evaluation of the proposed rapid setting formulations.

The regression equations for machine compressive strength (y) using polynomial functions are explained as below:

- $y = -9 \times 10^{-6}x^2 + 0.9331x + 41.715; R^2 = 0.8447$ (1)
  where $x =$ hammer strength in vertical orientation

- $y = 0.0003\, x^2 - 0.8516\, x + 1622.5; R^2 = 0.7914$ (2)
  where $x =$ hammer strength in horizontal orientation

As discussed above, in an ideal scenario, the equation should represent a straight line with a slope of 1. This would require the coefficient of x^2 to diminish to zero and coefficient of x to be equal to 1. This behavior is matched more closely in equation (1) than in equation (2) above. However, more experimentation of hammer testing is needed to establish data of RN values corresponding to actual compressive strength with a good confidence interval. The experimental data shown here shows the potential of using Schmidt hammer for obtaining compressive strengths for rapid setting patch repair material. Sufficient statistical data could help in establishing RN values that the construction crew could rely upon for opening the repair area and the lane to the traffic without requiring to do the laboratory testing of strength samples.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were drawn from the investigation of rapid setting patch repair formulations in this project:

- Workable rapid repair formulations for horizontal, vertical, and overhead repair applications can be achieved with the using 10 percent of styrene acrylate latex admixture of cement-water paste and 15 percent sand having particles in the range of No. 30 to No. 100 sieve size, and 1 percent of PVA fibers by weight of the cement-water paste.
- The inverted slump test method can be used as a measure of workability for rapid setting patch repair formulations without gravel. For repair products extended with gravel for higher volume applications, the slump cone diameters need to be adjusted for complete application of inverted slump cone test method.
- Compressive strengths of more than 3000 psi at 3 hours can be achieved using CSA cement based rapid setting formulations for the horizontal repairs. For the overhead and vertical repairs, compressive strengths of more than 2000 psi at 24 hours can be achieved using the Portland cement with admixtures and more than 1000 psi using the Portland cement with quartz.
- Modulus of rupture of more than 500 psi at 24 hours can be achieved for horizontal and overhead repair applications and about 400 psi at 24 hours can be achieved for vertical repair applications using the CSA based cement, Portland cement with admixtures, and Portland cement with quartz, respectively.
- Flexural toughness and strain hardening was exhibited in the developed repair formulations for horizontal, overhead, and vertical repair application with the use of 1 percent PVA fibers. Addition of gravel can compromise the fiber action and thus reduce the rebound of load post cracking and the multiple cracking as well.
- CSA cement and the Portland cement with admixture formulations with addition of 1 percent PVA fibers can resist cracking over all surfaces of varying roughness. The Portland cement with admixture formulation had less shrinkage with the addition of both gravel and PVA fibers. These successful formulations were: C1-F1-G00, C2-F1-G00 and C2-F1-G50.
- The addition of 1 percent PVA fibers could help in preventing shrinkage cracks and controlling the crack width significantly. The use of gravel may compromise the effects of fiber in controlling the shrinkage cracks.
- The maximum crack width could be controlled to less than 25 percent of allowable maximum crack per NJDOT requirements using 1 percent PVA fibers.
- Application of Schmidt hammer testing for the rapid setting patch repairs can be promising way of evaluating the field compressive strength of applied repairs for opening the repaired section to the traffic. However, the RN values from the Schmidt hammer shall be established for patching repair class of materials.

IMPLEMENTATION AND TRAINING

The Rutgers Team has identified repair materials and enhancement of their capabilities in the current project. Rapid implementation using new technologies including automation, and treatment of concrete surfaces to reduce damage from cracking and spalling can be achieved in future implementation. Future implementation would include the following:

1. Enhancement of crack filler material to improve flowability and penetration into the cracks. Existing research have shown that the depth of filler material is highly variable and difficult to measure.

2. Investigate automatic delivery methods for crack repair. Automation of the repair process can save time, reduce traffic disruption and reduce risk for NJDOT personnel. Gravity applied sealants could be adapted to an automated repair process. Pressurized injection may require special equipment for automated repair.

3. Investigate thin polymer overlays and hot asphalt overlays for deck preservation. Research has shown applying overlays 1 to 2 years-old bridge decks can extend their service life significantly. Applying overlays to deteriorated decks is not effective.

4. Field implementation of lab tested filler material and delivery methods in the field. Where they can be applied and when they should be applied is also as important. This field implementation need to be closely coordinated with NJDOT maintenance group.

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APPENDIX

Table 21 - List of current rapid set products, their manufacturers, and the states they are approved in

Product Name	Manufacturer	Approved in these States
Sika Quick 1000 Mortar Repair	Sika Coporation, Lyndhurst, NJ	SC, GA, FL, TX, NY, KS, IN, OR
Sikacrete, 211 SCC Plus		TN, VA, IN, OR
Sikacrete 321 Fast Set		TN, FL, TX
Sikacrete 421 CI Rapid		GA, TN, TX. MA, VA, IN, AZ, OR, **NJ**
SikaQuick 2500		SC, GA, TN, FL, TX, MA, KS, VA, WI, AZ, OR, **NJ**
Sika Repair 224		NY
SikaQuick VOH		GA, TX, KS, PA, VA, IN, OR**,** **NJ**
Sikaset Roadway Patch 2000		SC, TN
MasterEmaco Thoroc T-1060 Rapid Mortar	MBCC (MasterBuilder, BASF) Celevelnad, OH	SC, GA, FL, TN, MA, MI, IN, AZ, OR, **NJ**
MasterEmaco Thoroc T-1061 Rapid Mortar		SC, GA, FL, IN
MasterEmaco Thoroc T-1060 EX Rapid Mortar		FL, TX, NJ
MasterEmaco Thoroc T-1061 EX Rapid Mortar		FL, TX
MasterEmaco N 420 CI		NJ
MasterEmaco 415		SC, TN
MAsterEmaco 430		TN
MAsterEmaco 545 HT		TX, AZ
MasterEmaco S488 CI (sprayable Fiber Mortar)		SC, NY, IN
MasterEmaco S6000		TX
Sakrete Pro-Mix Accelerated Concrete Mix	Sakrete Corp, Atlanta, GA	GA, TX, NY, **NJ**
Sakrete PRO Mix Concrete Repair		GA, AZ, **NJ**
Sakrete Pro-Mix All Purpose Cement Mix		GA, TX, AZ, **NJ**
PROSPEC BLENDCRETE	HB Fuller Construction Inc., Aurora, IL	KS, **NJ**
PROSPEC PREMIUM 200		KS, **NJ**
Quikrete Fastset Non Shrink Grout	Quikrete Companies, Lawrenceville, GA	SC
Quikrete Fastset Repair Mortar Mix		SC, GA, TN, KS, OR
Quikrete Fastset Concrete Mix		SC, GA, TN, IL, AZ, **NJ**
Quikrete Fastset DOT Mix		SC, GA, TN, IL, KS, VA, MI, OR, **NJ**
Quikrete Rapid Road Repair Mix (No. 1242)		IL, WI, **NJ**

Quikrete Fastset DOT Mix Extended		SC, GA, FL, IL, TX, MA, KS, VA, **NJ**
EucoRepair V100	Euclid Chemical Co, Celveland, OH	SC, FL, KS, VA, IN, AZ, OR, **NJ**
EucoRepair SCC Fast		SC, FL, TN, TX, KS, PA, VA, OR, **NJ**
Express Repair		SC, FL, IL, MI, OR
Versaspeed		SC, TN, FL
VersaSpeed 100		FL, TN, TX, KS, VA, IN, AZ, OR
VersaSpeed LS 100		FL, AZ
EucoSpeed MP		SC, TN, FL
Speed Crete 2028		GA, FL, OR
Speed Crete PM		NY, IN, OR
Speed Crete Red Line		NY, OR
Speed Crete Green Line		GA, TN, NJ
Tamms Form and Pour		VA, OR
HP Concrete	US Concrete Products, Timonium, MD	SC, GA
DOT Mortar		SC
Multi-Purpose Repair Mortar		SC
HP Cement		SC
Duracrete II	Kaufman Products, Inc, Baltimore, MD	SC, TN, NY
Duracrete II FR		SC
Duracrete II FT		SC, VA
Duracrete II VOFT		SC, GA, NY, MA, VA, **NJ**
HiCap 15 (Light, Medium)		NY
HiCap FT		SC, GA, NY, MA, VA, **NJ**
Five Star Highway Patch	Five Star Products, Inc, Shelton, CT	SC, GA, MI, WI, OR
Five Star Rapid Surface Repair Easy Mix		SC
Five Star Structural Concrete		SC, GA, FL, NY
CTS Rapid Set Cement All	CTS Cement Mfg, Garden Grove, CA	SC, GA, TX
CTS Rapid Set Mortar Mix		SC, GA, IL, IN, AZ
CTS Rapid Set Concrete Mix		SC, GA, AZ
CTS Rapid Set DOT Repair Mix		SC, GA, IL, MA, KS, VA, WI, IN, AZ, OR
CTS Rapid Set DOT Concrete Mix		SC, GA, IL, VA, IN, AZ, **NJ**
CTS Rapid Set Mortar Mix Plus		SC, GA, TX, IN
CTS Rapid Set Cement Mix		**NJ**
CTS Rapid Set Low P Cement		TX
CTS Rapid Set V/O Repair Mix		SC, GA, TX, MA, KS, IN
Dayton Superior RE-crete 20	Dayton Superior, Miamisburg, OH	SC, GA, OR
Dayton Superior PavePatch 3000		SC, GA, IL, MA, KS, VA, AZ,

		OR
Dayton Superior Polyfast FS		NY
Dayton Superior PermaPatch		GA
Dayton Superior HD 25 VO		VA
Dayton Superior HD-50		GA, IL, NY, MA, KS, VA, MI, WI, IN, OR, **NJ**
Spec Chem Repcon 928	SpecChem,LLC, Kansas City, MO	SC, GA, TX, KS, VA, WI, IN, OR
Spec Chem RepCon V/O		GA, OR
Phoscrete Four Seasons	Phoscrete Corp., Boca Raton, FL	SC, OR
Phoscrete VO-Plus		SC, TN, OR
Phoscrete HC		SC, GA, FL, KS, PA, AZ, OR
ChemSpeed 65	Chem Masters, Madison, OH	SC, TN, MI
ChemSpeed 75		IL
ChemSpeed RepCon V/O		MA
Speed Patch XL		NY, OR
CONSET GROUT-NY		NY
Planitop 18	MAPEI, Deerfield Beach, FL	SC, GA, FL, TN, KS, MI, IN, OR, **NJ**
Planitop 18 ES		SC, GA, TN, IL, TX, KS, VA, IN, OR, **NJ**
Planitop 18 TG		SC, GA, FL, TN, TX, KS, VA, OR, **NJ**
Planitop FD		TX
Planitop 12 SR		VA, NY
Planitop X		GA, TX, MA, KS, VA, IN, AZ, OR, **NJ**
Planitop XS		SC, MA, KS, VA, OR, **NJ**
EcoFix AG 5000	USG, Chicago, IL	SC, GA, TN, FL
EcoFix Rapid Repair Patch		SC, GA, TN, FL
EcoFix Extended Rapid Repair Patch		SC, GA, TN
Duracal		TN, WI, IN
Duracal AG		TN, IN
Duracal HP		TN
US Spec SC Concrete	US Mix Company, Denver, CO	SC, TN, TX, GA, KS
US Spec QuickSet		GA, MA, KS, IN, OR, **NJ**
US Spec V/O Patch CI		OR
US Spec Transpatch		SC, TN, TX, KS, GA, IN, AZ, OR, **NJ**
US Spec STR Mortar CI		SC, TN, TX, GA, OR
SilproRepair VOH	Silpro, LLC, Ayer, MA	NY, GA
SilproRapid		SC, NY, GA, OR **NJ**
Fastrac 246 Concrete	Western Material and Design, LLC, Summit, MO	SC, GA, TN, TX, KS, PA, WI, IN, AZ
FasTrac 200 FQ		TX

Fastrac 300		GA, TX, KS
Fastrac 303		TX
Fastrac 400		TX, AZ
Futura Patching Mix	W R Meadows of Georgia, Austell, GA	SC, TN, IL, AZ
Fastrak	L&M Construction Materials, Bayville, NJ	NY
PaveQuick HR	Lyons Mfg, Inc., Dallas, TX	SC, TN, TX
HP Concrete	US Products Company	GA, TN
DOT Patch	Symons Corp	GA, TN, NY
DOT Poly Patch	Symons Corp	TN
Perma Patch	Dayton/Richmond Concrete Accessories	GA
Lambco R3 Repair Mortar	Lambert Coporation	FL
Kwik Mix Concrete Patch	Kwik Fix Corp	TN
Specco Patch RS	Specco Industries, Inc, Kankanakee, IL	IL, IN
QuadraSet	Redi-Mix, LLC	TX
PCS Highway Repair	Performance Cement Systems, LLC	TX
Pavement DOTLine	Aquafin Inc	TX
Pavement SL		TX
RS-Rapid Setting Road Repair	EarthBound Products, Gaston, SC	SC
LS-Low Porosity Cement		
Elephant Armor DOT	GST International, Santa Rosa, CA	SC
Unique High Performance Fsat Set	Unique Paving Material Cor, Celeveland, OH	SC
PaveMend SLQ	CeraTech (Aquafin) , Inc., Baltimore, MD	SC, GA
PaveMend TR, VR, EX, SL		GA, OR
PaveMend MAIN LINE		SC
PaveMend D.O.T. LINE		SC, GA, OR
Gill 33 - Superbond	Gill Industires, Lancaster, SC	SC
MRT ArmerCem VH	Mineral Resource Tech, Woodland, TX	SC
MRT ArmorFast 45		
POT-FILL	PotFill, LLC, Anniston, AL	SC
Uni Road Repair DOT	Universal Form Clamp Co., Bellwood, IL	SC
Prospec Blendcrete	H.B. Fuller Construction, Aurora, IL	SC, OR
Prospec Premium Patch 200		SC, OR
DECK REPAIR RAPID	Fibercrete Preservation Tech, Inc. Mt. Airy, NC	SC
FiberCrete G		GA
FiberCrete B		GA
FlexKrete	Flexkrete Technologies,	SC

	Littleton, NC	
Ulti-Pave3	Buzzi Unicem USA, inc., Bethlehem, PA	SC, TN
Ulti-Grout		
Road Patch II	Thoro Systems, Miami, Florida	SC
Hilti RM 800 PC	Hilti, Tulsa, OK	SC, TN
Patch 15	Continental Reserch Corp, St. Louis, MO	SC

Table 22 - Properties of Type 2 rapid repair materials listed on the NJDOT Approved Material QPL

Product Name	Manufacturer	Initial	Final	3 hrs	1 d	3d	7d	28 d	1 d	7d	28 d
NJDOT Specs		**15 (min)**		**-**	**1000**	**2000**	**-**	**3000**		**1000**	**2000**
Master Emaco N 420 CI	BASF Build Systems	< 35	< 45				4500	5500		1250	1700
EUCO Repiar V 100	Euclid Chemical, OH	20	35	2000	3000	-	4500	6000		1400	1800
EUCO Repiar SCC FAST	Euclid Chemical, OH	50		2500-2	4500	-	6000	8000	2200	3200	3500
DURACRETE II VOFT	Kaufman Products	22-28 m	40-50 m	2500	3000	-	6000	8500	1500	2400	N/A
HICAP FT	Kaufman Products	20	34	2500	3500		5500	7000	1800	2400	N/A
MAPEI PLANITOP 15	MAPEI	3 hr	10 hr		4350		8500	10800	1850	N/A	3000
MAPEI PLANITOP XS	MAPEI	40	60		3000		4000	5000	1000	N/A	1500
MAPEI PLANITOP X	MAPEI	6	25	2900	5000		5800	6600	1400	N/A	1800
SAKRETE ALL PRO CEMEN	OLDCASTLE, NC	15-30	25-35	3000-1	6000		7000	9000	1700	N/A	2400
SAKRETE ALL PRO CONCR	OLDCASTLE, NC	15-20	25-30	3000-1	5500		6000	7000	2200	N/A	2800
Quikrete Fast Ser Comm (	Quikrete,	20	20-40	2000	4000		5000	6000	1000	1500	2000
Sikacrete	SIKA	10-25	35	1500	3000		4500	5500	1000	1600	2000
US SPEC QuickSet		37	50	3000	4000		5000	6000	1500	2500	N/A
US SPEC R3		20	35	3500	5000		6000	7000	2000	2500	N/A

TYPE 2 (Cont'd)

Product Name	Manufacturer	Exp/Shrinakge (%)		Durability @ 50 cycles		Elastic	Comments			
		wet cured	Air cured	Ret strength	Visual Rating	Modulus	w/mix ra	Lifts		
NJDOT Specs		**0.2**	**-0.2**	**90%**	**3**	**N/A**				
Master Emaco N 420 CI	BASF Build Systems	0.027	-0.096	96.6%, 300	0.24 (light sca	N/A	0.145	1/4 - 2 in		
EUCO Repiar V 100	Euclid Chemical, OH		-0.02				0.182	1/8-4 V	1/8 - 2 overhead	
EUCO Repiar SCC FAST	Euclid Chemical, OH		-0.02%							
DURACRETE II VOFT	Kaufman Products	0.03	-0.05	96.5%,300 c	N/A	3200	o.105	1/2 - 4 in		
HICAP FT	Kaufman Products	0.06%	-0.06%	98%, 300 c	0.79		0.138		Chloride Content	
MAPEI PLANITOP 15	MAPEI	0.11%	-0.08%			4500				
MAPEI PLANITOP XS	MAPEI	0.15%	-0.15%	98.5%, 300 c		3230	0.167	1/16-4 V	1/16 - 2 overhead	
MAPEI PLANITOP X	MAPEI	0.15%	-0.15%	97%, 300 c			0.167	1/16-4 V	1/16 - 2 overhead	
SAKRETE ALL PRO CEMEN	OLDCASTLE, NC						0.156			
SAKRETE ALL PRO CONCR	OLDCASTLE, NC	0.025	-0.04				0.135			
Quikrete Fast Ser Comm (	Quikrete,	0.05	-0.05	95%, 300 c	0.5	2200	0.147			
Sikacrete	SIKA	N/A	0.05				0.133	1/8 - 3 V	flexure 400, 600,	
US SPEC QuickSet		0.03%	-0.05%	96%, 300 c		2930	0.148	1/8 - 2 in		
US SPEC R3		0.01%	-0.06%			3290	0.149			