Vertical and Overhead Concrete Patches for Bridges in Wisconsin

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16. Abstract

This study evaluated vertical and overhead (VOH) concrete repair practices for bridge structures and developed recommendations to improve repair performance for WisDOT. The work included a literature review, assessment of current WisDOT practices, laboratory testing of VOH repairs, and development of recommendations and guidance for VOH concrete patch repairs. General repair strategies employed by WisDOT are largely consistent with industry practices. However, several areas where additional guidance and standardization could improve repair consistency and durability within Wisconsin were identified. These areas include the absence of a repair material approval process and approved product list, lack of standardized procedures for VOH repairs, and variability in using abrasive blasting and supplemental anchorage during surface preparation. Laboratory investigations were conducted to examine the effects of anchorage configurations, surface preparation, repair depth, repair materials, and installation methods. Test results showed that materials with lower shrinkage, lower modulus of elasticity, and coefficient of thermal expansion closer to those of the substrate exhibited reduced cracking potential. Repair configurations that incorporated existing reinforcement performed best, while supplemental anchorage systems, such as screw anchors with welded wire reinforcement, proved to be effective alternatives when existing reinforcement cannot be included. Bond performance improved with sandblasting, although sensitivity varied among materials. The study also found that achieving adequate bond in overhead form-and-pour repairs can be challenging due to air entrapment, highlighting the importance of mechanical anchorage and proper placement techniques. This study provides WisDOT with guidance on repair strategies for VOH repairs; recommendations for repair material property requirements and for adjustments to the process for adding materials to the VOH repair material approved product list; and guidance for installation of VOH concrete repairs.

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PREPARED FOR:

Wisconsin Department of Transportation

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EXECUTIVE SUMMARY

This study evaluated vertical and overhead (VOH) concrete repair practices for bridge structures and developed recommendations to improve repair performance for the Wisconsin Department of Transportation (WisDOT). The work included a comprehensive literature review, assessment of current WisDOT practices, laboratory testing of VOH repairs, and development of recommendations for repair material properties and guidance for VOH concrete patch repairs.

The literature review examined guidance and practices documented by national organizations (including ACI, FHWA, ICRI, and US Bureau of Water Reclamation), as well as selected state transportation agencies. The review identified commonly used repair strategies, best practices for VOH concrete repairs, and gaps in guidance specific to VOH applications.

The evaluation of WisDOT's current practices indicates that its general repair strategies are largely consistent with industry practices. However, several areas where additional guidance and standardization could improve repair consistency and durability within Wisconsin were identified. These areas include the absence of a repair material approval process and approved product list, lack of standardized procedures for VOH repairs, and variability in using abrasive blasting and supplemental anchorage during surface preparation.

Laboratory investigations were conducted to evaluate the performance of representative VOH repairs. The study examined the effects of anchorage configurations, surface preparation, repair depth, repair materials, and installation methods. Material testing was performed to characterize key properties of the repair materials, while thermal cycling and structural loading were used to assess cracking and spalling resistance of the repairs. Test results showed that materials with lower shrinkage, lower modulus of elasticity, and coefficient of thermal expansion closer to those of the substrate exhibited reduced cracking potential. Repair configurations that incorporated existing reinforcement performed best, while supplemental anchorage systems, such as screw anchors with welded wire reinforcement, proved to be effective alternatives when existing reinforcement cannot be included. Bond performance improved with sandblasting, although sensitivity varied among materials. The study also found that achieving adequate bond in overhead form-and-pour repairs can be challenging due to air entrapment, highlighting the importance of mechanical anchorage and proper placement techniques.

Based on findings of the literature review, laboratory investigations, and WJE experience, the following are provided in this report:

- Guidance on repair strategies for VOH repairs, including hand-applied patching, form-and-pour repairs, shotcrete, FRP wraps, and coating of exposed reinforcement without patching
- Recommendations for repair material property requirements and for adjustments to the process for adding materials to the VOH repair material approved product list
- Guidance for installation of VOH concrete repairs

Implementation of this guidance and recommendations is expected to improve the durability, reliability, and consistency of VOH concrete repairs, leading to longer service life and reduced maintenance needs for Wisconsin bridge structures.

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1. INTRODUCTION

Bridge elements can undergo various types of damage throughout their life and may need to be repaired to maintain their integrity. Vertical and overhead concrete patch repairs are frequently used to rehabilitate concrete bridge decks and slabs, repair damaged prestressed concrete (PS) girders, and remediate spalls on substructure elements such as piers and abutments, to provide protection of reinforcement against environmental exposure and for aesthetics.

Current Wisconsin Department of Transportation (WisDOT) guidance, provided in Section 509 of the Standard Specifications, primarily addresses horizontal concrete surface repairs on concrete pavements and bridge decks. Type E or Type C concrete mixtures, defined in Section 501 of the Standard Specifications, are typically used for horizontal surface repairs. However, due to differences in access conditions and repair orientation, materials and procedures suitable for horizontal repairs may not be appropriate for vertical and overhead repairs.

Current WisDOT practice for repairs located over traffic is typically coordinated through professional engineers. Acceptance of vertical and overhead concrete surface repairs is often based on material manufacturer recommendations and the discretion of field engineers. However, a standardized approach for vertical and overhead repair patches is not currently established. As a result, WisDOT requires guidance for the design, material selection, specification, and acceptance of vertical and overhead concrete patch repairs to improve consistency and ensure the durability of these repairs.

In response to these needs, WisDOT initiated this project to evaluate current practices for vertical and overhead (VOH) concrete repairs and to develop recommendations for improving repair performance and consistency across the state. The objectives of this study were to review existing guidance and practices for VOH repairs, evaluate current WisDOT repair practices, perform laboratory investigations of repair materials, and develop recommendations to support improved repair design and implementation.

To achieve these objectives, the project included the following tasks:

- **Literature Review.** A literature review was conducted to summarize commonly used repair strategies, repair materials, installation procedures, and quality control practices documented in technical guidance and transportation agency specifications.
- **Critical Evaluation of Vertical and Overhead Repairs in Wisconsin.** Current WisDOT repair practices were evaluated through a survey of WisDOT staff and follow-up discussions to understand typical repair methods, materials, and field practices used across different regions.
- **Laboratory Investigations.** Laboratory investigations were performed to evaluate selected repair materials and their performance characteristics, including the effects of different anchorage approaches relevant to VOH patch repairs. The study focused on minor repairs (less than approximately 2 inches deep and not extending beyond reinforcing steel) and intermediate repairs (greater than approximately 2 inches deep, extending beyond reinforcing steel but with minor effects on sectional capacity).
- **Development of Recommendations.** Based on these findings, recommendations were developed regarding specifications for repair materials and procedures for vertical and overhead repairs of bridges in Wisconsin.

2. SUMMARY OF LITERATURE REVIEW

A literature review was conducted to support the development of VOH repair recommendations for WisDOT. Information was collected from technical guidance published by organizations including the American Concrete Institute (ACI), the International Concrete Repair Institute (ICRI), the Federal Highway Administration (FHWA), the U.S. Army Corps of Engineers, and various U.S. and Canadian transportation agencies. The review examines commonly used repair strategies, repair materials, installation procedures, and quality control practices relevant to VOH repairs.

Detailed findings of the review and a list of references are presented in Appendix A. Key observations are summarized below.

2.1. Repair Strategies for Vertical and Overhead Concrete

A variety of repair strategies are used for vertical and overhead concrete depending on the extent and cause of deterioration, such as corrosion, freeze–thaw damage, or impact. Selection of an appropriate method is typically based on condition assessment, environmental exposure, and desired service life.

Different repair approaches for VOH concrete are summarized below:

- **Concrete patching:** This is the most common repair method and can be implemented using several different techniques. Patching can be performed using hand-application or form-and-pour.
  - Hand-applied patching is typically used for localized repairs with relatively shallow depths (generally smaller than 2 square feet and thinner than 2 inches). Repair materials must be resistant to sagging in vertical or overhead applications. In addition, because the repair thickness is often limited, reinforcement within the original concrete may not be fully encapsulated, leaving the reinforcement susceptible to corrosion.
  - Form-and-pour or form-and-pump patching is used for larger or deeper repairs and often results in more consistent repair quality. In this method, formwork is constructed around the repair area, and repair material is poured or pumped into the cavity. The formwork helps retain moisture and supports curing. However, the need for formwork increases both labor and cost compared with hand-applied repairs.
- **Shotcrete**: Shotcrete involves spraying mortar or concrete onto the repair surface without formwork and can be effective for vertical and overhead surfaces. Shotcrete requires specialized equipment and skilled operators, and measures must be taken to contain rebound material generated during the spraying process.
- **Preplaced aggregate and dry packing**: These methods are less common and generally used only for specific situations (e.g. small repairs with limited access, underwater repairs).
- **Non-structural fiber reinforced (FRP) wraps**: FRP wraps, consisting of polymer resin impregnated fabric adhered to the concrete surface, are used to contain the concrete repair area to prevent detached concrete from falling and/or to provide additional protection against environmental exposure.
- **Coating exposed reinforcement and concrete surface without patching:** This approach is typically used when a temporary repair is needed. Coatings such as zinc-rich paint, cementitious materials, or epoxy can slow corrosion and protect the reinforcement from further environmental exposure.

2.2. Vertical and Overhead Concrete Patching

The literature review also examined repair materials and installation procedures used in VOH patching.

VOH Repair Materials

Common repair materials include portland-cement concrete, shrinkage-compensating cement concrete, rapid-setting cement concrete, silica-fume concrete, polymer-modified concrete, magnesium phosphate concrete, and polymer concrete. These materials differ in strength development, bond performance, shrinkage characteristics, and durability. Many repair materials are commercially available as prepackaged products.

Important material properties include shrinkage, coefficient of thermal expansion (CoTE), modulus of elasticity (MOE), bond strength, and compressive and tensile strengths. Durability considerations, such as resistance to freeze-thaw cycles, chloride penetration, and chemical attack, are also critical for long-term repair performance. It is generally desirable to use repair materials with low shrinkage and high bond strength, and CoTE and MOE similar to those of the substrate.

VOH Concrete Repair Procedures

Typical VOH concrete repair procedures include the following:

- Saw cut repair boundaries and remove concrete to sound concrete using chipping or hydrodemolition
- If existing reinforcing bars are exposed and corroded, remove concrete around the bars to a depth of ¾ inch behind the bars
- Clean concrete and reinforcement surfaces using abrasive blasting or high-pressure water blasting to remove corrosion products, dust, debris, and microcracked material.
- Bring the substrate to a saturated surface-dry condition (or similar) to prevent the substrate from absorbing moisture from the repair material.
- Repair material installation procedures depend on the chosen repair method.
  - For hand-applied patches, a bond coat or bonding agent may be applied, and the repair material is placed in lifts to achieve the design thickness.
  - For form-and-pour repairs, repair material is poured into formwork and consolidated by vibration and/or hammer tapping on the form.
- Cure repair materials, using curing compounds, wet burlap coverings, and plastic sheets, or keeping the formwork in place.
- Inspect the repairs using visual and sounding inspections and/or pull-off bond testing.

2.3. Transportation Agency Practices

The literature review also examined VOH repair practices used by sixteen (16) state transportation agencies across North America, including Illinois, Iowa, Kansas, Michigan, Missouri, Ohio, Indian, Minnesota, Nebraska, North Dakota, South Dakota, Wisconsin, New York, Texas, Washington, and Ontario (Canada). Documents reviewed included bridge manuals, construction specifications, and lists of prequalified repair materials from state agencies. Detailed findings are presented in Appendix A, with key observations summarized below.

2.3.1. Repair strategies for VOH spalls

A range of concrete repair strategies are employed by transportation agencies for the repair of vertical overhead (VOH) spalls. These strategies vary in frequency of use (relative to the 16 agencies for which data was collected), material requirements, and application limitations.

- Hand-applied patching repair: This strategy is defined by 8 agencies (Iowa, Kansas, Michigan, Missouri, New York, Ohio, Ontario, and Texas). Repairs are typically performed using prequalified, prepackaged materials and are subject to limitations on repair depth and area. The maximum depth of hand-applied repairs is typically between 1-1/2 and 3 inches. For example, New York restricts these repairs to a maximum depth of 2 inches and a repair area of less than 4 square feet.
- Form-and-pour: This strategy is identified by 9 agencies (Illinois, Iowa, Kansas, Michigan, Missouri, New York, Ontario, Texas, and Washington). Repairs are typically completed using prequalified prepackaged materials or ready-mix concrete.
- Shotcrete: This strategy is identified by 9 agencies (Illinois, Iowa, Kansas, Michigan, Missouri, New York, Ohio, Ontario, and Texas). This method typically includes specific requirements for materials, equipment, and application procedures.
- FRP wrap to contain concrete repair: This strategy is identified by 6 states (Indiana, Iowa, Michigan, Missouri, Texas, and Wisconsin)
- Coating exposed bars without patching: This strategy is not commonly specified and was identified only in the TxDOT concrete repair manual.

2.3.2. Concrete Patching Repair

Material Property Requirements

Seven transportation agencies (Missouri, Ohio, New York, Iowa, Texas, Washington, and Wisconsin) have requirements for repair materials to be included on approved product lists. Typical material properties specified include compressive strength, slant shear bond strength, length change (drying shrinkage and expansion), and freeze-thaw resistance. Common requirements include:

- Minimum 28-day compressive strength (ASTM C39): varies from 3,500 to 6,000 psi.
- Minimum 28-day slant shear strength (ASTM C882): varies 1,500 to 1,750 psi
- Freeze-thaw durability factor (ASTM C666, Procedure [A or B] varies among the agencies): varies from 70% to 90% after 300 cycles
- Length change (ASTM C157): requirements vary widely depending on agency specifications and curing conditions

Concrete Removal and Surface Preparation

Most agencies require saw cutting the repair perimeter, typically to a depth of ½ inch.

Minimum repair depths generally range from 1 to 4 inches, with a required clearance of ½ to 1 inch behind reinforcing bars.

Abrasive blasting is the most commonly specified surface preparation method. It is used to remove microcracking in the concrete substrate surface caused by concrete chipping and to clean exposed reinforcing bars. Some transportation agencies (Ohio and Washington) allow water blasting (minimum pressure 5,000 psi) as an alternative to abrasive blasting.

Anchorage and Reinforcement

In cases where the repair area lacks sufficient existing reinforcement, some agencies—including Illinois, Ontario, Ohio, and Texas—require the installation of supplemental reinforcement. This may include dowels, expansion bolts, and welded wire fabric.

Curing

Most agencies require curing duration from 1 to 4 days. Curing methods include moist curing, the use of curing compound, and leaving formwork in place.

Acceptance Criteria

Acceptance of completed repairs is typically based on sounding to detect delaminations or voids within the repair, and verification of compressive strength or tensile bond strength.

2.4. Previous Studies

Selected previous studies investigating the performance of VOH concrete repairs were reviewed. Many studies evaluated repaired slabs or beams subjected to environmental exposure or cyclic mechanical loading, but not both. These studies provided insights into cracking behavior, stiffness degradation, and long-term durability of repairs. However, most experiments involved repairs applied horizontally rather than vertically or overhead. As a result, they did not fully capture the practical challenges associated with installing VOH repairs in bridge structures.

2.5. Conclusions

The literature review indicates that a variety of repair strategies are available for vertical and overhead (VOH) concrete deterioration in bridge structures. These strategies include concrete patching using hand-applied or form-and-pour methods and shotcrete placement. Additional approaches such as fiber-reinforced polymer (FRP) wrapping or coating exposed reinforcement without patching may also be used in certain situations, particularly when safety concerns or access limitations restrict the use of conventional patching. Among these strategies, concrete patching remains the most widely used repair method in practice. Hand-applied repairs are commonly used for small or shallow repairs, whereas form-and-pour repairs are typically preferred for larger or deeper repairs where more consistent placement and curing conditions can be achieved.

The quality and durability of concrete patch repairs depend on several key factors, including appropriate selection of repair materials, thorough surface preparation, proper installation procedures, and adequate curing. Best practices identified in the literature emphasize the importance of removing all unsound concrete, establishing well-defined repair boundaries, and cleaning repair surfaces using methods such as abrasive blasting or high-pressure water blasting. Achieving proper surface condition and reinforcement cleaning is critical to developing adequate bond between the repair material and the substrate.

Despite the availability of general guidance, several gaps in current knowledge and practice remain. Requirements for repair materials, including test methods and performance criteria, vary significantly among transportation agencies. In addition, limited information is available regarding the design details, materials, and expected performance of different anchorage approaches used in concrete VOH repairs. Finally, much of the experimental research on concrete repairs has focused on horizontal repairs and therefore does not fully capture the installation challenges and performance considerations associated with VOH repairs in bridge structures.

3. EVALUATION OF VERTICAL AND OVERHEAD REPAIR PRACTICES IN WISCONSIN

WJE developed and conducted a survey of WisDOT staff to evaluate current vertical and overhead (VOH) repair practices. The survey was distributed to multiple engineers in each of WisDOT's five regions[1], as well as to members of the Bureau of Structures (BOS) Maintenance and Inspection team. Following the survey, WJE held virtual meetings with the respondents to discuss their responses in greater detail. The survey questions and responses are presented in Appendix B.

Using information obtained from the survey and follow-up discussions with WisDOT staff, along with the literature review and WJE's professional experience, a critical evaluation of current VOH repair practices in Wisconsin is presented in this section.

3.1. Repair Strategies

The survey of WisDOT indicates that hand-applied and form-and-pour repairs are the most common repair strategies for VOH patching. Most respondents indicated that form-and-pour is the preferred method when access allows for formwork installation, while hand-applied patching is generally limited to small, shallow repairs. This practice by WisDOT is in line with industry best practices as the quality of hand-applied patching is generally less consistent than form-and-pour repairs and can vary widely with surface preparation, installation, and curing and from one repair material to another.

Patching repairs are not typically performed for overhead locations above traffic, unless the patch is subsequently contained by FRP wraps. While the FRP can provide protection to the patch from falling onto traffic, it is expensive. There is little information from the industry and other transportation agencies on the cost effectiveness of using FRP for non-structural purposes. If the right repair material is used with proper surface preparation, anchorage, installation and curing, overhead repair can be durable and may be more cost-effective than using FRP wrap. Further research to evaluate benefits and cost-effectiveness of using FRP wraps to contain concrete patches is needed to assess the value provided by this strategy.

In lieu of patching in areas over traffic, coating of exposed reinforcing steel in the spalled area has been used by WisDOT and others to slow down corrosion of the steel. Surface preparation of the steel surface is typically minimal and may not completely remove chloride-contaminated materials from the steel. Further, it will not address chloride contamination in the surrounding concrete. Thus, corrosion may re-initiate under the coating and develop on the surface or embedded steel adjacent to the exposed and coated steel, resulting in additional delamination and spalling. Zinc-rich primers may be more effective than

[1] North Central (NC), Northeast (NE), Northwest (NW), Southeast (SE), and Southwest (SW)

epoxy or cementitious coatings, since the zinc can provide some level of galvanic protection, in addition to serving as a barrier.

Form-and-pump concrete repair is not common in Wisconsin. Repair materials intended for form-and-pump applications are commercially available, and when applied properly, this method can provide quality repairs in areas where the form-and-pour method is not viable, e.g. underside of bridge decks. However, this method requires special equipment and mix design, and can be expensive, since it requires a contractor with applicable expertise.

While many respondents indicated a positive impression with quality of shotcrete repairs, some failures have been reported on shotcrete repair of bridge deck underside within 2 years of installation where the repair spalled, exposing corroded reinforcing steel. Based on industry and WJE experience, quality VOH repairs can be achieved with shotcrete, but like other repair methods, proper surface preparation is critical for performance of the repair. In addition, shotcrete should be performed by an experienced and qualified contractor using materials specifically designed for this application. Finally, as observed by survey respondents, the cost of mobilizing to perform shotcrete repairs is typically justified only if the repair project is sufficiently large.

3.2. Repair materials

At the time this evaluation was initiated, WisDOT did not have a qualified product list or formal guidance for selecting materials for vertical and overhead (VOH) repairs. As a result, repair materials were typically selected by maintenance crews based on prior experience and/or material availability. Since then, WisDOT has issued an approved product list of VOH repair materials and an Approved Product List Application Process for Vertical and Overhead Repair Material. WJE has reviewed these documents and provided recommendations in Section 5.

The survey indicates that various repair materials have been used, but performance of the repairs is not monitored, and there is little information available for comparison of repair materials. Surface preparation and repair material installation also vary among counties and regions, making such a comparison complicated. In some cases, repair materials not intended for VOH applications were reportedly used for VOH repairs just because they were locally available. A wide range of VOH repair compatible materials are available; selection of materials specifically intended for the purpose of the repair can be expected to produce more durable results and easier installation.

3.3. Surface Preparation

WisDOT's Structure Inspection & Repair (SIR) Unit generally follows industry best practices in terms of concrete removal and surface preparation. However, practices by counties vary due to experience, knowledge, availability of equipment and environmental regulations, and sometimes deviate from the best practices. One respondent mentioned they have seen many repairs without saw cuts. Saw cuts around edges of the repair are important as they provide anchorage for the patch to the substrate and help reduce debonding along the edges of the repair.

Several respondents mentioned that concrete is not always removed behind exposed reinforcing bars during performance of VOH repairs. The need for removing concrete behind rebars depends on the cause of deterioration. If reinforcing bars are corroded due to chlorides, the concrete around the bar is likely chloride-contaminated, and thus, it is important to completely remove this chloride-contaminated concrete. It is also important to completely remove corrosion products on the reinforcing steel. Otherwise, the chloride left behind in the concrete or on the steel will continue to promote corrosion and reduce the life of the repair. When removing concrete behind bars is needed, the 1-inch clearance in the WisDOT Standard Specification 509.3.7 is consistent with industry standards and can be expected to meet the objective of removing detrimental contaminated concrete. If a concrete spall is not caused by corrosion (e.g. vehicle impact) and the remaining concrete is sound, removal behind the bar, which can be difficult or undesirable, may not be necessary. In addition, removing concrete around prestressing steel is generally not desired because of concerns about damaging the steel and/or changing structural behavior of the member. However, if the bars are not present to provide anchorage to the repair, an alternate supplemental anchorage should be provided to mechanically tie the patch to the substrate.

The types of supplemental anchorages used in Wisconsin varies among counties and regions. Different types of anchors have been used, including Tapcon screw anchors, wedge anchors, epoxy-doweled bars, and nails, but there are no track records on effectiveness of the anchorage. There is a lack of standard guidelines on anchor details, including type, size and configuration, and thus the anchor details are determined on a project basis based on experience and judgment of the maintenance crews.

Concrete removal for VOH repair is typically done using chipping hammers, which could leave microcracking/ bruising in the near-surface substrate. If not removed, the microcracking/bruising will adversely impact the bond between the repair and substrate. Abrasive blasting is one of the most effective methods to remove the weakened substrate surface layer and promote the bond between the repair and substrate. The use of abrasive blasting is inconsistent among the SIR and county crews. Abrasive blasting is typically not used when the repair is performed by county crews since blasting and safety equipment is not available. The SIR Unit has the capability of abrasive blasting, but the use varies depending on size and location of the repair and environmental restrictions.

An alternative method to remove microcracking in the substrate is water blasting at high- or ultra-high pressure (5,000 to 45,000 psi) (ICRI-310.2R-2013); however, none of the survey respondents reported the use of high- or ultra-high pressure waterblasting for surface preparation since the equipment is not readily available (Note: one survey respondent indicated that high- or ultra-high pressure waterblasting was used for hydrodemolition to remove concrete during girder repair.)

The survey indicates that the substate surface is typically not conditioned to a saturated surface dry (SSD) condition, which would require saturating the substrate for at least several hours and blowing off water from the surface. While the SSD condition is difficult to achieve for VOH repair, the recommendation from most manufacturers is that the substrate be prewetted without standing water prior to placement of the repair material, especially for hand-applied applications in which the repair mortar is highly sensitive to changes in the water content. A dry, hot substrate surface will absorb water from the repair material and can result in a layer of unhydrated repair material at the interface with the substrate, adversely impacting the bond between the repair and substrate.

3.4. Repair Materials Installation and Curing

Repair materials should be installed following manufacturer's instructions. Some repair materials, especially hand-applied repair mortar, are highly sensitive to changes of water content, and thus, the addition of water should strictly follow values recommended by the manufacturer.

Based on the survey and interviews with WisDOT staff, curing is only "sometimes" or "rarely" applied to VOH hand-applied repairs by the SIR Unit or county crews. As discussed in Section 2, curing is critical, especially for hand-applied mortars, which may be more susceptible to drying shrinkage due to the absence of coarse aggregate and the high paste-to-aggregate ratio. Curing of VOH repairs is important to reduce the risk of cracking, encourage hydration of cementitious repair materials, and improve the durability of repairs. Thin repairs are also more prone to shrinkage cracking.

While wet curing is typically the most effective for curing cementitious repair materials, it may not be practical for hand-applied VOH repairs. In lieu of wet curing, curing compound may be used to reduce the loss of water from the repair. Effectiveness of curing compound may vary with the repair materials, the type and application timing of curing compound; thus, manufacturer's instructions on the use of curing compound should be followed.

For formed repairs, the form provides initial curing for the repair material. The age and/or strength of repair material required before the form is removed may vary with the repair material. Some materials may need additional curing, e.g. curing compound, after removal of the form. Manufacturer's recommendations on curing should be followed.

3.5. Conclusions

The evaluation concludes that WisDOT's general repair strategies are largely consistent with industry practices, particularly the preference for form-and-pour repairs where feasible. However, several issues limiting the consistency and durability of repairs have been identified, including:

- Absence of a repair material approval process and approved product list,
- Lack of standardized procedures for VOH repairs,
- Variability in using abrasive blasting and supplemental anchorage during surface preparation.
- Inconsistent curing practices
- Limited long-term monitoring of repair performance

Improving guidance and standardization in these areas could enhance repair quality, durability, and cost effectiveness for vertical and overhead concrete repairs in Wisconsin's bridge infrastructure.

4. LABORATORY INVESTIGATIONS

WJE conducted a laboratory investigation to evaluate the performance of minor to intermediate vertical and overhead concrete patches. In this study, patches equal to or less than 2 inches deep and not beyond the reinforcing steel are considered minor, while intermediate patches are deeper than 2 inches and beyond the reinforcing steel. The testing program included: (1) material characterization and (2) structural performance testing of reinforced concrete slab specimens containing repair patches. The primary objective was to assess the influence of repair material type, installation method, anchorage, repair thickness, and surface preparation on cracking behavior, bond performance, and spall resistance of the patches.

4.1. Materials

The substrate concrete and the selected repair materials used to prepare the reinforced concrete slab specimens were independently characterized.

4.1.1. Substrate Concrete

The mix design used for the substrate concrete is shown in Table 1. A specified strength at 28 days of 5,000 psi was selected to be representative of typical Wisconsin bridge structures. Air content (4.5 to 7.5%) and slump (1 to 4 inches) were selected to reflect common bridge deck construction practices by WisDOT.

Table 1. Concrete mix design for substrate (Ozinga Mix Design 1098SX)

Material/Properties	Material Type/Product	Supplier/Source	Quantity/Target Value
Cement	Type IL	Holcim, Ste. Genevieve Plant, Bloomsdale, MO	536 lb
Slag	Grade 100	Anshan Iron & Steel Group Corp. Slag Dev., China	100 lb
Coarse Aggregate	ASTM C33	Vulcan Materials (50312-78), McCook, IL	1780 lb
Fine Aggregate	ASTM C33	Meyer Material, McHenry, IL	1225 lb
Water	-	-	30.7 gal.
Air Entraining Admixture	ASTM C260, AIRALON® 7000	GCP Applied Technologies	4.0 fl. oz.
Water Reducing Admixture	ASTM C494 Type A and D, ZYLA® 630	GCP Applied Technologies	19.0 fl. oz.
High-range Water Reducing Admixture	ASTM C494 Type A and F and ASTM C1017 Type I, ADVA® Cast 57	GCP Applied Technologies	6.4 fl. oz.
CarbonCure	ASTM C494 Type S	CarbonCure Technologies	Dosage rate varied
w/cm	-	-	0.40
Specified Strength	**-**	**-**	**5,000 psi at 28 days**
Air Content	**-**	**-**	**4.5 to 7.5%**
Slump	**-**	**-**	**1 to 4 inches**

4.1.2. Repair materials

Four commercially available repair materials with established performance records, based on a survey of WJE's experienced engineers and interviews with WisDOT maintenance staff, were selected: two hand-applied (trowel-applied) mortars and two form-and-pour materials. Selecting materials with demonstrated field performance allowed the study to focus on installation variables and anchorage effects rather than repair product performance. A description of the repair materials is provided in Table 2. Both the full product names and the abbreviated names used by WJE are presented. These names are used interchangeably throughout this report.

Table 2. Repair materials used in this study

Repair Material	Application Method	Manufacturer's Material Description
H1	Hand-applied	Two-component, polymer-modified, portland cement-based, fast-setting, non-sag mortar with penetrating corrosion inhibitor.
H2	Hand-applied	Proprietary blend of cement, water reducers, rheology modifying additives and selected aggregates. Not polymer modified.
F1	Form-and-pour	One-component, cementitious, polymer-modified, self consolidating concrete (SCC) mix with an integral migrating corrosion inhibitor. Contains factory blended coarse aggregate. Silica fume and polymer modified. The packaged concrete is pre-extended with coarse aggregate.
F2	Form-and-pour	Low dust one-component, shrinkage-compensated, self-consolidating concrete (SCC) mix. Proprietary blend of cement, graded aggregate, shrinkage-compensating agents, and additives. The packaged concrete is pre-extended with coarse aggregate.

4.1.3. Materials Testing

The following laboratory tests were conducted in accordance with applicable ASTM and AASHTO standards:

- **Compressive Strength (Concrete Cylinders):** Compressive strength was determined at 28 days for the substrate concrete (using 4x8-inch cylinders) and all four repair materials (using 3x6-inch cylinders) in accordance with ASTM C39.
- **Compressive Strength (Mortar Cubes):** For the two hand-applied repair materials, 28-day compressive strength was determined using 2-inch cube specimens in accordance with ASTM C109.
- **Drying Shrinkage:** Drying shrinkage was evaluated for the substrate concrete and all four repair materials using 3x3x11-1/4-inch prisms.
  - Testing of the substrate concrete was conducted in general accordance with ASTM C157. Substrate concrete specimens were cured in the mold for 1 day, wet-cured for 27 days, and then stored in air. Length change readings were obtained after 4, 7, 14, and 28 days of air storage, and after 52 weeks (reduced from 64 weeks, as specified in ASTM C157, to accommodate the project schedule).
  - Testing of the repair materials followed a procedure based on ASTM C157, modified in accordance with ACI PRC-364.3-22, Section 6.12. Repair material specimens were cured in the mold for 1 day and then stored in air. Length change readings were obtained at ages of 3, 7, 14, and 28 days, and after 8, 16, 32, and 52 weeks.
- **Coefficient of Thermal Expansion (CoTE):** The coefficient of thermal expansion was determined for the substrate concrete and all four repair materials in accordance with AASHTO T336 based on 4x8-inch cylinders.
- **Tensile Pull-Off Strength:** Bond strength between the repair materials and substrate concrete was evaluated at 28 days in accordance with ASTM C1583 and utilizing guidelines in ICRI 210.3R-2022.

- Test specimens consisted of concrete blocks measuring approximately 12 × 18 inches in plan and either 5 inches or 8 inches thick, with cavities of 1-1/2 and 4 inches thick, respectively. The thinner blocks with 1-1/2-inch cavities were used for hand-applied repairs, and the thicker blocks with 4-inch cavities were used for form-and-pour repairs. For hand-applied materials, the cavities were patched in an overhead orientation. For form-and-pour materials, both overhead and vertical orientations were evaluated. Fabrication of the specimens followed the procedures described for the performance test specimens in Section 4.2.2.
- After 27 days of curing, circular cuts were drilled through the patch material using a coring barrel with an internal diameter of 3 inches. The core barrel cuts extended through the repair material and approximately 1 inch into the substrate concrete. The patch material surface was cleaned and allowed to dry before a 3-inch-diameter aluminum puck was bonded to the surface using an epoxy adhesive. After approximately 24 hours of adhesive curing, pull-off testing was conducted using a calibrated pull-off tester at a loading rate of 5 psi per second (Figure 1).

Figure 1. Tensile pull-off testing

4.2. Performance Testing

In the repair performance testing, reinforced concrete slabs with a repair patch were subjected to both environmental exposure and mechanical loadings.

4.2.1. Test Specimens

The test specimen consisted of a reinforced concrete beam measuring 8 × 12 × 40 inches. The typical repair patch measured 12 × 12 inches except noted otherwise, with varying depths of 1-1/2, 2, or 4 inches as shown in Figure 2. Supplemental anchorage and reinforcement in the patch vary as described below and are not shown in Figure 2.

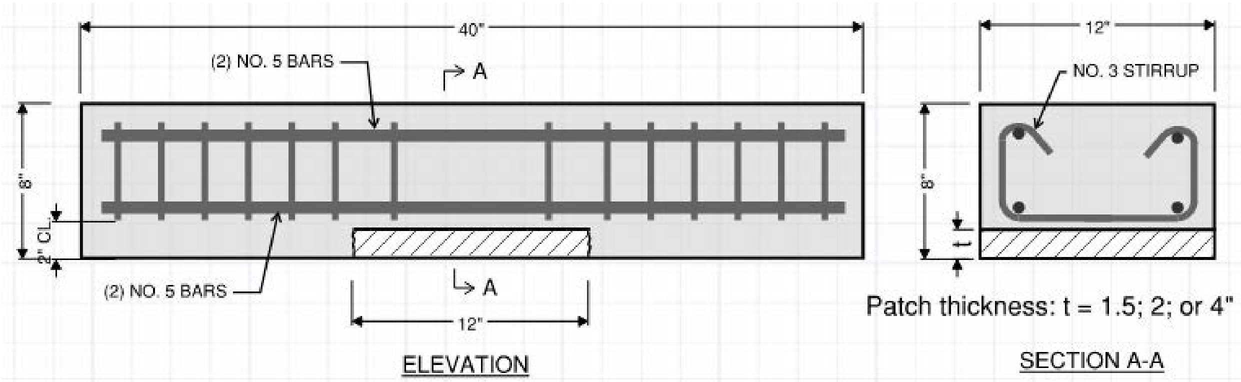


Figure 2. Specimen for thermal and load testing. (Notes: supplemental anchorage and reinforcement in the patch not shown; typical patch length is 12 inches unless otherwise noted).

4.2.1.1. Test Matrix

Test variables included repair material and installation method, anchorage type, repair thickness, and surface preparation (sandblasting). Two hand-applied materials and two form-and-pour materials were evaluated. A total of 32 specimens were fabricated and tested, with eight specimens prepared for each repair material. A complete list of specimens and associated test variables is provided in Table 3.

The **hand-applied** material-based samples are summarized as follows:

- Three anchorage conditions were evaluated: (1) no anchor, (2) threaded rod U, and (3) welded wire reinforcement (WWR) fastened with screw anchors. Within the no-anchor condition, three specimens were not sandblasted; all remaining specimens were sandblasted.
- All hand-applied repairs were installed in an overhead orientation.
- The nominal patch dimensions were 1-1/2 inches thick, 12 inches wide and 12 inches long, except for Specimens 15 and 16, which were 2 inches thick and 17-1/4 inches long. These two specimens were fabricated with increased length because the cavity edge was damaged during concrete removal. The thickness was increased to 2 inches because the substrate had been inadvertently sandblasted at the original 1-1/2-inch depth; therefore, an additional 1/2 inch of concrete was removed to obtain an unblasted substrate surface.
- Two replicate specimens were fabricated for each condition, except for Specimens 15 and 16 (Repair material H2), where one specimen was sandblasted and the other was not.

The **form-and-pour** material-based samples are summarized as follows:

- Two repair thicknesses were evaluated: 2 inches and 4 inches.
- All 2-inch-thick patches were installed in a vertical orientation and did not encompass existing reinforcement. For the 2-inch specimens, two anchorage configurations were evaluated: (1) threaded rod U and (2) welded wire reinforcement (WWR) fastened with screw anchors. The 4-inch specimens were cast in either vertical or overhead orientation.
- All 4-inch-thick patches encompassed existing reinforcement, including two No. 5 longitudinal reinforcing bars and two No. 3 stirrups.
- Two replicate specimens were fabricated for each test condition.

Table 3. Specimen List

Specimen ID	Patch Thickness (in.)	Sand Blasted?	Anchor type	Repair Orientation	Repair Material	Method
1	1-1/2	Blasted	No Anchor	Overhead	H1	Hand-applied
2	1-1/2	Blasted	No Anchor	Overhead	H1	Hand-applied
3	1-1/2	Blasted	No Anchor	Overhead	H2	Hand-applied
4	1-1/2	Blasted	No Anchor	Overhead	H2	Hand-applied
5	1-1/2	Blasted	Threaded rod U	Overhead	H1	Hand-applied
6	1-1/2	Blasted	Threaded rod U	Overhead	H1	Hand-applied
7	1-1/2	Blasted	Threaded rod U	Overhead	H2	Hand-applied
8	1-1/2	Blasted	Threaded rod U	Overhead	H2	Hand-applied
9	1-1/2	Blasted	Screw & WWR	Overhead	H1	Hand-applied
10	1-1/2	Blasted	Screw & WWR	Overhead	H1	Hand-applied
11	1-1/2	Blasted	Screw & WWR	Overhead	H2	Hand-applied
12	1-1/2	Blasted	Screw & WWR	Overhead	H2	Hand-applied
13	1-1/2	Not Blasted	No Anchor	Overhead	H1	Hand-applied
14	1-1/2	Not Blasted	No Anchor	Overhead	H1	Hand-applied
15	2	Not Blasted	No Anchor	Overhead	H2	Hand-applied
16	2	Blasted	No Anchor	Overhead	H2	Hand-applied
17	2	Blasted	Threaded rod U	Vertical	F1	Form & pour
18	2	Blasted	Threaded rod U	Vertical	F1	Form & pour
19	2	Blasted	Threaded rod U	Vertical	F2	Form & pour
20	2	Blasted	Threaded rod U	Vertical	F2	Form & pour
21	2	Blasted	Screw & WWR	Vertical	F1	Form & pour
22	2	Blasted	Screw & WWR	Vertical	F1	Form & pour
23	2	Blasted	Screw & WWR	Vertical	F2	Form & pour
24	2	Blasted	Screw & WWR	Vertical	F2	Form & pour
25	4	Blasted	Existing rebar	Vertical	F1	Form & pour
26	4	Blasted	Existing rebar	Vertical	F1	Form & pour
27	4	Blasted	Existing rebar	Vertical	F2	Form & pour
28	4	Blasted	Existing rebar	Vertical	F2	Form & pour
29	4	Blasted	Existing rebar	Overhead	F1	Form & pour
30	4	Blasted	Existing rebar	Overhead	F1	Form & pour
31	4	Blasted	Existing rebar	Overhead	F2	Form & pour
32	4	Blasted	Existing rebar	Overhead	F2	Form & pour

Notes: All patches were 12 inches long, except for patches of Specimens 15 and 16, which were 17-1/4 inches long.

4.2.1.2. Specimen Fabrication

Fabrication of the test specimens was performed by an experienced local repair contractor, Quality Restorations Inc., under WJE's supervision. Each specimen was cast with a preformed cavity measuring 12 × 12 inches (except as noted otherwise), with varying depths of 1, 1-1/2, or 2 inches. After fabrication and 14 days of curing, the cavity surfaces were prepared using a chipping hammer followed by sandblasting, as applicable. The chipping hammer was used to remove at least 1/2 inch of concrete to achieve the target repair depths of 1-1/2, 2, or 4 inches as specified in Table 3. For specimens designated for sandblasting, the substrate surface was sandblasted and subsequently cleaned with compressed air. For non-sandblasted specimens, the surface was cleaned using compressed air only. Examples of the prepared cavities with different anchorage conditions are shown in Figure 3 through Figure 6.

The cavities were subsequently patched in accordance with the manufacturer's recommended installation procedures for each material. Representatives from the respective manufacturers were present on site during installation to provide guidance and confirm that the mixing and repair procedures were consistent with their recommendations.

Detailed procedures for hand-applied materials:

- Hand-applied materials were applied with the test specimens inverted in an overhead orientation.
- The substrate surface was wetted using a spray bottle approximately 10 minutes prior to placement to achieve a moist condition without standing water.
- Powder and liquid components were weighed according to the manufacturer's specified proportions and adjusted during trial installations as needed based on the weight of the batch. Materials were mixed in a 5-gallon bucket using a low-speed drill (400–600 rpm) equipped with a large mixing paddle. Batch quantities were sized to allow placement within approximately 10 minutes.
- A scrub coat of repair material was first applied by hand. The repair material was then placed using a square steel trowel, starting at the edges of the cavity and working toward the center. Each patch was completed in a single lift.
- Approximately 20 to 25 minutes after finishing, the patches were sprayed with a curing compound recommended by the repair material manufacturer. Representative photos of hand-applied patch installation are shown in Figure 7 and Figure 8.

Detailed procedures for form-and-pour materials:

- Form-and-pour repairs were installed using formwork incorporating a "bird's mouth" detail extending approximately 2 inches above the top of the repair to facilitate placement. The gaps between formwork and substrate were intentionally left unsealed to facilitate air escape.
- The substrate surface was wetted approximately 10 minutes prior to placement, after which the formwork was secured to the substrate using screw anchors.
- One full bag of material was mixed at a time in a 5-gallon bucket using a low-speed drill (400–600 rpm) and mixing paddle. Water content was proportioned according to the manufacturer's recommendations and adjusted during trial installations as needed based on the measured weight of each bag of material.

- The repair material was poured through the bird's mouth opening to fill the cavity. The formwork was lightly tapped with a hammer during placement to facilitate consolidation and reduce air entrapment. No vibration was used since the repair materials are self-consolidating.
- After placement, the bird's mouth was covered with wet burlap and plastic sheeting to minimize moisture loss. Formwork was removed after approximately 4 days, and the bird's mouth was ground flush with the patch surface. In several specimens, minor edge damage (approximately 1 × 2 × 4 inches) occurred during formwork removal and grinding. The damaged areas were subsequently repaired using repair material H2. Photos of form-and-pour patches installed in vertical and overhead positions are shown in Figure 9 and Figure 10.
- After the patches were installed and cured, a sounding test was performed using hammer tapping to identify potential debonding within the patch or at the repair–substrate interface. No debonding was detected using this method. However, it is noted that some patches were 4-inches thick, which rendered the sounding method less reliable due to the reduced sensitivity to subsurface defects.

Additional photos illustrating the sample fabrication process are provided in Appendix C1.

Figure 3. No anchor in 1-1/2-inch cavity

Figure 4. Anchorage by threaded rods U (red arrows) in 1-1/2-inch and 2-inch cavities

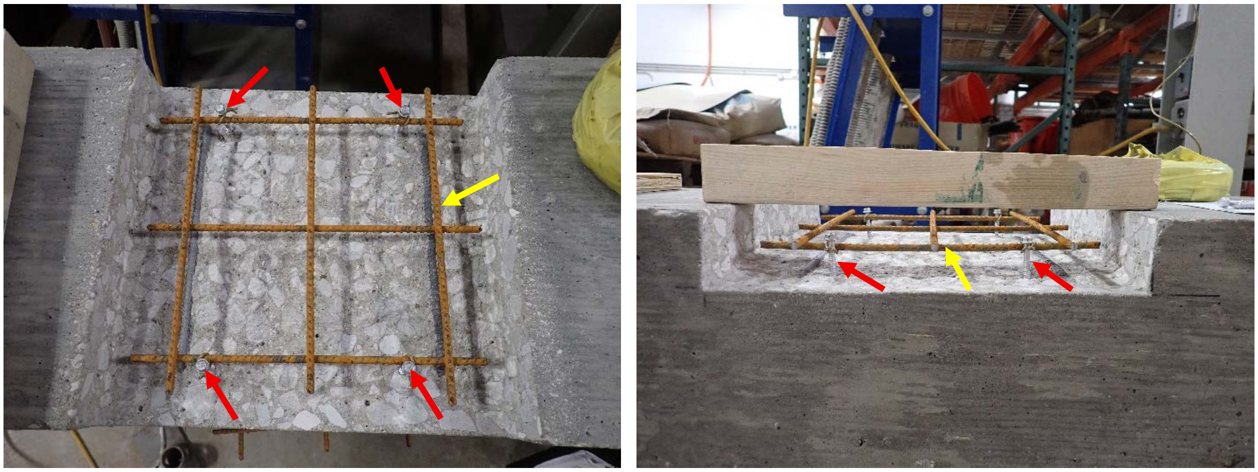


Figure 5. Anchorage by screw anchors (red arrows) and WWR (yellow arrows) in 1-1/2-inch and 2-inch cavities

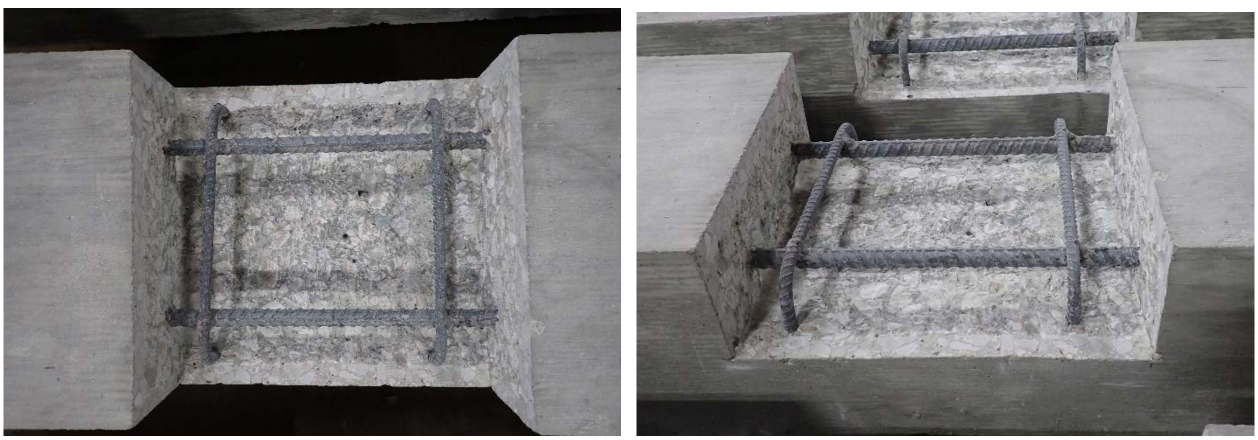


Figure 6. Anchorage by existing rebars in 4-inch cavity

Figure 7. Hand-applied patch in overhead orientation

Figure 8. Finishing of a hand-applied patch in overhead orientation

Figure 9. Form-and-pour in vertical orientation

Figure 10. Form-and-pour in overhead orientation

4.2.2. Cyclic Thermal Testing

After completion of patch installation, the specimens were stored in WJE's laboratory for approximately 5 to 9 months prior to the initiation of thermal testing while awaiting availability of the walk-in environmental chamber. Eight specimens were placed in the environmental chamber at a time (see Figure 11), and each specimen was subjected to 28 thermal cycles.

During each cycle, the temperature at the center of a control concrete block was cycled between a representative high summer temperature (approximately 120°F) and a representative low winter temperature (approximately −10°F).

The specimens were visually examined for cracking at the start of testing (0 cycles), after 7 cycles, and after 28 cycles. The objective of the thermal exposure was to evaluate the cracking behavior of the repair patches under cyclic temperature variations.

Figure 11. Thermal testing. Specimens in walk-in environmental chamber. Control concrete block (yellow arrow) had embedded thermocouples for controlling temperature cycles. Each cycle lasted approximately 1 day.

4.2.3. Flexural Load Testing

4.2.3.1. Load Test Setup

Upon completion of thermal testing, the specimens were removed from the environmental chamber and subjected to monotonic and cyclic flexural loading.

Each specimen was tested as a simply supported beam with a 36-inch span. Loads were applied at the third points, which generally coincided with the ends of the repair patch. The patch was located on the bottom face of the beam and therefore subjected to tensile stresses during loading. A schematic of the loading configuration is shown in Figure 12.

At WJE’s structural laboratory, the specimen was placed beneath a load reaction frame anchored to the laboratory's strong floor. The load was applied using a computer-controlled fatigue-rated hydraulic actuator. The actuator applied load to the specimens through a universal joint to a steel spreader beam having two cylindrical bearings spaced 12 inches on center and aligned transverse to the beam. The applied load was measured using a calibrated 100-kip load cell. During monotonic loading, mid-span deflections were measured using string potentiometers mounted on both sides of the beam. During cyclic loading, deflections were determined from actuator displacement measurements. Representative photographs of specimens during load testing are provided in Figure 13. To ensure uniform distribution of load, the top surface of the beam was ground or capped with a thin (approximately 1/8-inch) layer of hydrostone prior to load testing. In addition, leather shims were used at the top and bottom bearing to avoid local stress concentrations.

An overview of the complete load test setup is presented in Figure 14.

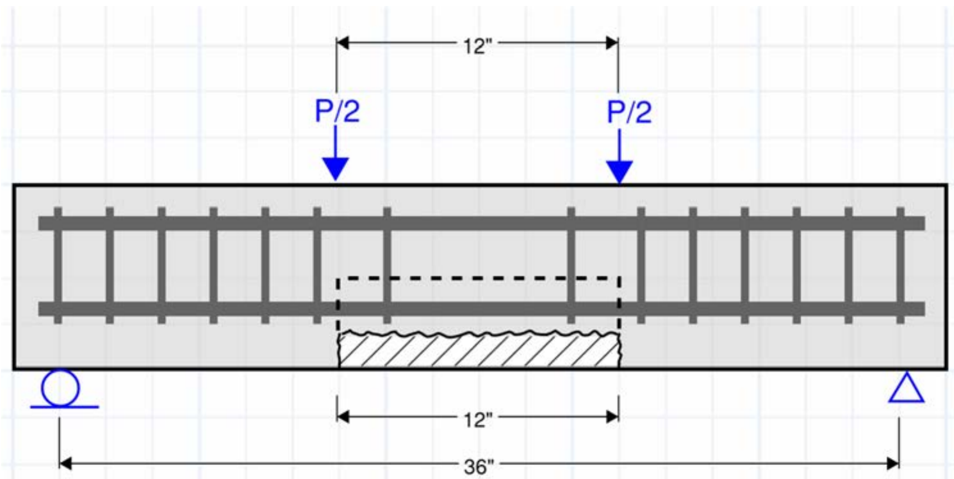


Figure 12. Flexural load test schematic

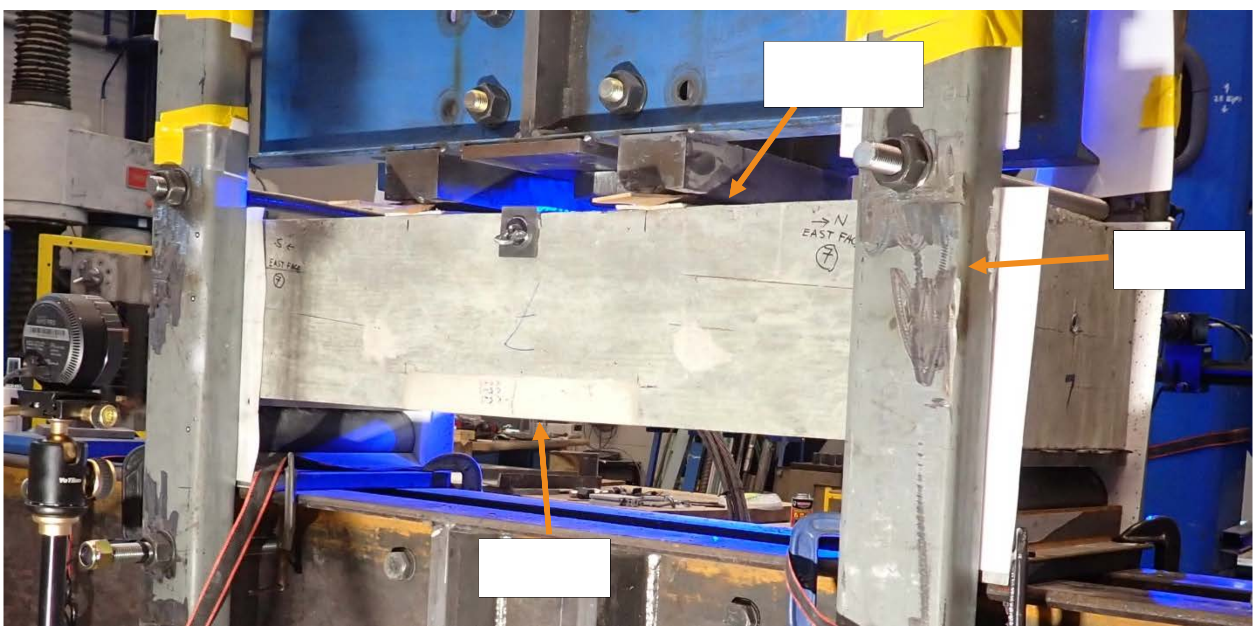


Figure 13. Specimen ready for flexural load testing. Full view of bottom bearings blocked by vertical posts used to prevent “walking” during cyclic loading.

Figure 14. Overview of test setup: 1) Beam specimen; 2) 55-kip actuator; 3) Cross-head for reaction frame; 4) Spreader beam; 5) String potentiometer; 6) Camera system for 3D-DIC; 7) High-resolution digital cameras

4.2.3.2. Digital Image Correlation (DIC)

A stereo-vision digital image correlation (DIC) system was used to measure surface displacements and strains on the vertical face of each beam specimen. This non-contact measurement technique captures a series of digital images during testing, which are compared to a reference image (representing zero displacement and strain) to determine relative deformations and strain fields. In this study, the DIC system was used to monitor displacement and strain development throughout the loading program.

Prior to testing, the specimen surfaces were prepared with a contrasting black-and-white stochastic speckle pattern (an example is shown in Figure 15). The speckle pattern enables tracking of uniquely identifiable surface regions (facets) over time, allowing deformation and strain measurements at selected locations or across defined areas of interest.

Two DIC systems were utilized:

- 3D-DIC system: This system consisted of a pair of 2.3-megapixel CMOS cameras mounted on an 800 mm adjustable base manufactured by GOM. Camera calibration was performed using a CP40/200 calibration object supplied by GOM.

- 2D-DIC system: High-resolution images were captured at predetermined time intervals using two Nikon Z7 II mirrorless cameras (45.7 megapixels).

Images obtained by both DIC systems for representative specimens were processed using GOM software, and the results are discussed in Section 4.3.3.4.

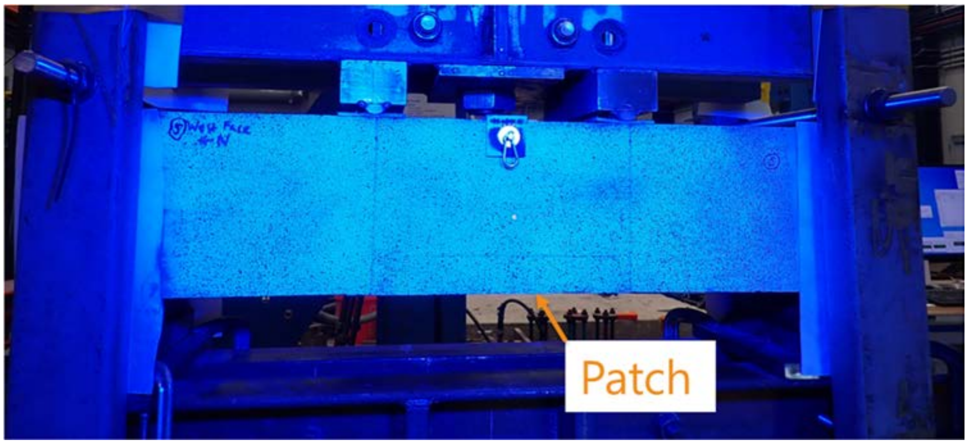


Figure 15. Speckle patterned specimen for DIC analysis

4.2.3.3. Loading Protocol

The loading protocol consisted of:

1. Initial monotonic loading,
2. Cyclic loading, and
3. Final monotonic loading to failure.

Initial Loading

The specimen was subjected to monotonic loading from 0 to 12.9 kips over a period of approximately 3 minutes. At 12.9 kips, the tensile stress in the bottom longitudinal No. 5 reinforcing bars was estimated to be approximately 26 ksi, corresponding to about 43% of the specified yield strength. This stress level corresponds to the upper limit for the constant-amplitude fatigue threshold for straight reinforcing bars per AASHTO LRFD Bridge Design Specifications. The loading was paused at 2.1, 4.2, 6.3, 9.6, and 12.9 kips to capture photographs. Upon completion of the initial loading sequence, the specimen was unloaded.

Cyclic Loading

The load was reapplied and cycled between 1.0 and 12.9 kips. The lower bound of 1.0 kip was selected to maintain continuous contact between the actuator and the specimen throughout testing.

The loading frequency was initially set at 1 Hz and gradually increased to approximately 6 Hz within the first few minutes of testing. A frequency of 6 Hz was maintained for the remainder of the cyclic loading phase. Each specimen was subjected to between 300,000 and 500,000 load cycles.

Actuator load and displacement were continuously recorded. Actuator displacement measurements were used to calculate beam deflection.

Final Loading

Following cyclic loading, the specimen was unloaded and reloaded monotonically from 0 to 12.9 kips over approximately 3 minutes. Loading then continued at a displacement-controlled rate of 0.1 inch per minute until ultimate load was reached and subsequently to a total deflection of 1 inch relative to position of the beam at the beginning of the final loading. The loading was paused at specified load levels of 12.9, 20, 30, 40, and 50 kips to capture photographs. The 50-kip load level was near the 55-kip capacity of the actuator and encompassed the ultimate capacity range of most specimens. Additional photographs were taken at the end of the test, corresponding to a 1-inch deflection. Typical failure modes included crushing of the top concrete in compression and fracture of the bottom longitudinal reinforcing bars in tension.

The cracking and spalling conditions of the patch were documented throughout the final loading sequence.

4.3. Test Results

4.3.1. Materials Test Results

4.3.1.1. Compressive Strength and Modulus of Elasticity

The 28-day compressive strength and modulus of elasticity (MOE) results of the substrate concrete and repair materials are shown in Table 4. Detailed test results are provided in Appendix C2.

The average compressive strength of the substrate concrete was 6,310 psi. The average compressive strengths of the repair material cylinders ranged from 6,110 psi to 7,320 psi. For materials tested using cube specimens, measured cube strengths were higher than corresponding cylinder strengths.

The average 28-day MOE of the substrate concrete was 4,725,000 psi. The average MOE values of the repair materials ranged from 2,962,500 to 5,212,500 psi.

Table 4. 28-day Compressive Strength

Material	Compressive strength – Cylinder[1] (psi)	Compressive strength - Cube[1] (psi)	Modulus of Elasticity[2] (psi)
Concrete substrate	6,310	--	4,725,000
Repair material H1	6,110	6,320	2,962,500
Repair material H2	6,980	7,690	4,200,000
Repair material F1	6,510	--	4,700,000
Repair material F2	7,320	--	5,212,500

Notes: [1] Average of three specimens; [2] Average of two specimens; the first of three specimens was loaded to failure to obtain compressive strength; the other two specimens were loaded to 40% of strength to obtain MOE, and then loaded to failure for compressive strengths.

4.3.1.2. Tensile Bond Strength

Pull-off tensile test results are presented in Table 5 and Figure 16. Detailed test results are provided in Appendix C2.

For sandblasted specimens, the average of three pull-off tensile strengths for each condition ranged from 167 to 245 psi. However, for the two form-and-pour materials installed in the overhead orientation, the cores separated at the interface between the repair material and substrate during coring; therefore, pull-off testing was not completed for these specimens. The exposed interfaces appeared smooth and contained numerous air voids in the material (Figure 17), indicating that adequate bond was not achieved.

For repair material H1, specimens that were not sandblasted exhibited approximately 5% lower average bond strength compared to sandblasted specimens. In contrast, H2 specimens that were not sandblasted exhibited approximately 50% lower average bond strength than their sandblasted counterparts, demonstrating a stronger dependence on surface preparation.

Table 5. Pull-off tensile test results

Repair Material	Installation Method & Orientation	Surface Preparation	Individual Pull-off Tensile Strength (psi)			Average (psi)
			A	B	C	
H1	Hand-applied; Overhead	Sandblasted	290	267	176	**245**
H2	Hand-applied; Overhead	Sandblasted	128	233	168	**177**
F1	Form-and-pour; Vertical	Sandblasted	236	189	179	**201**
F2	Form-and-pour; Vertical	Sandblasted	103	148	250	**167**
F1	Form-and-pour; Overhead	Sandblasted	Sample separated [1]	Sample separated [1]	Sample separated [1]	**-**
F2	Form-and-pour; Overhead	Sandblasted	Sample separated [1]	Sample separated [1]	Sample separated [1]	**-**
H1	Hand-applied; Overhead	Not Sandblasted	234	164	301	**233**
H2	Hand-applied; Overhead	Not Sandblasted	110	89	51	**83**

Notes: [1] Sample separated at the interface between the repair material and substrate during coring, and pull-off testing was not performed.

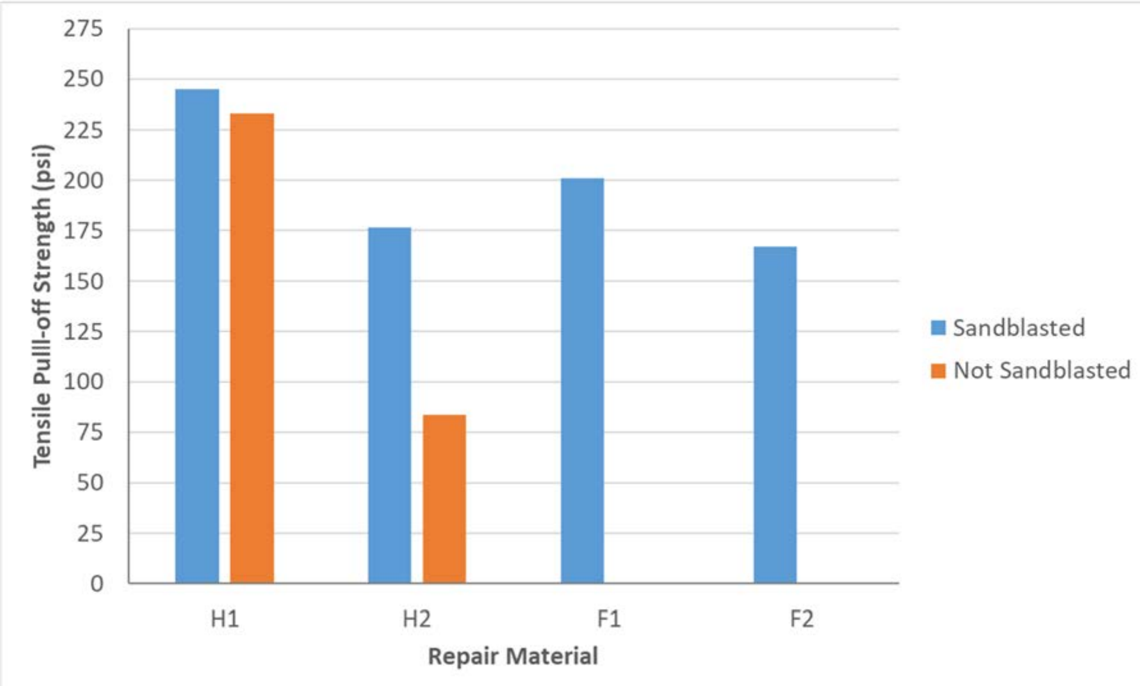


Figure 16. Tensile pull-off strength (average of three specimens); the first two materials were hand-applied in an overhead orientation, while the last two materials were installed by form-and-pour method in a vertical orientation.

Figure 17. Pull-off test sample for an overhead, form-and-pour repair (Material F2); sample separated during coring at the interface where large air voids in the material were present.

4.3.1.3. Coefficient of Thermal Expansion

The coefficient of thermal expansion (CoTE) test results are presented in Table 6. Detailed test results are provided in Appendix C2.

The average CoTE values of the repair materials ranged from 7.3 to 8.6 × 10^{-6}/°F, compared to 5.6 × 10^{-6}/°F for the substrate concrete. All repair materials exhibited higher thermal expansion coefficients than the substrate concrete.

Table 6. Coefficient of Thermal Expansion (Average of two specimens)

Material	**Coefficient of Thermal Expansion (×10^{-6}/°F)**	**Average Age at Testing (days)[1]**
Concrete substrate	5.6	30
Repair material H1	8.6	42
Repair material H2	7.8	40
Repair material F1	7.3	42
Repair material F2	7.6	35

Notes: [1] Specimen ages varied due to availability of test equipment

4.3.1.4. Dry shrinkage

Drying shrinkage test results are presented in Figure 18 and Figure 19. Detailed test results are provided in Appendix C2.

Ultimate drying shrinkage was estimated using the method described in ASTM C596. Measured shrinkage strains after 28 days and 52 weeks of air storage and estimated ultimate shrinkage are summarized in Table 7. Among the repair materials, H1 exhibited the lowest drying shrinkage, followed by H2, F1, and F2.

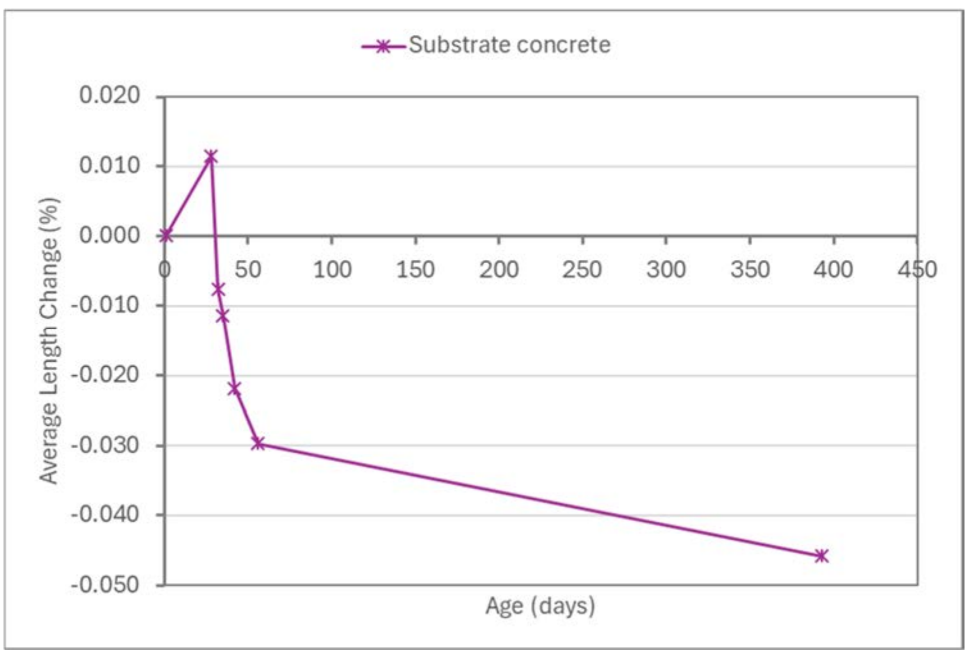


Figure 18. Drying shrinkage of repair materials and substrate concrete (substrate concrete specimens were cured in the mold for 1 day and wet-cured for 27 days before initiation of air storage)

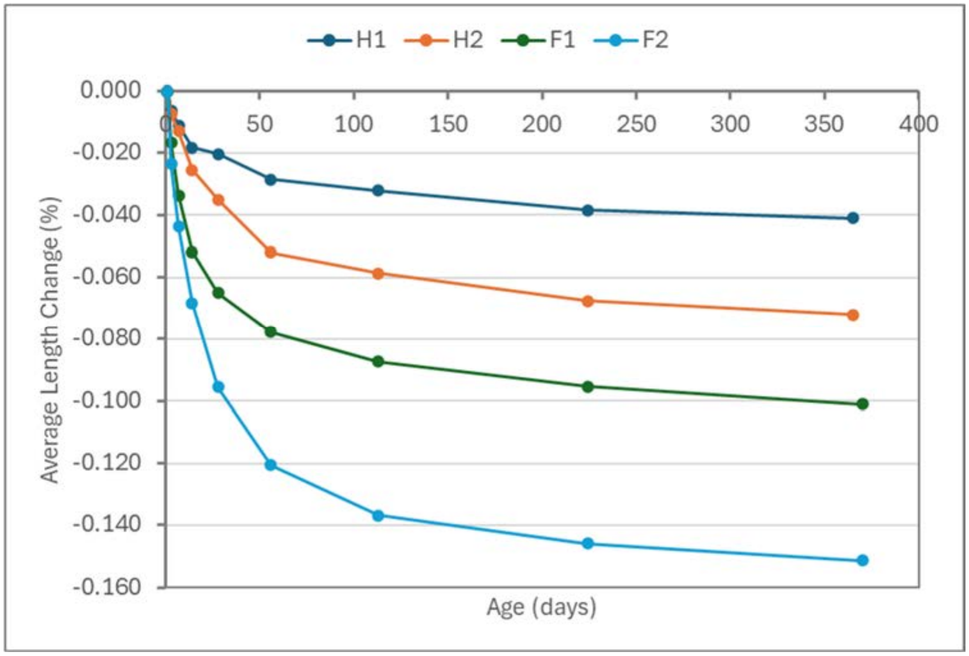


Figure 19. Drying shrinkage of repair materials. (Repair material specimens were cured in the mold for 1 day before initiation of air storage.)

Table 7. Drying shrinkage of repair materials and substrate concrete (Average of three specimens)

Material	**Length Change [1] (%)**		
	28-day[2] Air Storage	**52-week Air Storage**	**Ultimate**
Concrete substrate	-0.030	-0.046	-0.051
Repair material H1	-0.020	-0.041	-0.042
Repair material H2	-0.035	-0.072	-0.074
Repair material F1	-0.065	-0.101[3]	-0.103
Repair material F2	-0.095	-0.151[3]	-0.157

Notes:

[1] Negative values indicate shrinkage. Substrate concrete specimens were cured in the mold for 1 day, wet-cured for 27 days, and then stored in air (50% RH). Repair material specimens were cured in the mold for 1 day and then stored in air (50% RH)

[2] Substrate concrete was stored in air for 28 days. Repair materials were stored in air for 27 days.

[3] Reported value corresponds to 53 weeks of air storage.

4.3.2. Thermal Exposure Test Results

Crack density results for the repair patches for individual specimens are provided in Appendix C3, including cracking observed prior to thermal testing (0 cycles), after 7 cycles, and after 28 cycles. Crack density was calculated as the total crack length divided by the surface area of the repair patch (typically 12 x 12 inches). Average crack density values for each repair material are shown in Figure 20. Cracking observed prior to thermal cycling is attributed primarily to drying shrinkage. Cracking observed after thermal cycling is attributed to the combined effects of drying shrinkage and thermal movement of the specimens.

Cracking Prior to Thermal Cycling (0 Cycles)

Initial crack density varied among the repair materials. Repair material H1 exhibited the least amount of cracking, with most specimens showing no visible cracks. This observation is consistent with the comparatively low drying shrinkage measured for this material.

Repair material H2 exhibited the highest initial crack density. Most hand-applied specimens developed transverse cracks, and several exhibited both transverse and longitudinal cracking within the patch.

Repair materials F1 and F2 showed mixed performance. Some specimens exhibited transverse cracking at the ends of the patch and short longitudinal cracks within the patch, while others exhibited no visible cracking. For the form-and-pour specimens, the crack densities observed in the 2-inch and 4-inch patches were similar.

For all materials, crack widths were tight, generally less than 0.005 inches (5 mils) over the 12-inch square patch.

Cracking After Thermal Cycling

After 28 thermal cycles, additional cracking was observed in most specimens. Most specimens developed transverse cracks at the ends of the patch, and some specimens also exhibited additional cracks within the patch. For all repair materials, crack widths did not appear to increase after thermal cycling, and most cracks remained less than 0.005 inches wide. For the form-and-pour specimens, the crack densities observed in the 2-inch and 4-inch patches were similar. The percentage of cracks increased more after thermal cycling in the hand-applied specimens compared to the form-and-pour specimens with a greater overall crack density in the hand-applied specimens.

Representative photographs showing cracking conditions at 0, 7, and 28 cycles are provided in Figure 21 through Figure 24. Close-up images of cracking after 28 cycles are shown in Figure 25 and Figure 26.

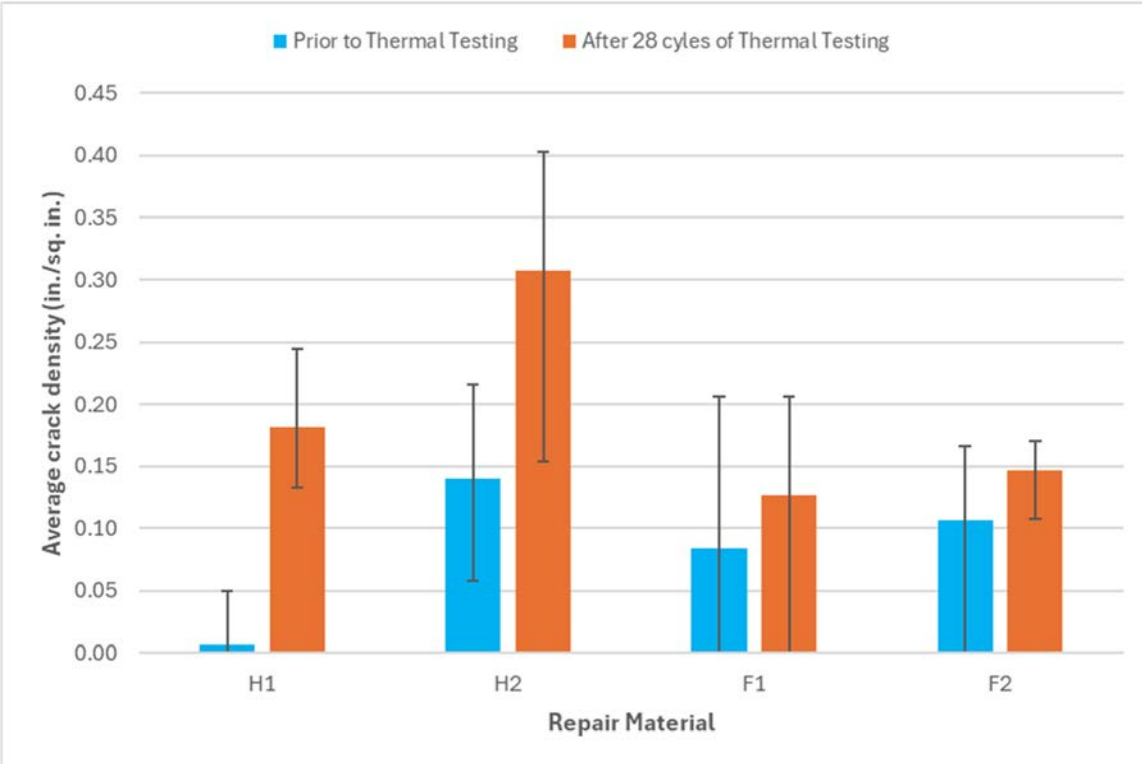
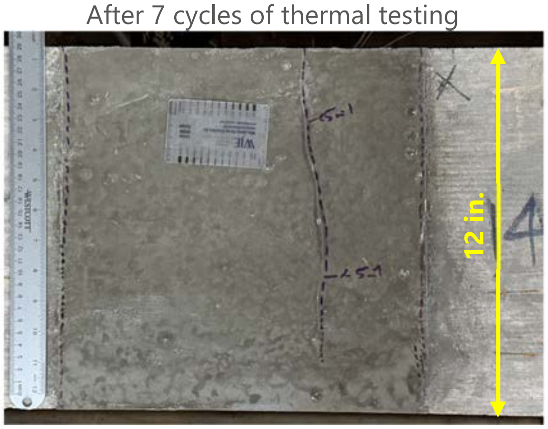


Figure 20. Cracking prior to thermal testing and after 28 cycles of thermal testing. Value is average of 8 specimens for each material. Error bar indicates range of values.

At 0 cycles (~7 months of age)

After 7 cycles of thermal testing



After 28 cycles of thermal testing

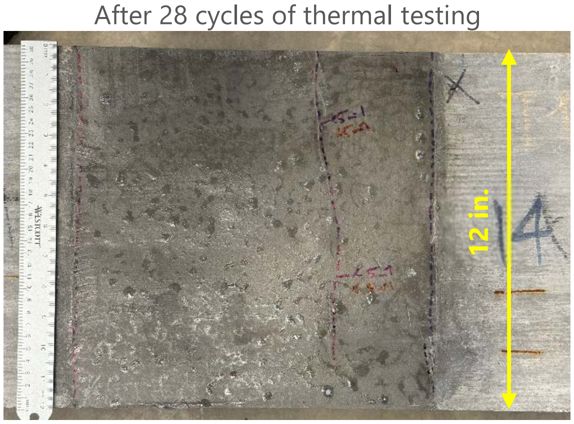
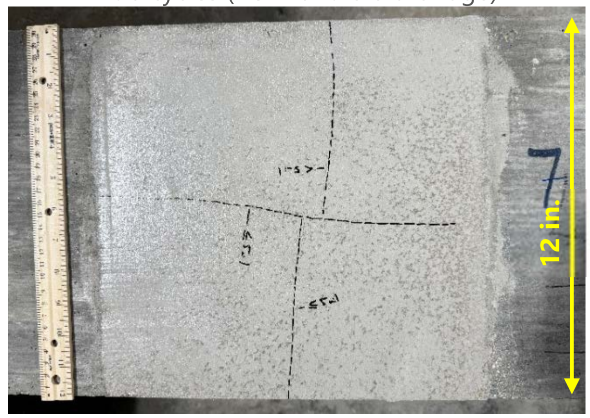
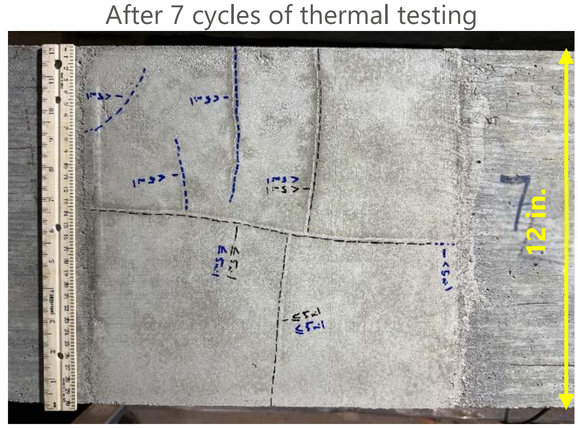


Figure 21. Specimen 14 (H1)

At 0 cycles (~5 months old of age)



After 7 cycles of thermal testing



After 28 cycles of thermal testing

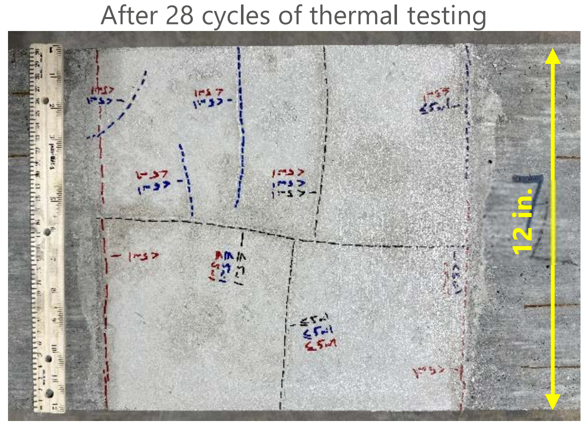
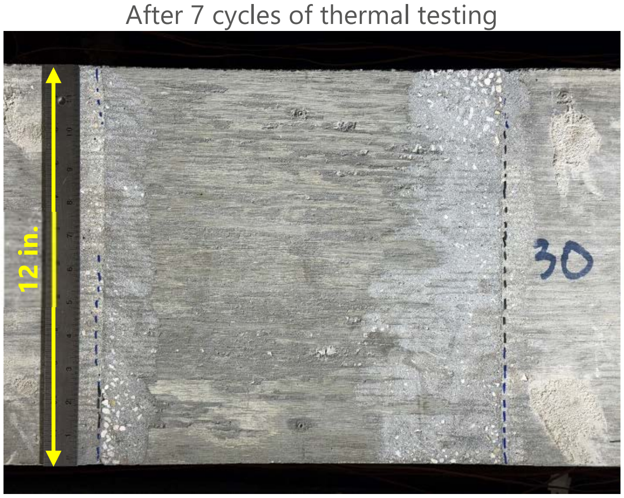


Figure 22. Specimen 7 (H2)

(Sharpie lines indicate cracks within patch or at interface with substrate. Sharpie notes indicate all crack widths were less than 5 mils)

At 0 cycles (~9 months old of age)

After 7 cycles of thermal testing



After 28 cycles of thermal testing

Figure 23. Specimen 30 (F1)

At 0 cycles (~9 months old of age)

After 7 cycles of thermal testing

After 28 cycles of thermal testing

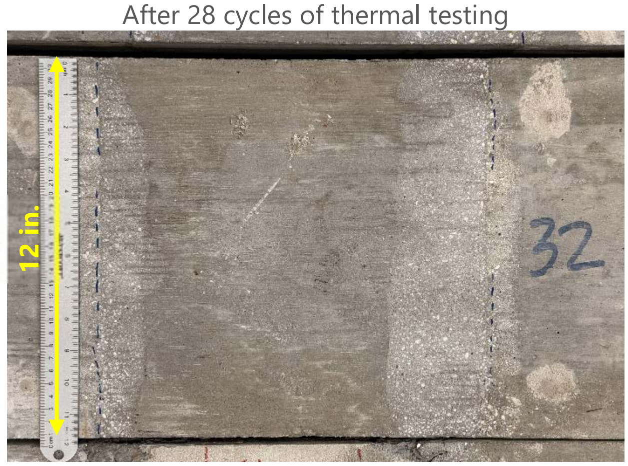


Figure 24. Specimen 32 (F2)

(Sharpie lines indicate cracks within patch or at interface with substrate. Sharpie notes indicate all crack widths were less than 5 mils)

Figure 25. Specimen 7 (H2) after 28 thermal cycles. Close-up view of cracking; crack width less than 0.005 inches.

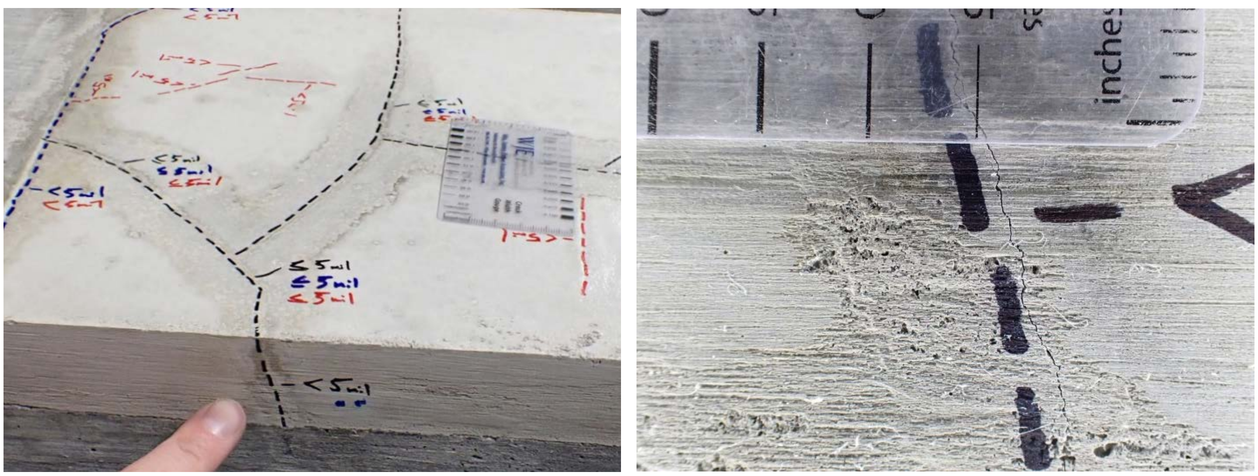


Figure 26. Specimen 3 (H2) after 28 thermal cycles. Close-up view of a crack extending through the full thickness of the patch; crack width less than 0.005 inches.

4.3.3. Load Test Results

4.3.3.1. Initial and Final Loadings

Load–deflection responses during the initial and final monotonic loading stages were recorded. Deflection represents the average of measurements obtained from string potentiometers mounted on both sides of the beam from the start of loading.

The initial loading response was essentially linear. During the final loading, the response was initially linear; however, the slope decreased as cracking progressed and the longitudinal reinforcing bars approached and reached their yield stress.

Observed failure modes included (1) crushing of the concrete at the top of the beam in compression and (2) fracture of the bottom longitudinal reinforcing bars in tension. The ultimate loads recorded during the final monotonic loading phase are provided in Appendix C4, along with stiffness results of the cyclic loading described in the next section.

4.3.3.2. Cyclic Loading

Beam deflection at load levels of 1.0 and 12.9 kips was monitored throughout cyclic loading (Figure 27). Beam stiffness was calculated as the ratio of load to deflection. The initial stiffness was determined at 4,000 cycles, after the specimen response had stabilized and the loading frequency was fixed at approximately 6 Hz. Subsequent stiffness values were calculated at intervals of 100,000 cycles (unless otherwise noted), using the average deflection over 360 cycles (approximately 10 seconds) at each interval. Additional stiffness calculations were performed for selected specimens to identify sudden reductions in stiffness. The results are provided in Appendix C4, along with the ultimate load recorded during the final monotonic loading phase.

Twenty-one of the 32 specimens were originally planned to undergo 500,000 load cycles. However, as noted in the subsequent section, six specimens (1, 2, 5, 19, 23, and 29) experienced unexpected significant stiffness reductions, likely due to fracture of the bottom No. 5 longitudinal reinforcing bars before reaching 500,000 cycles. To reduce the risk of additional bar fractures in the remaining eleven specimens, cyclic loading for those specimens was terminated at 300,000 cycles. However, two of these eleven specimens (24 and 32) still experienced a sudden drop in stiffness as noted below.

4.3.3.3. Specimen Behavior During Monotonic and Cyclic Loadings

The observed specimen behavior can be summarized as follows:

- During cyclic loading between 1.0 and 12.9 kips, all repair patches, including those with no anchors, remained largely attached to the beam for at least 300,000 cycles, and many specimens completed 500,000 cycles.
- Twenty-four specimens did not exhibit any sudden drop in stiffness during cyclic loading. For these specimens, the total change in stiffness over the cyclic loading regime ranged from −8% to +5%, with an average change of approximately −1%. The ultimate loads during final loading ranged from 37.7 to 52.2 kips, with an average of 46.6 kips.
- Specimen 2, 19 and 23 experienced two sudden drops in stiffness during cyclic loading, with a total stiffness reduction of approximately 65 to 67%. Specimens 1, 5, 24, 29, and 32 experienced one sudden drop in stiffness during cyclic loading, with total stiffness reductions ranging from 8% to 16%. Review of the specimen conditions and ultimate load data indicated that these stiffness drops were likely caused by fatigue fractures of the bottom longitudinal bars. Despite the occurrence of bar fatigue failures in some specimens, the patches generally remained attached to the beams.

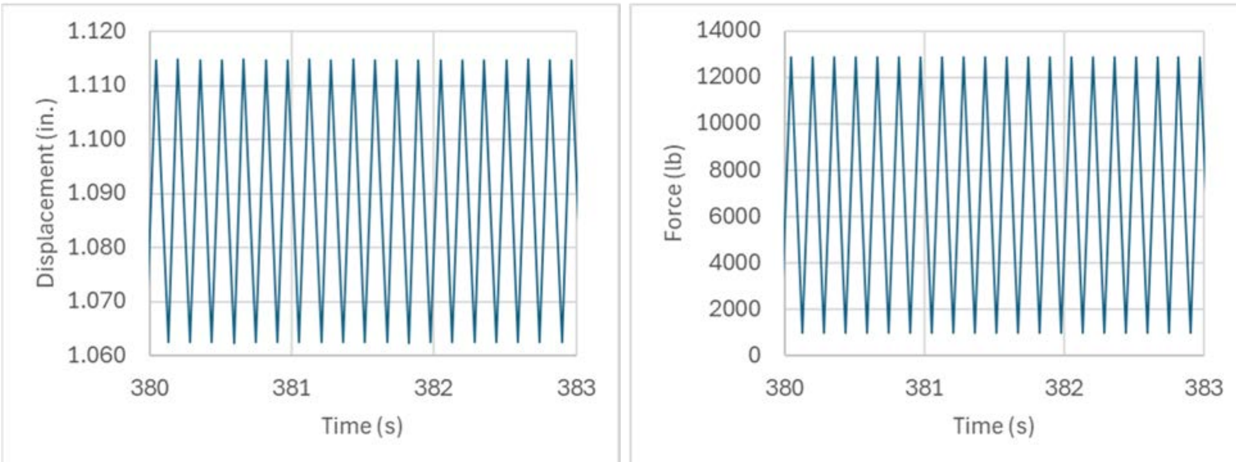


Figure 27. Example of actuator displacement and force data during cyclic loading (at a frequency ~6Hz) used to determine beam deflection and stiffness

4.3.3.4. Cracking During Initial and Final Loadings for Selected Specimens

Vertical and horizontal crack lengths along the perimeter of the repair patch and within the patch on the vertical faces of the flexural test specimens (see Figure 28) were estimated for ten selected representative specimens before and after cyclic loading. Crack lengths were determined using major strain (maximum tensile strain) contours obtained from DIC analysis of the concrete surface encompassing the patch and adjacent substrate. Cracks within the substrate concrete were excluded from this evaluation. An example DIC image is shown in Figure 29. Crack lengths were measured on both sides of each specimen, and average values were calculated.

During the initial loading phase, crack lengths were determined at load levels of 2.1, 4.2, 6.3, 9.6, and 12.9 kips. Example plots illustrating vertical and horizontal crack development at different load levels are shown in Figure 30 and Figure 31, respectively. During the final loading phase, crack lengths were evaluated at 12.9 kips.

Results for individual specimens are provided in Appendix C4. The total crack length for each specimen was normalized by dividing it by the patch thickness (for vertical cracking) and patch length (for horizontal cracking). The average normalized crack length at 12.9 kips, during initial loading and final loading, grouped by anchorage type, is shown in Figure 32 (vertical cracking) and Figure 33 (horizontal cracking).

Observations on cracking during initial monotonic loading and cyclic loading are summarized as follows.

- Vertical crack length increased with increasing static load across all anchorage types. On average, little to no increase in vertical crack length was observed due to cyclic loading. Specimens incorporating existing reinforcement or screw anchors with welded wire reinforcement (WWR) generally exhibited less vertical cracking compared to other anchorage configurations. Specimens without anchorage and those with threaded rod U anchors exhibited similar levels of vertical cracking.
- Horizontal crack length increased with increasing static load across all anchorage types. Different from vertical cracking, horizontal crack length increased significantly due to cyclic loading. Specimens incorporating existing reinforcement generally exhibited slightly less horizontal cracking, and the

horizontal crack appeared to be restrained by the vertical stirrups. Specimens with screw anchors and WWR, no anchorage, and threaded rod U anchors exhibited comparable levels of horizontal cracking both before and after cyclic loading. While patches with screw anchors and WWR appeared to restrain the horizontal crack in some specimens, this was not consistent in all cases. Example DIC images at 12.9 kips during the final loading for specimens with different anchorage types are shown in Figure 34.

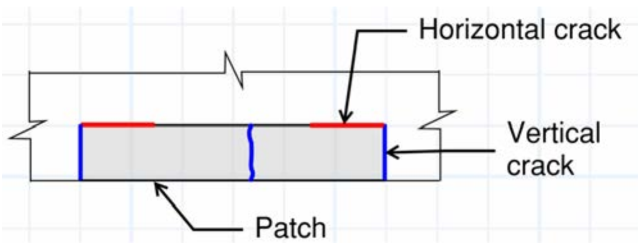


Figure 28. Schematic vertical and horizontal cracks within and around patch

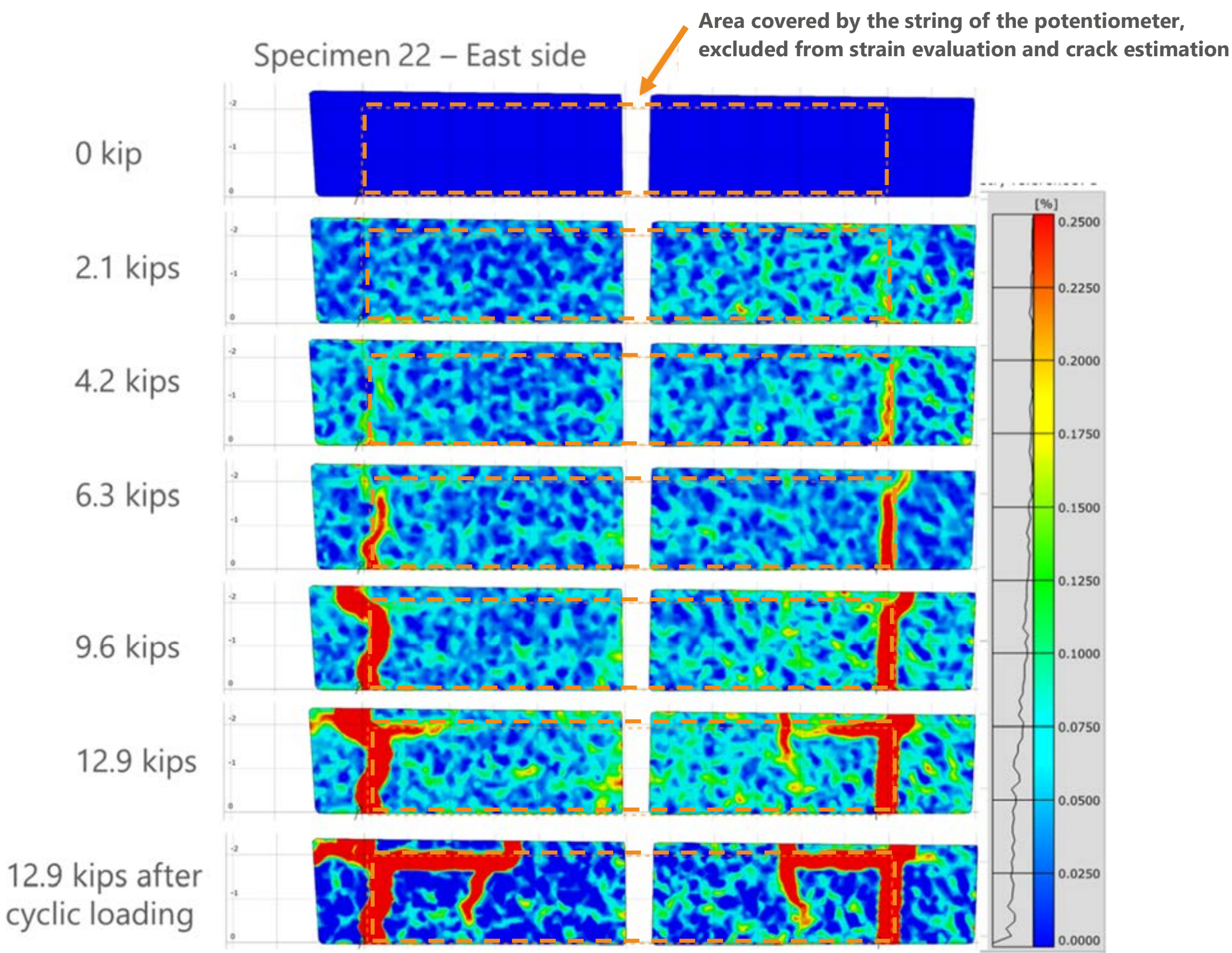


Figure 29. Example of major strain contour of the concrete surface (elevation view) obtained from DIC analysis for Specimen 22 (form-and-pour, 2-inch patch, with screws and WWR). The orange rectangle indicates the repair patch (2 × 12 inches). Continuous red regions indicate cracking.

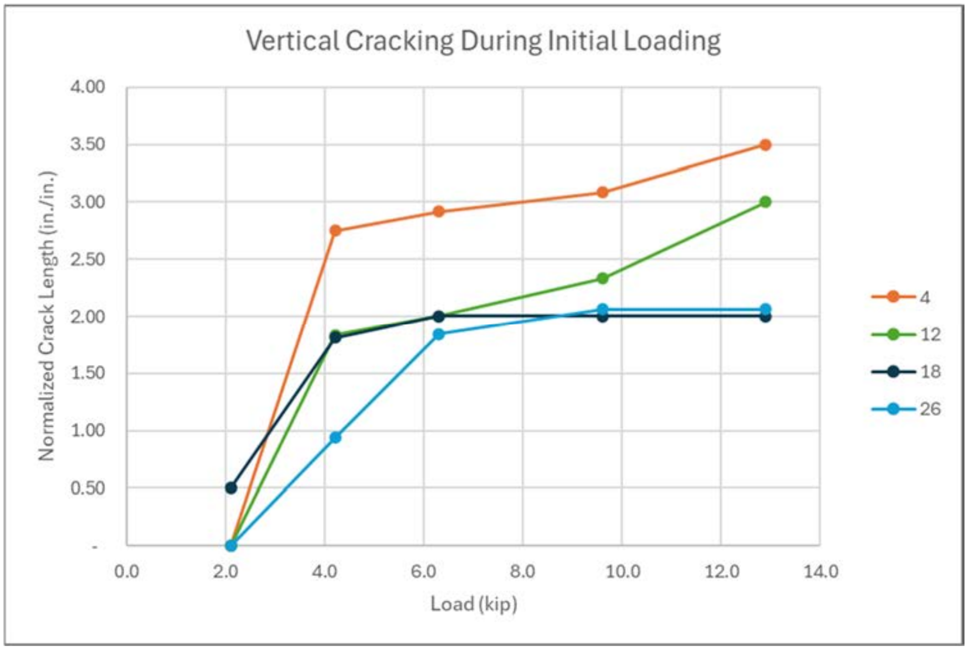


Figure 30. Examples of vertical crack lengths at different load levels during initial loading. Specimens 4 (no anchors), 12 (screws with WWR), 18 (threaded rod U), and 26 (existing rebars)

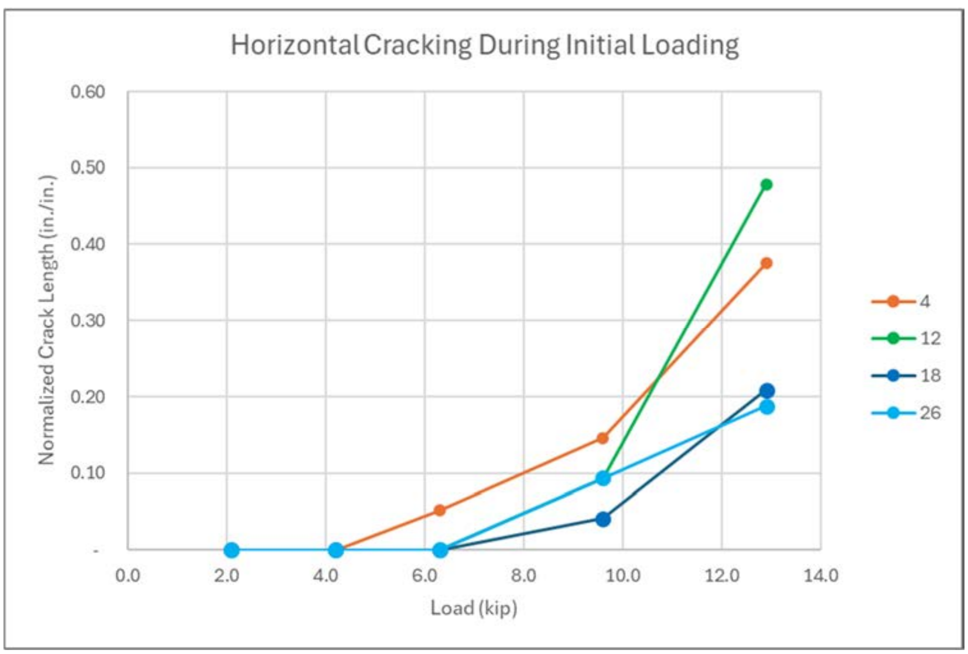


Figure 31. Examples of horizontal crack lengths at different load levels during initial loading. Specimens 4 (no anchor), 12 (screws with WWR), 18 (threaded rod U), and 26 (existing rebars)

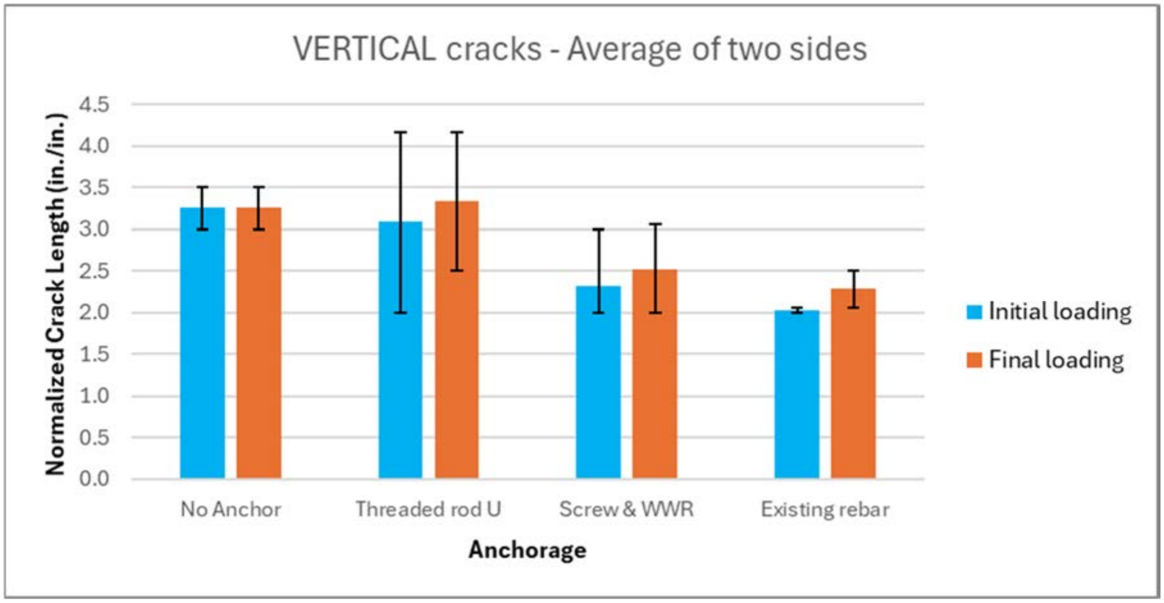


Figure 32. Normalized vertical crack length, average value for each anchorage type. Error bar indicates range of values.

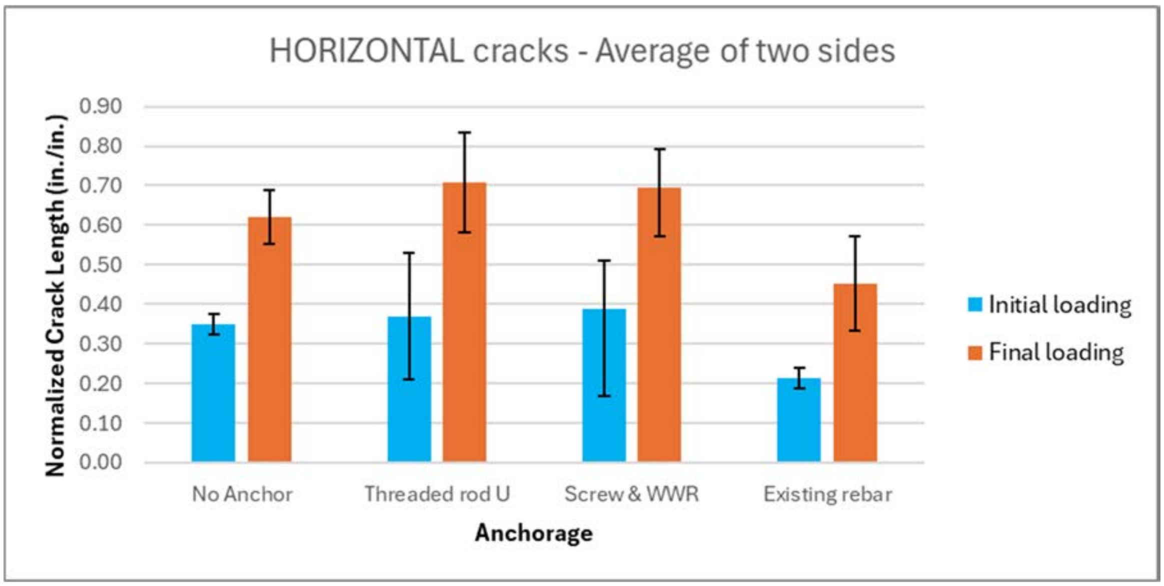
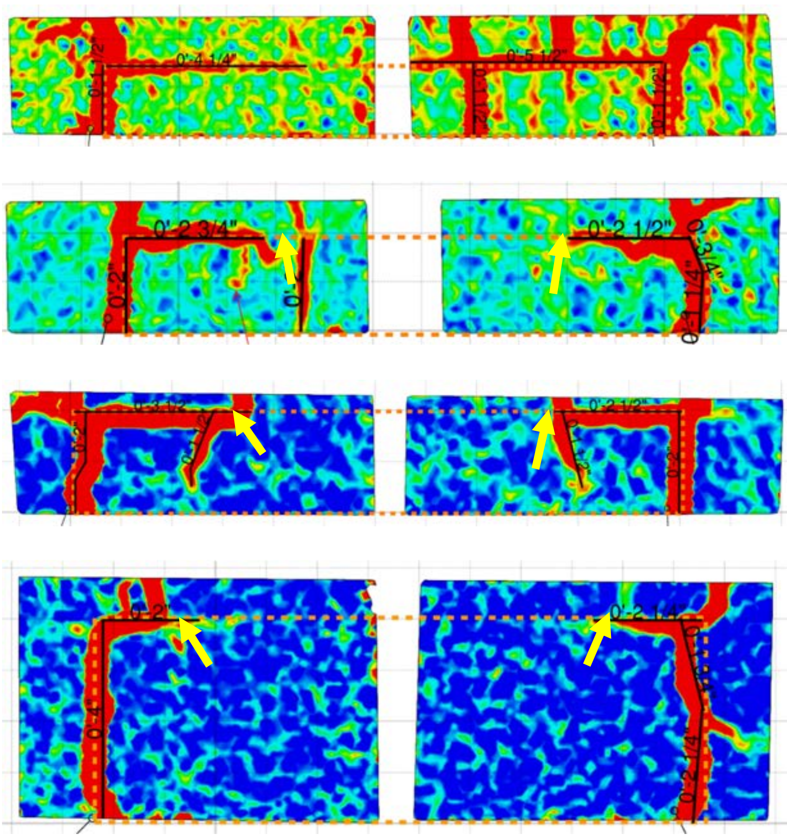


Figure 33. Normalized horizontal crack length, average value for each anchorage type. Error bar indicates range of values.



Specimen 14 – No Anchor; 1-1/2-inch patch

Specimen 18 – Threaded Rod U – 2-inch patch. Arrows indicate approx. locations of threaded rods at top of patch

Specimen 22 – Screws w/ WWR – 2-inch patch. Arrows indicate approx. locations of screw anchors top of patch

Specimen 26 – Existing Bars – 4-inch patch. Arrows indicate approx. locations of stirrups at top of patch

Figure 34. Examples of DIC images at 12.9 kips during final loading for specimens with different anchorage types. Black lines indicate cracks in and around patch. Note the restraining of horizontal crack propagation in specimens with anchors or stirrups crossing the interface.

4.3.3.5. Spall Conditions at End of Final Loading

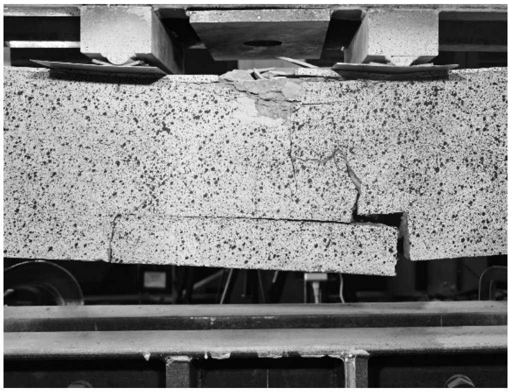
The spalling condition of each repair patch was qualitatively evaluated at the conclusion of final loading. Spall performance was assessed to evaluate the reliability of the repair, particularly for overhead applications where falling debris presents a safety concern. Each specimen was assigned a spall rating ranging from 1 to 5, corresponding to increasing spall area, as defined in Figure 35. Representative examples of each spall rating are shown in Figure 35. Spall ratings for all specimens are summarized in Table 8.

Observations are summarized as follows:

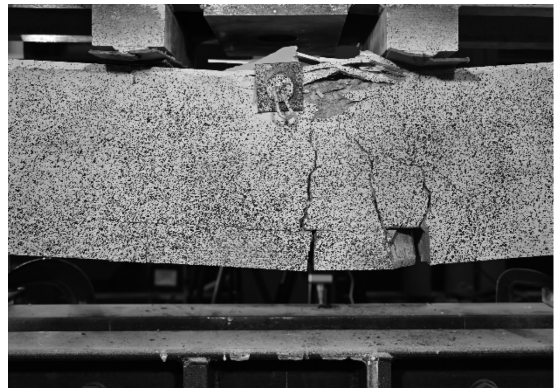
- Anchorage type had the most significant influence on spall performance.
- Patches anchored with either existing reinforcement or screw anchors with welded wire reinforcement (WWR) consistently achieved a spall rating of 1, with one exception (Specimen 29). In Specimen 29, localized spalling occurred at the end of the patch where a longitudinal reinforcing bar fractured.
- Patches anchored with threaded rod U exhibited spall ratings ranging from 1 to 4, indicating more variable performance.

- Patches without supplemental anchorage exhibited the highest spall severity, with ratings ranging from 4 to 5.

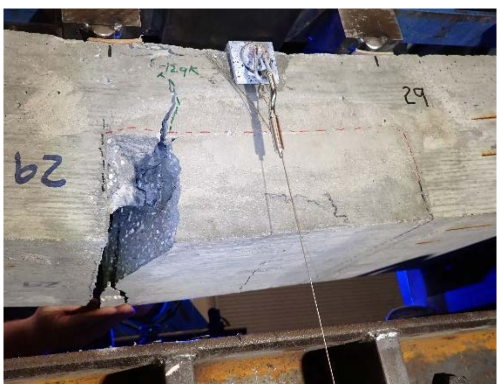
Rating 1 (Specimen 22)



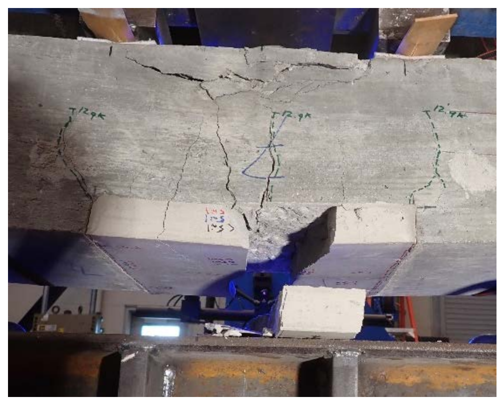
Rating 2 (Specimen 8)



Rating 3 (Specimen 29)



Rating 4 (Specimen 7)



Rating 5 (Specimen 14)

Patch spall rating	Patch spall area
1	<1%
2	1% - 5%
3	5% to 20%
4	20% to 50%
5	> 50%

Figure 35. Examples of spall condition ratings for patch at the end of the final loading

Table 8. Spall ratings of patch repair at end of final loading

Specimen ID	Sand Blasted?	Anchor type	Repair Orientation	Repair Material	Method	Spall rating
1	Blasted	No Anchor	Overhead	H1	Hand-applied	4
2	Blasted	No Anchor	Overhead	H1	Hand-applied	No final loading[1]
3	Blasted	No Anchor	Overhead	H2	Hand-applied	5
4	Blasted	No Anchor	Overhead	H2	Hand-applied	5
5	Blasted	Threaded rod U	Overhead	H1	Hand-applied	4
6	Blasted	Threaded rod U	Overhead	H1	Hand-applied	1
7	Blasted	Threaded rod U	Overhead	H2	Hand-applied	4
8	Blasted	Threaded rod U	Overhead	H2	Hand-applied	2
9	Blasted	Screw & WWR	Overhead	H1	Hand-applied	1
10	Blasted	Screw & WWR	Overhead	H1	Hand-applied	1
11	Blasted	Screw & WWR	Overhead	H2	Hand-applied	1
12	Blasted	Screw & WWR	Overhead	H2	Hand-applied	1
13	Not Blasted	No Anchor	Overhead	H1	Hand-applied	5
14	Not Blasted	No Anchor	Overhead	H1	Hand-applied	5
15	Not Blasted	No Anchor	Overhead	H2	Hand-applied	5
16	Blasted	No Anchor	Overhead	H2	Hand-applied	5
17	Blasted	Threaded rod U	Vertical	F1	Form & pour	4
18	Blasted	Threaded rod U	Vertical	F1	Form & pour	2
19	Blasted	Threaded rod U	Vertical	F2	Form & pour	2
20	Blasted	Threaded rod U	Vertical	F2	Form & pour	1
21	Blasted	Screw & WWR	Vertical	F1	Form & pour	1
22	Blasted	Screw & WWR	Vertical	F1	Form & pour	1
23	Blasted	Screw & WWR	Vertical	F2	Form & pour	1
24	Blasted	Screw & WWR	Vertical	F2	Form & pour	1
25	Blasted	Existing rebar	Vertical	F1	Form & pour	1
26	Blasted	Existing rebar	Vertical	F1	Form & pour	1
27	Blasted	Existing rebar	Vertical	F2	Form & pour	1
28	Blasted	Existing rebar	Vertical	F2	Form & pour	1
29	Blasted	Existing rebar	Overhead	F1	Form & pour	3
30	Blasted	Existing rebar	Overhead	F1	Form & pour	1
31	Blasted	Existing rebar	Overhead	F2	Form & pour	1
32	Blasted	Existing rebar	Overhead	F2	Form & pour	1

[1] Specimen failed during cyclic loading after both bottom longitudinal rebars fractured due to fatigue; hence, no final loading

4.4. Discussion and Conclusions

This section discusses the compatibility of the selected repair materials with the substrate concrete and the performance of the repair patches. The measured mechanical, thermal, shrinkage, and bond properties of the repair materials are compared with typical and recommended values reported in the literature, including the following documents:

- ACI PRC-546.3-23, Materials Selection for Concrete Repair—Guide.
- ACI PRC-546-23, Concrete Repair—Guide 210.3R-2022, Guide for Using In-Situ Tensile Pull-off Tests to Evaluate Concrete Surface Repairs and Bonded Overlays
- ACI RAP Bulletin 7 (2010), Field Guide to Concrete Repair Application Procedures, Spall Repair of Horizontal Concrete Surfaces
- FHWA FP-14 (2014), Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects

The potential influence of repair material properties on patch cracking performance due to volume change is discussed. In addition, patch performance in terms of cracking and spalling resistance under structural loading is evaluated.

4.4.1. Repair Materials Properties

Compressive Strength

Typical 28-day compressive strengths for concrete repair materials range from 3,000 to 10,000 psi for ASTM C39 cylinders and from 4,000 to 12,000 psi for ASTM C109 cubes. ACI PRC-546.3 recommends that repair material compressive strength be similar to that of the substrate concrete.

The repair materials evaluated in this study fell within the typical ranges and were generally comparable to the substrate concrete strength, consistent with ACI recommendations.

Modulus of Elasticity (MOE)

Typical MOE values for concrete repair materials range from approximately 1,000,000 to 5,500,000 psi. For non-structural repairs, ACI PRC-546.3 recommends that the repair material have a lower MOE than the substrate to better accommodate movements within the repair and at the repair–substrate interface.

Measured MOE values of the repair materials in this study were within the typical range and overall were generally consistent with ACI guidance. Three of the four materials had MOE values similar to that of the substrate concrete (within approximately 10%), and the MOE of the fourth material (H1) was approximately 37% lower than that of the substrate.

Coefficient of Thermal Expansion (CoTE)

The CoTE for concrete typically ranges from 2 to 8 × 10^{-6}/°F, depending primarily on the aggregate type and content. ACI PRC-546.3 recommends that the CoTE of repair material be similar to that of the substrate concrete, so the two materials behave similarly under daily and seasonal temperature variations.

The repair materials in this study had CoTE values ranging from 7.3 to 8.6 × 10^{-6}/°F, compared to 5.6 × 10^{-6}/°F for the substrate. The higher CoTE values are consistent with the absence of coarse aggregate in the hand-applied repair materials and the lower coarse aggregate content of the two form-and-pour repair materials, as cement paste generally exhibits a higher thermal expansion coefficient than aggregate.

Drying Shrinkage

Typical drying shrinkage values range from +0.02% (expansion) to -0.12% (shrinkage) for concrete repair materials tested per ASTM C157, depending primarily on storage condition, and -0.05% to -0.15% (shrinkage) for mortar repair materials tested per ASTM C596. ACI PRC-546.3 recommends that ultimate mortar drying shrinkage be less than 0.10% (i.e., strain values less negative than -0.10%) but does not provide a recommended value for concrete repair materials.

The estimated ultimate drying shrinkage strains of the repair materials varied from 0.042% to 0.157%, which fell within or near the typical ranges. It should be noted that ASTM C157 includes 27-day wet curing and ASTM C596 includes a 48-hour limewater immersion prior to air storage, whereas the procedure used in this study (based on ACI PRC-364.3-22/ICRI 320.3R-22) were based on shorter wet curing periods. The curing procedures in ASTM C157 and ASTM C596 would likely result in lower measured drying shrinkage strains than those reported in this study.

4.4.2. Bond Strength

Typical tensile bond strengths measured in accordance with ASTM C1583 for concrete repair materials installed against a sound and well-prepared concrete substrate range from 250 to 300 psi. ICRI 210.3R indicates typical minimum bond strength requirements of 150 to 175 psi. ACI RAP-7 recommends a minimum tensile bond strength of at least 150 psi for horizontal spall repairs. FHWA FP-14 specifies a minimum average tensile bond strength of 150 psi at 14 days for latex-modified and high-performance concrete overlays on bridge decks. Bond strengths below 100 psi may indicate a bond deficiency.

Measured bond strengths in this study, as the average of three samples for each condition, ranged from 83 to 245 psi. These values are generally lower than the typical range of 200 to 300 psi cited in ACI PRC-546.3. One contributing factor is that repairs were installed in vertical and overhead orientations, whereas literature values are commonly obtained from horizontal applications. In horizontal applications, the weight of the repair material improves contact at the repair–substrate interface, and air entrapment is less likely. In contrast, vertical and overhead placements into closed forms increase the potential for voids at the interface, which can reduce effective bond strength.

Despite these challenges, the average bond strengths for most conditions evaluated in this research exceeded 150 psi, except as discussed below.

For form-and-pour repairs installed in the overhead orientation in this study, the samples separated at the repair-substrate interface during coring, and extensive voids or gaps within the repair material paste at the interface were observed at the repair–substrate interface. This occurred despite the use of a bird’s mouth extending approximately 2 inches above the top surface of the repair and intentionally unsealed gaps between the formwork and substrate to facilitate air escape. In addition, the contractor repeatedly tapped the formwork with a hammer during placement to promote consolidation. These results suggest that overhead form-and-pour repairs present a risk of voids or gaps at the interface which could result in bond deficiencies at the horizontal interface, even when installed by an experienced contractor. Potential methods to reduce this risk include incorporating more than one placement opening (bird’s mouth), vent holes in the formwork and increasing placement head or using a flowable concrete repair material that is not self-consolidating and can be vibrated. In addition, the SCC repair material appeared to have air voids in the upper layer of paste at the interface which are likely related to the trapped air or hydration of the

SCC concrete. Additional study is needed to evaluate the effectiveness of these methods and the air voids in the material at the interface.

As shown in Table 5, H2 non-sandblasted specimens exhibited low bond strength (average 83 psi), representing a 53% reduction compared to sandblasted specimens (average 177 psi). For comparison, H1 non-sandblasted specimens exhibited similar bond strength compared to sandblasted specimens (average 233 psi and 245 psi, respectively), indicating potentially lower sensitivity to surface preparation. It is worth noting that per the product datasheets, H1 is a polymer-modified repair material, whereas H2 is not. The polymer in the repair material may be contributing to improving bond strength although additional testing would be needed to verify.

4.4.3. Effect of Materials Properties on Cracking Due to Volume Change

Cracking was observed in the repair patches during laboratory storage as the specimens dried and during thermal testing. The mechanisms contributing to cracking due to volume change are discussed below to facilitate interpretation of the observed behavior.

Cracking observed prior to thermal testing is attributed primarily to drying shrinkage. At the time of patch installation, the substrate concrete was approximately 6 to 7 weeks old and had already undergone substantial drying shrinkage. Thus, the repair patches tended to shrink more than the substrate during the storage period (approximately 5 to 7 months). However, this shrinkage was restrained by bond at the repair–substrate interface and by mechanical anchorage and reinforcement, where present. This restraint generated elastic tensile strain within the repair material to offset the shrinkage strain. The resulting tensile strain produced tensile stress in the repair material, with higher stress expected in materials with higher modulus of elasticity. When the tensile stress exceeded the tensile capacity (i.e. strength) of the repair material, cracking occurred.

During thermal cycling, a similar cracking mechanism was present. As temperature decreased during each cycle, the repair materials tended to contract more than the substrate concrete due to their higher coefficients of thermal expansion. This differential contraction was restrained at the interface and by reinforcement, resulting in tensile stresses within the patch and subsequent cracking.

Material properties and cracking data are summarized in Table 9 to facilitate discussion.

Table 9. Materials Properties and Cracking Due to Volume Change

Material	28-day Compressive Strength (psi)	28-day Splitting Tensile Strength (psi) from product datasheets	28-day MOE (psi)	CoTE ($\times10^{-6}$/°F)	Ultimate Shrinkage Strain (%)	Cracking Density (in/in^2) BEFORE thermal cycling	Cracking Density (in/in^2) AFTER thermal cycling
Substrate	6,310	--	4,725,000	5.6	0.051	--	--
Repair H1	6,110	900	2,962,500	8.6	0.042	0.01	0.18
Repair H2	6,980	Not available	4,200,000	7.8	0.074	0.14	0.31
Repair F1	6,510	1,000	4,700,000	7.3	0.103	0.08	0.13
Repair F2	7,320	500	5,212,500	7.6	0.157	0.11	0.15

Notes: For each parameter, a color scale from red to green was applied to show relative magnitude. Red indicates least favorable to anticipated repair performance and green indicates most favorable to anticipated repair performance.

Cracking Prior to Thermal Cycling

As shown in Table 9, prior to thermal cycling, H1 specimens exhibited minimal cracking, consistent with their relatively low measured drying shrinkage and lower MOE. Repair material F1 exhibited less cracking than F2, which appears consistent with its lower shrinkage and MOE values.

H2 specimens exhibited more cracking than the two form-and-pour materials, despite having moderate shrinkage and MOE values in standard laboratory testing. This suggests that additional factors, such as patch geometry and tensile capacity, may influence cracking behavior of the H2 repair material. All hand-applied patches were 1-1/2 inches thick (except for two specimens), resulting in a volume-to-surface area ratio (V/A) of 1.2 inches. The two thicker specimens were also longer, which resulted in a similar V/A ratio. In contrast, the form-and-pour patches had V/A values of 1.5 inches (2-inch thickness) and 2.4 inches (4-inch thickness). Both the rate and ultimate magnitude of shrinkage are generally higher for elements with lower V/A ratios. Therefore, the lower V/A ratio of the H2 specimens may have contributed to greater shrinkage-induced cracking relative to the thicker form-and-pour repairs.

Product data sheets indicate 28-day splitting tensile strengths of 900 psi for H1, 1,000 psi for F1, and 500 psi for F2. However, flexural and tensile strength data for H2 were not available. Therefore, the potential influence of tensile strength on the cracking behavior of H2 relative to the other materials could not be evaluated.

Cracking Under Thermal Cycling

During thermal cycling, most specimens exhibited additional cracking, and the average crack density for each repair material increased. This behavior is consistent with the measured CoTE values of all repair materials being greater than that of the substrate concrete, resulting in differential thermal movement between the patch and substrate.

As shown in Table 9, both H1 and H2 specimens experienced a greater increase in cracking relative to the form-and-pour materials, suggesting that higher CoTE values may have contributed to the increased cracking under temperature variation. Overall, H2 specimens exhibited more cracking compared to the other materials.

Although crack lengths increased in most specimens after thermal cycling, no appreciable crack widening was observed, and crack widths measured at room temperature (approximately 70°F) generally remained tight (less than approximately 0.005 inches).

4.4.4. Repair Performance Under Structural Loading

Repair performance under structural loading was evaluated based on cracking behavior and spalling resistance. Cracking within the patch or along the repair–substrate interface may allow moisture and chloride access into the repair, substrate concrete, and embedded reinforcement, potentially leading to freeze-thaw damage and corrosion-induced deterioration. In addition, spalling of repair patches, particularly in overhead applications, presents a safety concern for vehicular and pedestrian traffic.

Cracking Due to Structural Loading

Cracking under monotonic and cyclic loadings was influenced more strongly by anchorage configuration and reinforcement than by repair material type. Specimens encompassing existing reinforcing bars or incorporating supplemental welded wire reinforcement (WWR) fastened with screw anchors cracked at the edges of the patches but exhibited less vertical cracking within the patch.

Horizontal interface cracking occurred in most specimens but was less in patches that encompassed existing reinforcement. As previously discussed, existing reinforcing bars crossing the repair–substrate interface likely provided restraint against crack propagation. Supplemental anchors, including threaded rod U anchors and screw anchors, restrained horizontal cracking along the interface in some specimens; however, their effect was not consistent across all cases.

Spalling of Repair Patches

All patches of the beam specimens remained attached during the initial monotonic loadings and cyclic loading, even in cases where reinforcing bars fractured.

Spalling was evaluated during final loading to structural failure. While it is not expected that repair patches remain intact as the structural member approaches failure, this evaluation provides insight into relative resistance to detachment. In practice, repair patch spalling may result from other mechanisms such as corrosion and cyclic freezing and thawing.

Anchorage and reinforcement had a clear influence on spall resistance:

- Specimens encompassing existing reinforcement or incorporating screw anchors with WWR remained attached with minimal spalling.
- Threaded rod U anchors reduced spalling in some specimens but were more variable in performance. Combining WWR with threaded rod U anchors would likely improve spall resistance.
- Patches without supplemental anchorage were prone to spalling, and in many cases, final loading caused the entire patch to fall out of the flexural beam specimen.

4.4.5. Conclusions

Based on the results of this laboratory study, the following conclusions are drawn:

- Four established repair materials were evaluated as part of this study. These materials varied widely, particularly in terms of shrinkage and modulus of elasticity, but had generally similar compressive strength and CoTE. Repair materials with lower drying shrinkage, lower MOE, and CoTE values closer to that of the substrate exhibited less tendency for cracking.
- Surface preparation through sandblasting improved bond performance for both of the tested repair materials although not significantly for H1, which is a is a polymer-modified repair material. Sensitivity to surface preparation varied between the hand-applied repair materials.
- The configuration of repair patches encompassing existing reinforcing bars was the most effective of the tested configurations at controlling cracking and spalling. In practice, removal of concrete around reinforcing steel in corrosion-related repairs has the added benefit of eliminating the chloride contamination at the bar surface, thereby delaying the onset of additional corrosion.
- When existing reinforcement cannot be encompassed within the repair, screw anchors with WWR tied to the anchors were also generally effective in reducing cracking and spalling and relatively simple to install. Threaded rod U anchors embedded with epoxy adhesive, used in conjunction with WWR, may

also be effective. However, installation of epoxy-embedded anchors requires additional time for cleaning drilled holes, installing the anchors, and allowing the epoxy adhesive to cure. In addition, the quality of epoxy-embedded anchors is sensitive to installation orientation, and achieving consistent installation quality can be particularly challenging for overhead applications.

- For overhead repairs, obtaining a sound bond between the patch and original concrete is inherently more challenging than in vertical or horizontal repairs. In particular, overhead form-and-pour repairs present a risk of voiding resulting in bond deficiencies at the repair–substrate interface due to the potential for air entrapment and reduced consolidation as gravity pulls the material away from the substrate. Accordingly, incorporation of mechanical anchorage or reinforcement crossing the interface is strongly recommended to reduce the likelihood of debonding and spalling. Potential measures to reduce air entrapment and improve bond include incorporating more than one placement opening (bird's mouth), providing vent holes in the formwork, and increasing the pressure head; however, additional study is needed to evaluate the effectiveness and practicality of these methods, and their effectiveness is likely to vary by material, repair configuration, and placement conditions. Using flowable concrete that can be vibrated may also reduce the risk of voids at the interface.

5. RECOMMENDATIONS

This section presents recommendations for vertical and overhead (VOH) concrete repairs in Wisconsin, developed based on the literature review, evaluation of current WisDOT practices, WJE's experience, and findings from the laboratory program. Recommendations are provided for:

- Repair strategies for VOH concrete repairs
- Materials specifications and repair procedures for VOH concrete patches

5.1. Repair Strategies for VOH concrete repairs

The following repair strategies were evaluated:

- Coating spalled area of concrete without patching
- Hand-applied patching
- Form-and-pour patching
- Non-structural FRP wraps in addition to patching
- Shotcrete

5.1.1. Coating Exposed Reinforcement Without Patching

Coating the spalled concrete and exposed reinforcing steel without patching has been used by WisDOT and some other agencies as an interim risk-reduction measure rather than a long-term repair. This approach may temporarily reduce moisture intrusion, provide limited corrosion mitigation (if a zinc-rich coating is used), and slow further deterioration in limited situations; however, it does not address the underlying deterioration mechanism when chloride contamination and reinforcement corrosion are present and may only conceal ongoing deterioration.

Recommendations:

- Apply coatings without patching only as temporary measure for limited spalled conditions with the intent to patch as soon as practical.
- Applying coating without patching is most appropriate for small, shallow spalls where the concrete distress is primarily physical (e.g., impact damage) rather than spalling due to corrosion-driven section loss of reinforcing steel.
- Surface preparation: Remove loose concrete, debris, and corrosion products to the extent practical. At minimum, clean exposed reinforcement to remove loose rust and clean the adjacent concrete surface using wire brush.
- Materials: Use coating materials suitable for field application on bridges (e.g., epoxy or zinc-rich primers) and follow manufacturer requirements for surface condition and thickness.

5.1.2. Concrete Patching Repair

Concrete patching is WisDOT's primary approach for most non-structural VOH concrete repairs. Two primary patching methods are commonly used and are discussed in this section: (1) hand-applied patching and (2) form-and-pour patching.

5.1.2.1. Hand-applied Repair

Hand-applied (trowel-applied) patches are widely used for smaller repairs, particularly where access for formwork is challenging. WisDOT's experience indicates mixed performance for hand-applied repairs, depending on material selection, installation conditions, and workmanship.

Hand-applied repair materials typically have relatively short working times. As a result, the quality of hand-applied repairs is more variable and sensitive to workmanship and environmental conditions during installation than typical form-and-pour patches. In addition, due to the lack of coarse aggregate, hand-applied materials typically have higher coefficients of thermal expansion and are less able to resist paste-related drying shrinkage relative to form-and-pour materials, and thus hand-applied repair materials are more prone to cracking in service due to volume changes. Most hand-applied repair materials have a maximum lift thickness of approximately 1½ to 2 inches. When multiple lifts are used, achieving adequate bond between lifts is difficult under field conditions. For these reasons, hand-applied patching should be limited to small, shallow repairs that can be placed in a single lift.

Recommendations:

- Hand-applied patching should be limited to small repairs with a maximum depth of 2 inches and a surface area not exceeding 2 square feet.
- All hand-applied patches should be mechanically anchored to the substrate concrete with physical anchors and not rely solely on adhesive bond.

A curing compound should be applied to hand-applied patches to minimize cracking.

5.1.2.2. Form-and-pour Repair

Form-and-pour is an established repair method that is generally more durable than hand-applied patching, particularly for larger repairs. Formed placement is typically less dependent on workmanship and weather conditions. Placement of material in a form-and-pour repair is more uniform and less time-consuming. Form-and-pour patches generally perform better long-term, since the material can incorporate coarse aggregates and be more dimensionally stable.

Recommendations:

- Form-and-pour patching is preferred over hand-applied patching when access allows installation of formwork, particularly for thicker and/or larger repair cavities.
- Form-and-pour materials should be pre-extended with coarse aggregate which can provide consistent uniformity and ensure quality coarse aggregate. In addition, batching form and pour materials with pre-extended coarse aggregate is simpler.
- Overhead formed placements present a risk of air entrapment and bond deficiencies at the repair–substrate interface. Measures to reduce entrapped air and improve consolidation of material at the bond interface, along with the use of anchorage crossing the interface, are recommended. Installation quality should be verified. Additional discussion of anchorage and installation details is provided in subsequent sections.

5.1.2.3. Anchorage

Anchorage approaches include mechanical anchors, dowels, supplemental reinforcement (e.g., welded wire reinforcement, WWR), and/or repair configurations that engage existing reinforcing steel.

WJE laboratory testing demonstrated that anchorage configuration had a strong influence on spall resistance and may also influence cracking behavior by restraining crack propagation. Repairs incorporating reinforcement or anchorage crossing the repair–substrate interface exhibited significantly improved resistance to spalling under structural loading.

These findings should be interpreted recognizing that other long-term deterioration mechanisms (e.g., freeze–thaw cycling and corrosion progression) were not evaluated in the laboratory program.

Recommendations:

- When feasible, repairs should encompass existing reinforcement, as this generally provides the best resistance to spalling and improved crack control. In corrosion-related repairs, removal of concrete around reinforcing steel also helps remove chloride-contaminated concrete at the bar surface, which may delay the onset of further corrosion.
- When existing reinforcement cannot be encompassed within the repair, supplemental anchors and reinforcement are recommended. The type of anchorage should be selected based on repair size and geometry.
    - For repairs less than 3 inches deep, 1/4-inch diameter screw anchors with tied-in WWR similar to those used in the laboratory program are recommended based on constructability and demonstrated spall resistance.

- For deeper repairs, a larger anchor system is recommended using epoxy-embedded hooked dowel bars (No. 3 or No. 4), in conjunction with WWR or reinforcing bars. Other alternatives could include expansion anchors, screw anchors, and epoxy-embedded threaded rods.

5.1.3. Non-structural FRP wraps

Non-structural FRP wraps have been used in Wisconsin and other states for repairs over traffic to provide containment and reduce the hazard associated with falling debris. Additional potential benefits include the wrap providing a barrier to water and chlorides. However, FRP systems may also trap moisture under certain conditions if detailing is not carefully managed, and this may be detrimental to durability. FRP installation also increases both repair cost and construction time and requires specialized expertise.

Published literature providing quantitative benefit-to-cost comparisons for FRP as non-structural containment for VOH patches is limited.

Results from the laboratory investigation indicate that minor-to-intermediate patches incorporating anchorage, either by encompassing existing reinforcement or through supplemental screw anchors with welded wire reinforcement, can provide adequate resistance to cracking and spalling. Based on these findings and WJE experience, non-structural FRP wraps are generally not necessary for containment of minor-to-intermediate patches when repairs are properly installed using appropriate materials, surface preparation, and anchorage/reinforcement.

FRP wraps may be considered for special cases, including:

- Bridges with a higher risk of repeated impacts from over-height vehicles or where the consequences of falling debris are particularly high.
- Locations with extreme exposure conditions that may increase susceptibility to repeated corrosion-related damage.
- Repairs with complex geometries where it may be difficult to remove all unsound concrete and/or install effective anchorage and reinforcement.

5.1.4. Shotcrete

Shotcrete has been used in Wisconsin for larger overhead repairs. Short-term performance has been mixed in some reported cases (including early failures), and long-term performance data within Wisconsin practice are limited. However, shotcrete is widely used by other agencies, and published literature and our experience indicate that shotcrete can produce durable repairs when properly specified and installed.

Shotcrete placement requires specialized equipment and an experienced contractor/nozzleman. Repair quality is highly dependent on surface preparation and workmanship.

Shotcrete is most suitable for larger overhead repairs, particularly where:

- Repair areas are too large for reliable installation using hand-applied materials.
- Access constraints and/or time sensitivity make installing and subsequently removing formwork difficult.
- Achieving full consolidation with formed placement is challenging.

Key implementation recommendations:

- Surface preparation is critical, including removal to sound substrate, appropriate surface roughening, and cleaning of substrate concrete and reinforcement. When existing reinforcement cannot be encompassed within the repair, supplemental anchors and reinforcement are needed.
- Shotcrete must be performed by an experienced and qualified contractor, including an ACI-certified shotcrete nozzleman.
- Shotcrete construction should conform to ACI 506.2 – Specification for Shotcrete, including construction and testing of test panels prior to production work.

5.2. Recommendations on Concrete Patching Repairs

This section provides: 1) recommendations for repair materials properties requirements and approval process and 2) guidance on installation procedures for VOH repairs. Shotcrete repair procedures and FRP installation procedures are not discussed further in this report.

5.2.1. Recommendations on VOH Repair Material Requirements and Approval Process

WisDOT has issued a document titled *Approved Product List Application Process for VOH Repair Material* (dated April 14, 2025) and an associated approved product list (APL) for VOH repair materials (dated December 18, 2025).

The approval process requires manufacturers to submit technical and safety data sheets, test data from an independent qualified laboratory, and manufacturer installation instructions that describe surface preparation, bonding, and curing requirements for the product seeking approval. The test data must demonstrate that the repair material satisfies the material property requirements outlined in the WisDOT document.

This section presents WJE's recommended revisions to the material property requirements and approval process to better ensure compatibility and long-term performance of approved repair materials. Requirements for VOH repair materials and the approval process, written in a format consistent with WisDOT specifications, are provided in Appendix D.

5.2.1.1. Repair Material Property Requirements

WisDOT's VOH Repair Material Test Requirements include compressive strength, freeze-thaw durability, length change (shrinkage and expansion), bond strength in direct tension, slant shear bond strength, and rapid chloride permeability.

Based on the literature review and WJE experience, recommended material property requirements for patching repair materials are presented in Table 10, and important material properties are discussed in this section. Recommended revisions to WisDOT's VOH Repair Material Test Requirements include the following:

- Reduce the maximum permitted shrinkage and expansion limits and reference modified testing procedures described in ACI PRC-364.3/ICRI 320.3R. These procedures apply to a broader range of repair materials than ASTM C928, which is primarily intended for rapid-hardening repair materials.
- Increase the required compressive strength.

- Add splitting tensile strength requirements.
- Incorporate bond strength in direct tension into the WisDOT Mockup Program (see Section 5.2.1.2)

The primary references used in developing these recommendations include the following:

- ACI's Guide on Materials Selection for Concrete Repair (ACI PRC-546.3-23, 2023)
- TxDOT Concrete Repair Materials (DMS-4655, December 2023)
- WisDOT Qualified Products for VOH Repairs (December 2025)

Volume Stability

Volume stability properties affect the compatibility of the repair material with the substrate concrete. Substrate concrete is typically mature and relatively stable, with minimal residual shrinkage expected after the repair is installed. Repair materials, however, may experience volume changes due to drying shrinkage and thermal movements associated with seasonal environmental variations. Significant differences in volume change behavior between the repair material and the substrate concrete can lead to cracking or debonding.

- **Shrinkage/Expansion.** Repair materials should exhibit low drying shrinkage and not undergo excessive expansion under wet exposure. Shrinkage and expansion of repair materials are recommended to be evaluated using ASTM C157, with modifications described in ACI PRC 364.3/ICRI 320.3R to better capture the early-age behavior of repair materials. In particular, the curing regimen for air-stored specimens in ACI PRC 364.3/ICRI 320.3R is modified from ASTM C157 to eliminate the 27 days of moist-curing between the first comparator reading and subsequent readings, allowing the specimens to be stored directly in air after demolding. This modification provides a more realistic representation of the early-age shrinkage experienced by repair materials in field applications. The expansion is measured for specimens stored in water and is intended to assess the risk of excessive expansion that can occur from ettringite, calcium oxide, or magnesium oxide-driven reactions. Further, some repair materials (particularly hand-applied products) may be blended with gypsum or some form of calcium sulfate that assists in the material setting up quickly. Some calcium sulfate is necessary to control the rate of hydration of cementitious components of the repair material. However, if all the gypsum is not reacted after initial mixing, unreacted gypsum in the hardened repair material can react later with exposure to moisture and result in after-hardening expansion and cracking of the repair. Some contribution of this expansion mechanism will be captured in the dimensional changes in the water-stored specimens.
- **Coefficient of thermal expansion (CoTE).** Repair materials should have a coefficient of thermal expansion similar to that of the substrate concrete so that both materials respond similarly to daily and seasonal temperature variations. This helps minimize differential strains caused by temperature changes and reduces the risk of cracking or debonding at the repair interface. Typical CoTE values of structural concrete tested in accordance with AASHTO T336 range from 4 to 8 x 10^{-6}/°F at 28 days. However, WJE does not recommend specific acceptance limits for CoTE of repair materials, as this property should be evaluated in conjunction with other material properties.
- **Modulus of elasticity (MOE).** It is desirable to use repair materials that have a modulus of elasticity similar to or lower than that of the substrate concrete. A lower or comparable MOE helps reduce stresses caused by restrained contraction and expansion associated with drying shrinkage and

temperature changes. Typical MOE values of structural concrete tested in accordance with ASTM C469 range from 3,000 to 6,000 ksi at 28 days. However, WJE does not recommend specific acceptance limits for MOE of repair materials, as this property should be evaluated in conjunction with other material properties.

Compressive strength and splitting tensile strength. Compressive and tensile strengths are normally not the limiting properties in the performance of repair materials but may serve as indicators of the material quality. In most cases, it is desirable for compressive strength of repair material to be comparable to that of the substrate concrete. Repair materials with higher tensile strength may resist cracking caused by restrained shrinkage and thermal contraction, but higher strength may be associated with greater shrinkage and higher modulus, which may exacerbate the factors that cause cracking.

Bond strength. Bond strength between the repair material and the existing concrete is a critical performance parameter. Two common test methods for bond strength are ASTM C1583 (tensile pull-off) and ASTM C882 (slant shear). Based on ACI PRC-546.3, the ASTM C1583 pull-off test is considered more appropriate for repair applications than slant-shear testing (ASTM C882) because it applies direct tension at the bond interface and better represents the bond condition at the repair–substrate interface. In contrast, the slant shear tests are highly dependent on the compressive strength of the substrate concrete and the surface profile (particularly the profile depth) achieved during sample preparation. Therefore, while slant-shear strength values are recommended in Table 10 as a baseline screening requirement, pull-off tensile testing is recommended as part of the WisDOT Mockup Program described in Section 5.2.1.2.

Freeze–thaw durability and rapid chloride permeability. The recommended test values for freeze–thaw durability and rapid chloride permeability shown in Table 10 are consistent with WisDOT's current requirements for VOH repair materials. These properties are important to ensure adequate resistance to freeze–thaw cycles and chloride ingress for bridge repairs exposed to Wisconsin environmental conditions.

Table 10. WJE Recommended Requirements for VOH Repair Materials for Non-structural Repairs

Property/Performance Criterion	Test Method	Requirement[1]
Drying shrinkage and Expansion	ASTM C157, modified per ACI PRC-364.3-22.	Maximum shrinkage: 0.07% at 28 days Maximum expansion: 0.05% at 28 days
Compressive strength	Concrete or extended mortar: ASTM C39. Mortar: ASTM C109.	≥ 4,500 psi at 28 days
Splitting tensile strength	ASTM C496/C496M	≥ 400 psi at 28 days
Freeze-thaw durability	ASTM C666 Procedure A	Durability factor ≥ 90 at 300 cycles
Rapid chloride permeability	ASTM C1202	Charge passed ≤ 2,000 Coulombs
Bond strength	ASTM C882, modified per ASTM C928	≥1,000 psi at 1 day ≥ 1,500 psi at 7 days

[1] Based on average of a minimum of three specimens unless otherwise defined by the test standards

5.2.1.2. Approval Process

WisDOT's APL approval process requires manufacturers to submit technical and safety data sheets, test data from an independent qualified laboratory, and manufacturer installation instructions that describe surface preparation, bonding, and curing requirements for the product seeking approval.

In addition to these requirements, WJE recommends that the approval process include the following:

- A mockup program to evaluate installation and bond performance.
- Submission of documented field performance records for candidate products.
- A letter from the manufacturer regarding the sulfate content in the repair material.

Additional details regarding these recommendations are discussed below.

WisDOT Mockup Program

Because VOH repairs are highly sensitive to installation orientation and constructability, a prequalification mockup program is recommended. For larger repair projects, it is common industry practice to include field mockups as part of the project to demonstrate that the contractor's methods and materials are suitable for the application. However, performing a mockup for every routine small project is not practical. Accordingly, it is proposed that a prequalification mockup program be conducted by the material supplier and overseen and evaluated by WisDOT. This mockup is intended to assess the constructability and performance of the repair material installed in vertical and overhead orientations in a manner representative of typical WisDOT repair conditions. While this program is expected to improve the reliability of VOH repair approval, it would introduce additional cost and effort to the material approval process. Therefore, the feasibility and implementation of such a program should be evaluated.

Recommended requirements for the mockup program include the following elements:

- Substrate: substrate should be cast using a concrete mixture meeting requirements of WisDOT Grade A, Class 1 concrete (Standard Specifications sections 501.3.2.2.2 and 715.2.2.2) with the following properties:
  - Compressive strength: 4,000 to 6,000 psi at 28 days
  - Cementitious materials: 565 lb/cy minimum
  - Supplementary cementitious materials (SCMs): 15 to 30 percent replacement by weight of total cementitious materials with SCMs complying with WisDOT requirements
  - Air content: 6±1.5%
  - Water–cementitious materials ratio (w/cm): 0.40 to 0.45
- Installation:
  - Prepare clean and sound substrate surface in accordance with the product data sheets.
  - Sandblast the concrete substrate followed by air blasting. These methods provide the most consistent surface for achieving adequate bonding of repair material to the substrate based on our experience and the testing program.
  - Each repair material should be installed in the orientation(s) that the manufacturer indicates is appropriate for their material (i.e. in both vertical and overhead orientations or in just one orientation), using the intended repair method (i.e., hand-applied and/or form-and-pour methods, as applicable).

  - The repair area should be 1 ft x 1 ft minimum. For hand-applied materials, the repair depth should be the maximum lift thickness recommended by the manufacturer. For form-and-pour materials, the repair depth should be 2 inches.
  - The material should be mixed, installed, and cured in accordance with the manufacturer's recommendations.
  - The mockup installation should be thoroughly documented, including substrate surface preparation; batch weights, mixing, installation and curing procedures; and photos of substrate before installation and of repair after finishing and after curing.
- Inspection:
  - Inspect the mockup repairs for cracking, delamination, or debonding of the repair material using the sounding method in accordance with ASTM C4580. Any cracks wider than 0.010 inch shall be considered unacceptable. Any identified delaminated area should be investigated through coring (see below).
  - Perform pull-off testing on each mockup repair in accordance with ASTM C1583. Acceptance criteria should meet the following requirements:
    - Minimum five tests per installation orientation.
    - Average bond strength ≥ 150 psi.
    - Individual test value ≥ 120 psi.
  - Published literature commonly reports pull-off bond strengths in the range of 200 to 300 psi; however, these values are generally based on horizontal repairs. Achieving similar values for vertical and overhead repairs can be more challenging due to installation constraints. Therefore, a minimum average bond strength of 150 psi is recommended for APL approval. For structural repairs, bond strength requirements should be evaluated by the Engineer of Record on a case-by-case basis.
  - Obtain two cores through the repair and substrate for visual inspection. Core locations will be selected by WisDOT. The presence of voids or irregularities at the repair–substrate interface or within the repair material that may adversely affect bond shall be considered grounds for rejection.
- Documentation:
  - Upon completion of the mockup program, provide WisDOT with a report documenting the mockup installation procedures and inspection results.
- WisDOT mockup witness:
  - WisDOT will witness the mockup installation, sounding inspection, and pull-off testing, and will select the locations for coring. The manufacturer shall provide advance notice to allow a WisDOT representative to observe these activities.

Performance Records

To reduce the risk of poor-performing repair strategies, documentation of field performance is also required. Documentation of field performance should be submitted by the repair material manufacturer to demonstrate a minimum of five years of successful use on a minimum of five projects of the repair materials in vertical and overhead repair conditions on bridge projects.

Letter On Sulfate Content

The manufacturer shall provide a letter identifying the maximum total sulfate content of the cementitious portion of the product, expressed as a percentage of SO_3 (sulfur trioxide), and stating that the product does not contain substances that are reactive in amounts sufficient to cause deleterious expansion of the concrete.

5.2.2. Guidance for Installation of VOH Repairs

Current WisDOT repair procedures in Section 509.3 of the Standard Specifications are primarily intended for horizontal repairs. Therefore, repair procedures specifically addressing vertical and overhead repairs are recommended as follows. The recommendations in this section are also provided in Appendix E, which may be used as a repair guide for WisDOT maintenance personnel.

5.2.2.1. Patch Geometry, Anchorage, and Reinforcement

- Use rectangular patch geometry where feasible and avoid reentrant corners.
- Whenever practical, repairs should encompass existing reinforcement.
- When repairs cannot encompass existing reinforcement, provide supplemental anchorage and reinforcement crossing the repair–substrate interface:
  - Repairs less than 3 inches deep: Provide screw anchors with welded wire reinforcement (WWR). The following details may be used:
    - ¼-inch diameter concrete screw anchors; stainless steel anchors are recommended for improved corrosion resistance; Maximum anchor spacing: 6 inches on center in both directions
    - WWR: 4 x 4 inches, D4.0 x D4.0 or W4.0 x W4.0
    - Minimum cover to anchor head: ¾ inch
    - Minimum clearance between WWR and substrate:
      - ¾ inch for form-and-pour repairs
      - ½ inch for hand-applied repairs
  - Repairs deeper than 3 inches: Provide larger anchorage using hooked dowel bars (No. 3 or No. 4) in conjunction with supplemental grid of reinforcement in plan (WWR or reinforcing bars). Final detailing should be based on the repair geometry and site conditions.

5.2.2.2. Concrete Removal and Surface Preparation

- Sawcut the perimeter of the repair area to a depth of 1/2 to 3/4 inch. The sawcut should be made at least 2 inches beyond the perimeter of the spalled areas. Do not cut existing reinforcing steel.
- Remove concrete to sound substrate using a hand-held chipping hammer of nominal 15-lbs or less.
- If existing reinforcing steel is exposed and corroded, remove concrete behind the reinforcing bars to a minimum clearance of 3/4 inch. This helps remove chloride-contaminated concrete and provides sufficient space for the repair material to fully encapsulate the reinforcement.
- When repairs cannot encompass existing reinforcement, provide supplemental anchorage and reinforcement crossing the repair–substrate interface.

- Clean the substrate surface by sandblasting to remove loose material and microcracking. Where sandblasting is not permitted, clean the substrate using water blasting (minimum pressure of 5,000 psi) and/or mechanical needle scaling.
- The prepared substrate shall have a concrete surface profile (CSP) consistent with the repair material manufacturer's recommendations.
- Clean the repair area using oil-free compressed air to remove dust and debris.
- Condition the substrate surface in accordance with the repair material manufacturer's recommendations. If no specific guidance is provided, the substrate surface should be moist with no standing water, consistent with a saturated-surface-dry (SSD) condition prior to placement of cementitious repair materials.

5.2.2.3. Placement of Repair Materials

Hand-applied repairs:

- Use repair materials specifically intended for VOH, hand-applied (troweled-applied) applications.
- Hand-applied patching should be limited to small repairs with a maximum depth of 2 inches and an area not exceeding 2 square feet.
- Repairs should be placed in a single lift to minimize the risk of voids and poor bond between lifts. Do not exceed the maximum lift thickness recommended by the manufacturer.
- Follow the manufacturer's recommended mixing and batching. Measure components accurately and maintain batch records.
- Follow the manufacturer's installation procedures including applying a scrub coat of the material when recommended.
- Do not retemper repair materials once workability is lost. Discard batches that lose workability.

Form-and-pour repairs:

- Use repair materials specifically intended for VOH, form-and-pour applications. Form-and-pour materials should be pre-extended with coarse aggregate.
- Minimum repair depth should generally be a minimum of 2 inches, and as recommended by repair material manufacturer to allow the repair material to flow around anchors and reinforcement.
- Formwork should be securely attached to the structure. Provide a bird's-mouth opening with sufficient placement head (recommended ≥4 inches, unless otherwise specified by the manufacturer).
- Overhead form-and-pour applications require special attention to venting and placement head to mitigate air entrapment.
  - Where feasible, taper the repair geometry toward the bird's mouth to promote flow of the repair material.
  - Consider using more than one bird's mouth opening during placement.
  - Provide air vents or vent paths to allow trapped air to escape during placement.
- Follow the manufacturer's recommended mixing and installation procedures.
- Mix full-bag batches to maintain proper material proportions.

- Measure water accurately and maintain batch records where applicable.
- For self-consolidating concrete (SCC) repair materials, tapping of formwork may be used to assist flow and reduce voids.
- For non-SCC materials, internal or external vibration will be required, consistent with manufacturer guidance and formwork constraints.

5.2.2.4. Curing

Patches should be cured in accordance with the repair material manufacturer's recommendations. The following minimum curing requirements are recommended:

- Hand-applied repairs:
  - Apply a curing compound in accordance with the manufacturer's guidance, typically 15 to 30 minutes after finishing.
- Form-and-pour repairs:
  - Leave formwork in place for a minimum of 3 days, and until the repair material has achieved a compressive strength of at least 3,500 psi, or as recommended by the repair material manufacturer, whichever is longer.

5.2.2.5. Post-Installation Inspection

After curing the patch, the following inspections are recommended:

- Perform sounding (hammer tapping) to identify hollow areas or potential debonding of the repair material.
- For larger projects, or where bond performance is critical, perform pull-off testing in accordance with ASTM C1583. The recommended acceptance criteria are an average bond strength of at least 150 psi, with no individual test result less than 120 psi.

If debonding or insufficient bond strength is identified, the patch should be replaced.

6. SUMMARY AND RECOMMENDATIONS FOR FURTHER STUDIES

6.1. Summary

This study evaluated vertical and overhead (VOH) concrete repair practices used for bridge structures and developed recommendations to improve repair performance for the Wisconsin Department of Transportation (WisDOT). The work included a literature review, an evaluation of current WisDOT VOH repair practices, laboratory investigations of VOH repairs, and the development of recommendations for VOH concrete patch repairs.

The literature review examined guidance and practices documented by national organizations (including ACI, FHWA, ICRI, US Water Reclamation), as well as selected state transportation agencies. The review identified commonly used repair strategies, key factors influencing repair performance, and best practices for vertical and overhead repairs. Although general guidance for concrete repairs is widely available, gaps remain in current knowledge and practice, particularly regarding material performance requirements, anchorage approaches, and installation procedures specific to vertical and overhead repairs.

The evaluation of WisDOT practices provided insight into current repair methods used by maintenance personnel and highlighted areas where additional guidance and standardization could improve repair consistency and durability within Wisconsin. These areas include the absence of a repair material approval process and approved product list, lack of standardized procedures for VOH repairs, and variability in using abrasive blasting and supplemental anchorage during surface preparation.

Laboratory investigations were conducted to evaluate selected repair materials and repair configurations relevant to VOH patch repairs. Unlike most previous laboratory studies on concrete repair materials, which primarily evaluated horizontal repairs, this study examined repairs installed in vertical and overhead orientations. In addition, the laboratory program evaluated repair performance related to volume changes due to drying shrinkage and thermal exposure, as well as performance under structural loading. Key findings from the laboratory investigations include the following:

- Four repair materials were evaluated and showed significant differences in drying shrinkage and modulus of elasticity, while compressive strength and coefficient of thermal expansion (CoTE) were generally similar. Materials with lower shrinkage, lower modulus of elasticity, and CoTE values closer to those of the substrate exhibited reduced cracking potential.
- Sandblasting improved bond performance, however, sensitivity to surface preparation varied among the hand-applied repair materials.
- Repair configurations that encompassed existing reinforcing bars were most effective in controlling cracking and spalling.
- Evaluated as an option for when existing reinforcement cannot be included in the repair, screw anchors used with welded wire reinforcement (WWR) were effective in reducing cracking and spalling and were relatively simple to install. Epoxy-embedded threaded rod anchors may also be effective but require additional installation time and are more sensitive to installation orientation, particularly for overhead applications.
- Achieving adequate bond in overhead form-and-pour repairs can be challenging due to the potential for air entrapment and reduced consolidation at the repair–substrate interface. Mechanical anchorage or reinforcement crossing the interface is recommended to reduce the likelihood of debonding. Measures such as additional placement openings, vent holes, or the use of flowable concrete mixtures that can be vibrated are expected to help reduce voids, although further study is needed. Verification of adequate bond is recommended.

Based on the results of the literature review, laboratory investigations, and WJE's experience, guidelines for repair strategies addressing VOH spalls were developed. The following repair strategies were evaluated:

- Coating spalled area of concrete without patching
- Hand-applied patching
- Form-and-pour patching
- Non-structural FRP wraps in addition to patching

- Shotcrete

WJE recommends several revisions to WisDOT's VOH repair material property requirements and approval process to improve compatibility and long-term performance of approved repair materials. The recommended revisions are described in Section 5.2.1 and summarized as follows.

- Material property requirements
  - Reduce the maximum permitted shrinkage and expansion limits and reference modified testing procedures described in ACI PRC-364.3 and ICRI 320.3R. These procedures apply to a broader range of repair materials compared with ASTM C928, which is primarily intended for rapid-hardening repair materials.
  - Increase the required compressive strength.
  - Add splitting tensile strength requirements.
- Approval process
  - Require a mockup installation program to evaluate installation and bond performance under field conditions.
  - Require submission of documented field performance history for candidate repair materials.
  - Require a letter from the manufacturer regarding sulfate content in the repair material.

In addition, WJE provided guidance for installation of VOH repairs. The guidance is presented in Section 5.2.2 and includes the following:

- Limits of application for hand-applied and form-and-pour repairs.
- Anchorage and reinforcement details.
- Concrete removal and surface preparation methods (such as sandblasting or water blasting at approximately 5,000 psi).
- Placement and curing procedures for repair materials.
- Post-installation inspection of completed repairs.

Implementation of these recommendations is expected to improve the durability, consistency, and performance of vertical and overhead concrete patch repairs used by WisDOT.

6.2. Recommendations for Further Study

Field Performance Verification

The laboratory investigations were conducted under simulated field conditions but involved a limited number of repair materials, specimens, and exposure conditions. Therefore, collection of field performance data is recommended. This could include a directed research study and/or a monitoring program to capture statewide experience with VOH repair performance.

- The directed study could include trial installations of selected VOH repair materials on representative bridge structures in Wisconsin. Repair materials would be installed under field conditions, and material properties could be evaluated using samples prepared during installation. The performance of the repairs should then be monitored over several years through periodic inspections, including visual assessments, sounding tests, and pull-off bond testing.

- Long-term field monitoring would provide valuable information regarding durability, installation variability, and long-term performance of VOH concrete patch repairs under actual service conditions. This effort could include development of a centralized database populated through standardized survey forms completed by WisDOT staff or contractors performing VOH repairs. Similar forms could be used during follow-up inspections to document repair conditions, including photographs, with all information tracked over time.

Further Laboratory Study

- Achieving sufficient bond in overhead form-and-pour repairs can be challenging, as indicated by the laboratory investigations and previous experience. Additional study is recommended to evaluate the impact of repair materials and installation procedures on bond performance for overhead form-and-pour repairs.
- While sandblasting is typically recommended for surface preparation, it may not be practical in certain circumstances (e.g., due to dust regulations or environmental constraints). Alternative methods such as needle scaling, water blasting, and wire brushing have been used. Further study is recommended to evaluate the effectiveness of these surface preparation methods at producing well-bonded repairs across a broader range of repair materials.

Pilot Implementation of WisDOT Mockup Program

- A WisDOT Mockup Program is recommended in Section 5.2 to improve the reliability of VOH repairs on bridges in Wisconsin. However, implementation of this program will introduce additional cost and effort. A pilot implementation is recommended to evaluate its feasibility and effectiveness.

FRP Wrap Evaluation

- Non-structural FRP wraps have been used in Wisconsin and other states to contain overhead repairs. While this approach provides an added level of protection, it is also relatively costly and time-consuming. The literature review and interviews performed as part of the scope of this research found only limited or anecdotal information. A more comprehensive study evaluating the performance of FRP wraps and the cost-benefit ratio of their use is recommended.

REFERENCES

American Concrete Institute (ACI)

ACI 546.3-23, Materials Selection for Concrete Repair—Guide

ACI 546R-14, Guide to Concrete Repair

ACI PRC 364.3-23, Cementitious Repair Material Data Sheet - Guide

ACI RAP Bulletin 4, Field Guide to Concrete Repair Application Procedures, Surface Repair Using Form-and-Pour Techniques

ACI RAP Bulletin 5, Field Guide to Concrete Repair Application Procedures, Surface Repair Using Form-and-Pump Techniques

ACI RAP Bulletin 6, Field Guide to Concrete Repair Application Procedures, Vertical and Overhead Spall Repair by Hand Application

American Society for Testing and Materials (ASTM)

ASTM C109/C109M-21, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)

ASTM C1202-22, Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration

ASTM C157/C157M-23, Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete

ASTM C1583/C1583M-20, Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method)

ASTM C260/C260M-23, Standard Specification for Air-Entraining Admixtures for Concrete

ASTM C33/C33M-23, Standard Specification for Concrete Aggregates

ASTM C39/C39M-23, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens

ASTM C469/C469M-22, Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression

ASTM C494/C494M-23, Standard Specification for Chemical Admixtures for Concrete

ASTM C496/C496M-17 (Reapproved 2022), Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens

ASTM C596-18 (Reapproved 2022), Standard Test Method for Drying Shrinkage of Mortar Containing Hydraulic Cement

ASTM C666/C666M-23, Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing

ASTM C882/C882M-23, Standard Test Method for Bond Strength of Epoxy-Resin Systems Used with Concrete by Slant Shear

ASTM C928/C928M-20, Standard Specification for Packaged, Rapid-Hardening Cementitious Materials for Concrete Repairs

ASTM D4580-03 (Reapproved 2007), Standard Practice for Measuring Delaminations in Concrete Bridge Decks by Sounding

International Concrete Repair Institute (ICRI)

ICRI 310.1R-2008, Guideline for Surface Preparation for the Repair of Deteriorated Concrete Resulting from Reinforcing Steel Corrosion

ICRI 310.2R-2013, Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, Polymer Overlays, and Concrete Repair

ICRI 310.3R-2014, Guideline for the Preparation of Concrete Surfaces for Repair Using Hydrodemolition Methods

ICRI 320.1R-2019, Guideline for Selecting Application Methods for the Repair of Concrete Surfaces

ICRI 320.3R-2022, Guideline for Inorganic Repair Material Data Sheet Protocol

State DOT References

Illinois DOT Bridge Manual 2023

Illinois DOT Standard Specifications for Road and Bridge Construction (2022)

Illinois DOT Guide Bridge Special Provisions (GBSP) 53 - Structural Repair of Concrete

Illinois DOT Qualified Product List - Packaged, Dry, Rapid Hardening Cementitious Materials for Concrete Repairs

Iowa DOT LRFD Bridge Design Manual 2024

Iowa DOT Standard Specifications for Highway and Bridge Construction 2023

Iowa DOT Instructional Memorandum (I.M): I.M 447 Packaged, Dry, Combined Materials for PC Concrete; I.M 491.20 Rapid-setting Concrete Patching Materials

Kansas DOT Bridge Construction Manual (2012)

Kansas DOT Standard Specifications for State Road & Bridge Construction (2015)

Kansas DOT Special Provision – Section 2009 Rapid Hardening Hydraulic Cement

Kansas DOT List of Prequalified Rapid-set Concrete Patching Material

Kansas DOT List of Prequalified Rapid Hardening Hydraulic Cement

Michigan DOT Bridge Design Manual

Michigan DOT Construction Manual

Michigan DOT Standard Specifications for Construction (2020)

Michigan DOT Capital Scheduled Maintenance Manual (2010)

Michigan DOT Special Provision for Concrete Beam Repair Preparation

Michigan DOT Special Provision for Shotcreting Vertical and Overhead Structure Repair

Michigan DOT Special Provision for Column Wrapping with Fiber Reinforced Polymer Sheets

Michigan DOT Materials Source Guide – Prepackaged Hydraulic Fast Set Mortar

Missouri DOT Bridge Design Manual (2010)

2024 Missouri Standard Specifications for Highway Construction

Missouri DOT Job Special Provision (JSP) – Rapid Set Concrete Patching Material – Vertical and Overhead Repairs JSP-02-01

Missouri DOT Materials Qualified List - Qualified Rapid Set Concrete Patching Material (Vertical & Overhead) FS-704

Ohio DOT Bridge Design Manual (2020)

Ohio DOT Construction and Material Specifications (2023)

Ohio DOT Supplemental Specification 843 – Patching Concrete Structures with Trowelable Mortar

Indiana DOT Standard Specifications (2024)

Indiana DOT Qualified Lists & Qualified Source Lists – Rapid Setting Patch Materials

Minnesota DOT Standard Specifications for Construction 2020

Nebraska DOT Standard Specifications for Highway Construction (2017)

Nebraska Dot Concrete Repair Manual

North Dakota DOT Standard Specifications for Road and Bridge Construction (2024)

South Dakota DOT Standard Specifications for Roads and Bridges (2015)

Wisconsin DOT Bridge Manual (2022)

Wisconsin DOT Standard Specifications for Highway and Structure Construction (2024)

Wisconsin DOT Prequalified Products – Rapid set concrete repair materials

Ontario Provisional Standard Specification – Construction Specification for Structure Rehabilitation – Concrete Patches, Refacing, and Overlays

New York State DOT Bridge Manual (2021)

New York State Dot Standard Specifications (2024)

New York State DOT Materials – Approved List – Concrete Repair Materials – Vertical and Overhead Patching Materials (701-08)

Texas DOT Bridge Design Manual – LRFD (2024)

Texas DOT standard Specifications for Construction and Maintenance of Highways, streets, and Bridges (2014)

Texas DOT Concrete Repair Manual (2021)

Texas DOT Departmental Materials Specification (DMS) – DMS-4655 Concrete Repair Materials

Texas DOT Concrete Repair Materials – Material Producer List

Washington State DOT Bridge Design Manual LRFD (2024)

Washington State DOT Standard Specifications (2024)

Washington State DOT Construction Bulletin – Structural Repairs (2018)

Washington State DOT Maintenance Manual (2020)

Washington State DOT Qualified Products List

Other References

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Kurt F. von Fay, Guide to Concrete Repair, Second edition, U.S. Department of the Interior Bureau of Reclamation

M. Lemieux, R. Gagné, B. Bissonnette and M. Lachemi, "Behavior of Overlaid Reinforced Concrete Slab Panels Under Cyclic Loading—Effect of Interface Location and Overlay Thickness," ACI Structural Journal, 2005.

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P. Paramasivam, K. C. G. Ong, B. G. Ong and S. L. Lee, "Performance of Repaired Reinforced Concrete Slabs Under Static and Cyclic Loadings," Cement and Concrete Composites, no. 17, pp. 37–45, 1995.

Papas, S., "Cementitious Concrete Repair Materials and Grouts: When is Fast Too Fast?," International Institute of Building Enclosure Consultants (IIBEC), 2014.

APPENDIX A. LITERATURE REVIEW

APPENDIX A. LITERATURE REVIEW

To assist with developing recommendations on vertical and overhead (VOH) concrete repairs for WisDOT, WJE performed a literature review of the recommendations of industry organizations as well as current practices at selected US and Canadian transportation agencies. This literature review focused on VOH concrete repair, especially through patching but also with fiber-reinforced polymer (FRP) and coatings, of concrete bridge components including bridge decks, girders, piers, and abutments. This literature review examined relevant documents from industry and national organizations including the American Concrete Institute (ACI) and International Concrete Repair Institute (ICRI), the U.S. Army Corps of Engineers, Federal Highway Administration (FHWA), and Bureau of Reclamation, and various state transportation agencies (i.e. departments of transportation or equivalent).

The main findings of the review are summarized in this section.

A.1 Strategies for Vertical and Overhead Repairs

Repair strategies are typically selected based on the extent and cause of the deterioration or distress in the concrete. Examples of common types of distress leading to VOH repairs include chloride- or carbonation-induced corrosion of embedded metals, freeze thaw damage, and vehicular impact. Common steps involved in a repair project before determination of a repair method and material involve condition assessment, identification of the cause behind the damage, characterization of the application and service conditions, and determination of repair objectives, including the service life desired for the repair. Several repair methods are available for VOH repairs. Based on the cause and nature of the damage, the material and method used to repair the concrete can vary. In this section, the following strategies for VOH repairs are briefly summarized:

- Concrete patching – Hand applied
- Concrete patching – Formed and cast
- Concrete patching – Shotcrete
- Concrete patching – Other Methods
- Non-structural FRP wrap
- Coating exposed steel reinforcement without concrete patching

A.1.1 Concrete Patching – Hand-Applied

In this method, repair material is applied directly to the surface being repaired either by hand or with a trowel as illustrated in Figure A.1. When necessary, multiple layers of the repair material are pressed against one another to fill a void. This method is suited for thin patches (typically 1/8 to 4 inches per ACI RAP Bulletin 6 and 1-1/2 to 3 inches per ICRI 320.1R-2019) and is used for localized repairs. This method allows for a relatively quick and easy application of the repair material. It is used for non-structural repairs and is susceptible to sagging, especially in overhead, applications. Since repair thickness is small, hand-applied patches may not encompass existing reinforcement; in this case, supplemental anchorages are sometimes used to mechanically tie the patch to the substrate.

Figure A.1. Example of trowel-applied concrete repair.

A.1.2 Concrete Patching – Formed and Cast

In this method, the area being repaired is formed and repair material is poured (or pumped) into the formwork as illustrated in Figure A.2. If the repair material is being poured, the material should be flowable, and vibration may be needed to ensure adequate compaction. When the forms are not open at the top, the geometry of the repair cavity and the need for vent holes should be considered to ensure air is not trapped in the repair volume. If the repair material is being pumped, the material must be pumpable, and formwork needs to be designed and strong enough to support the applied pressures. Form-and-cast methods typically result in more consistent repair quality than hand-applied method, and the forms help in the curing of the repair material. However, formwork can increase the cost of the repair.

Figure A.2. Illustration of formed and poured overhead repair

A.1.3 Concrete Patching – Shotcrete

In this method, shown in Figure A.3, a special mortar or concrete mix, which may contain fiber reinforcement, is sprayed to the repair area at a high velocity. This method can help place large volume of material continuously without the need for formwork. However, shotcreting requires special equipment and skilled laborers. There is also a need for securing the area around the repair to contain repair material rebounding from the shotcreting process.

Figure A.3. Illustration of shotcrete repair

A.1.4 Concrete Patching – Other Methods

Other methods, including pre-placed aggregates and dry packing, are less common but can be useful in certain scenarios.

Pre-placed aggregates – In this method, the repair area is formed and pre-filled with coarse aggregate. A low-viscosity binder (cement-sand grout or resinous material) is then injected to the form from its lowest point until the binder fills to the top of the repair cavity. This method is typically used when extremely low shrinkage of repair material is desired or if the repair work is being done underwater and there is a need to reduce washout during placement. Watertight formwork and experienced crew are necessary for this method.

Dry packing – In this method, a low-slump repair material is placed in repair cavities (with the least dimension not more than 1- to 3- inch) in 3-to-5-inch lifts and compacted using flat-faced wooden or metal rodding tools. Typically used in relatively low-volume repair areas that have a high-degree of confinement and one-sided access, this method can provide intimate contact of repair material with substrate at relatively low costs. The effort required for proper manual compaction makes this a labor-intensive repair method. Formwork, if any, needs not be tight-fitting but needs to be well braced to accommodate the compactive forces.

A.1.5 Non-structural FRP wrap

Fiber-reinforced polymers (FRP) are composite laminate materials made with fibers in polymeric resin. FRPs are typically thin, lightweight, non-corroding, and have high tensile strength. They can be wrapped around elements with a variety of geometries because of their ability to conform to the shape of the structure as seen in Figure A.4.

While FRP is more commonly used for structural strengthening, FRP wraps have also been used for non-structural purposes (Wisconsin DOT Bridge Manual - 2020) to reduce exposure of bridge members to corrosion-promoting elements such as water and deicing salts, and to contain concrete patches above traffic to prevent delaminated patches from falling, which could endanger vehicles and/or pedestrians. FRP wraps may slow but will not stop on-going corrosion of the reinforcing steel in repairs they cover if the driving cause of corrosion (e.g., chloride) is not removed. Thus, to maximize benefits of FRP wraps, the area being wrapped must be first repaired to address the underlying issue which caused the distress in the concrete being repaired. Before installation of the FRP wraps, the repair needs also to be sufficiently cured and the surface needs to be properly prepared (following FRP manufacturer's instruction). FRP wraps are installed over the patch and extended onto the sound concrete surfaces adjacent to the repairs.

FRP wrap can be installed relatively quickly, and when installed correctly, can improve lifespan of the repair and help reduce maintenance costs. However, FRP wrap installation requires skilled workers and increases the costs of the repair. FRP materials are also susceptible to ultraviolet radiation damage.

Figure A.4. FRP repairs (painted in white) wrapped around pier caps. (These were structural repairs and extend further than necessarily required for VOH repairs.)

A.1.6 Coating exposed steel reinforcement without concrete patching

This strategy is used as a non-structural repair option. Instead of a concrete repair, coating of exposed steel reinforcement (shown in Figure A.5) is used to slow down corrosion while leaving the repair area open. Situations for the use of this strategy are when there is limited access for repair, or when there is need for a small and/or temporary fix. A zinc-rich paint, cementitious materials or neat epoxy are commonly used. Zinc-rich paint can provide some level of cathodic protection to the exposed steel in addition to acting as a barrier coating. Cementitious materials and neat epoxy are used to protect against water, chlorides, and other contaminants, which can cause deterioration of the concrete.

Figure A.5. Coating of exposed reinforcement.

A.2 Vertical and Overhead (VOH) Concrete Patching

This section discusses various important technical aspects of VOH patch repair including the following:

1. Repair materials
2. Concrete removal and surface preparation
    a. Edge conditioning
    b. Surface cleaning
    c. Conditioning of exposed reinforcement
    d. Substrate saturation
3. Repair material installation
4. Curing
5. Quality Control

A.2.1 Repair Materials

A.2.1.1 Common Types of Materials Used for Concrete Repairs

As outlined in ACI PRC 546.3-23, various types of materials may be used for concrete repair including the following, largely differentiated by matrix (i.e. binder system):

- Portland-cement concrete (PCC) and mortar
- Shrinkage-compensating cement concrete and mortar
- Rapid-setting cement concrete and mortar
- Silica-fume concrete and mortar
- Polymer-modified concrete (PMC) and mortar
- Magnesium phosphate concrete and mortar
- Polymer concrete and mortar

These types of matrix cover a wide range of hardening-time characteristics, from normal-hardening portland cement concrete to ultra-rapid hardening magnesium phosphate concrete. An ultra-rapid hardening cement, as defined in ASTM C1600, has a minimum compressive strength of 3,000 psi at 1.5 hours and 4,100 psi at 3 hours.

Properties and applications of these different materials are discussed extensively in ACI PRC 564.3-23; a summary of this discussion as it relates to VOH concrete repair is given in Table A.1.

For each type of repair material, repair mortars have similar components and general characteristics to those of the corresponding repair concretes produced with the same binder system. The key difference between mortar and concrete is that in the mortar, coarse aggregate is excluded and the paste-to-aggregate ratio is higher; thus, repair mortars generally have higher drying shrinkage and higher coefficient of thermal expansion than the corresponding concrete. Repair mortars are typically used for shallower repairs in small areas and for hand-applied patching.

Many of the repair materials discussed here are commercially available as prepackaged materials. In prepackaged repair mortars, all dry components including cement, fine aggregate, dry admixtures, and, frequently, proprietary ingredients, are blended and then packaged in a production plant. Some prepackaged repair materials have coarse aggregate premixed into the package, and in some cases coarse aggregate can be added on site (i.e. the material can be extended). Advantages of prepackaged repair materials include convenience of use and more consistent performance. Limitations of prepackaged repair materials include that they may have different mechanical properties than the concrete being repaired and can have a propensity for high shrinkage compared with conventional concrete. Many prepackaged repair materials have proprietary chemical compositions that are not publicly available, which can make it difficult for the materials specifier to evaluate the appropriateness of the repair materials for the project needs or to track changes in formulation.

Table A.1. Common types of repair materials used for VOH concrete repair (adopted from ACI 546R-23)

Repair material	Description	Typical applications	Advantages	Limitations	Applicable standards/ guidelines
Portland-cement concrete (PCC)	Composed of portland or blended cement, fine and coarse aggregates, and water. May include chemical or mineral admixtures.	Large (thick sections and large volumes), partial- and full-depth placements	Readily available, economical, familiar, properties typically similar to substrate concrete	Susceptible to degradation if underlying issue that caused original distress is not addressed	ASTM C94
Shrinkage-compensating cement concrete	Similar to PCC, but contain shrinkage-compensating cement	Concrete slabs, pavements, bridge decks, and structures where shrinkage cracking is a concern	Can reduce or eliminate shrinkage cracking and reduce warping	Need to obtain sufficient expansion and/or compressive stresses to compensate for subsequent drying shrinkage	ASTM C845; ACI PRC-223
Rapid-setting cement concrete	Faster setting times than conventional cements, often achieved through blends of portland cement with calcium aluminate or calcium sulfoaluminate cements.	Where an early return to traffic is required, such as repair of pavements, bridge decks, airport runways, and industrial plants.	Accelerated strength development compared with conventional PCC	Potential issues include delayed ettringite formation, reduced durability in wet environments (for gypsum-based cement), sulfate attack	ASTM C1600; ASTM C928
Silica-fume concrete	PCC with silica fume (5-10% replacement by mass of cement) and high-range water reducer	Repairs and overlays on parking structures and bridge decks	Decreased permeability, increase density and strength, higher bond strength, more resistant to attack by some chemicals than PCC	More cohesive and less bleed water than conventional PCC; more difficult to finish, potentially more susceptible to plastic shrinkage cracking	ACI 234R
Polymer-modified concrete (PMC)	Portland or blended cement-based concrete with polymer modifiers added.	Surface repairs and overlays of bridge decks, parking structures	Increased flexural and bond strength, reduced permeability, increased protection against corrosion compared with PCC	More difficult to place and finish than PCC; relatively short working time (15 to 30 minutes); more sensitive to plastic shrinkage	ACI 548.1R; ACI 548.3R

Repair material	Description	Typical applications	Advantages	Limitations	Applicable standards/ guidelines
Magnesium phosphate concrete	Concrete in which magnesium-ammonium-phosphate is substituted for the portland or blended cement.	Rapid repair, cold weather repairs (32°F or lower); used in highway, bridge deck, airport, tunnel, and industrial repairs	Increased bond strength, low drying shrinkage, rapid strength gain, and low permeability compared to PCC	Can only be extended with noncalcareous aggregates, requires well prepared substrate with complete removal of carbonation layer, small workability window, sensitive to water content (low tolerance ± 10%)	C1600
Polymer concrete	Polymer binder (polyester, epoxy, furan, vinyl ester, high-molecular-weight methacrylates (HMWM), styrene) and aggregate	Rapid repairs; Thin repairs and overlays	Low shrinkage, enhanced bond strength, high tensile and flexural strength, low permeability, increased protection against corrosion, improved resistance to chemical attack compared to PCC	Small workability window (< 15 min. to an hour), low modulus of elasticity, higher coefficient of thermal expansion than the substrate concrete; loss of mechanical properties when heated; typically not for repair of wet/damp concrete; potentially hazardous material requiring special cleaning and disposal protocols	ACI 503.4, ASTM C881

A.2.1.2 General Requirements for Properties of Repair Materials

The property requirements for repair materials vary from project to project, depending on the expected service conditions. Factors that may influence the selection of repair materials include desired application thickness, rate of strength gain, ease of application, color, cost, downtime to finish the repair, and service life. For a successful repair, based on the repair project, consideration should be given to several different properties of repair materials:

- Mechanical properties of the repair material, including compatibility of the repair material with the properties of the substrate. It is not desirable to have the mechanical properties of the repair differ greatly from the substrate. The modulus of elasticity, coefficient of thermal expansion, shrinkage, creep, bond strength, compressive strength, tensile strength, and flexural strength (modulus of rupture) are all properties of the repair material that can influence the success of a repair. The volume stability of the repair is important because the substrate is typically mature and will not undergo large deformations due to creep and shrinkage. The substrate may however undergo thermal contraction/expansion due to seasonal temperature changes. ACI 546.3-23 recommends the use of repair materials with a lower modulus of elasticity or a higher rate of creep than the surrounding substrate to reduce the stresses caused by restrained contraction and expansion. These stresses can cause the repair material to debond from the substrate or crack. It is also recommended to have the coefficient of thermal expansion of the repair material to be similar to that of the substrate to reduce the differential movements due to daily and seasonal temperature variations. Many prepackaged repair materials include shrinkage-compensating cement or shrinkage-reducing chemical admixtures to limit the shrinkage of the repair material.

  ACI 546.3-23 provides a list of common test methods and typical and recommended test values for portland-cement concrete repair materials, a summary of this list as applicable to VOH repair is provided in Table A.2.

Table A.2. Test methods and test values for selected properties of portland-cement concrete repair material (adopted from ACI PRC-546.3-23)

Description	Test Method	Typical Value	Recommended Value
Length Change – concrete	ASTM C157	0.02 percent (expansion) to -0.05 percent (shrinkage)	--
Drying Shrinkage - mortar	ASTM C596	0.05 to 0.15 percent shrinkage	< 0.10 percent shrinkage
Restrained Expansion	ASTM C806	0.06 percent	--
Restrained shrinkage crack resistance	ASTM C1581	Net time to cracking, t_{cr}, days 0 to ≤7 (high potential) 7 to ≤14 (moderate-high) 14 to ≤28 (moderate-low) >28 (low)	--
Modulus of Elasticity (MOE)	ASTM C469	1,000,000 to 5,500,000 psi	Less than MOE of substrate if repair is non-structural. Closely match MOE of substrate if repair is structural.
	ASTM C580	300,000 to 3,000,000 psi	
Coefficient of Thermal Expansion	ASTM C531 (mortar)	0.000014/°F	Similar to that of substrate
	ASTM D696 (mortar)	0.000014/°F	
	USACE CRD-C 39 (concrete)	0.000006/°F	
	ASTM C884	Qualitative test	--
Creep	ASTM C512	0.000000001/psi	--
Slant Shear Bond	ASTM C882	1 day – 400 to 1000 psi 7 days – 1000 to 1800 psi 28 days – 2000 to 3000 psi	--
Direct Tensile Bond	ASTM C1583, ICRI 210.3	1 day – 70 to 150 psi 7 days – 150 to 250 psi 28 days – 250 to 300 psi	Bond strength below 100 psi may indicate a serious problem with the repair material bond
Compressive Strength	ASTM C39	28 days – 3000 to 10,000 psi	Similar to that of substrate
	ASTM C109	28 days – 4000 to 12,000 psi	
Tensile Strength	ASTM C496	400 to 1800 psi	> 400 psi

Description	Test Method	Typical Value	Recommended Value
Flexural Strength	ASTM C78	28 days – 1200 psi	--
	ASTM C293	28 days – 500 to 1200 psi	
	ASTM C348	28 days – 1500 psi	
	ASTM C580	7 days – 2400 psi	
Resistance to freezing and thawing	ASTM C666	28 days – 80 to 100 durability factor (DF) at 300 cycles	>80 DF
Scaling resistance	ASTM C672	28 days — 0 to 5 visual rating at 50 to 300 cycles	<2
	ASTM C672 modified by ICRI 320.2R	<0.10 lb/ft^2 (0.5 kg/m^2) loss at 50 cycles	<0.10 lb/ft^2 (0.5 kg/m^2) loss at 50 cycles
90-day Chloride Ponding	AASHTO T259	0.42 percent at 0.5 in. 0.15 percent at 1.0 in.	--
Rapid Chloride Permeability	AASHTO T277, ASTM C1202	Coulombs (C) >4000 (high) 2000 to 4000 (moderate) 1000 to 2000 (low) 100 to 1000 (very low) <100 (negligible)	≤4000 C
Absorption after Immersion	ASTM C642	4 to 6 percent	<6 percent
Volume of Permeable Pore Space	ASTM C642	5 to 12 percent	Not available
Alkali-aggregate reaction (AAR)	ASTM C227	--	< 0.1 percent
	ASTM C1260	--	< 0.1 percent
	ASTM C1293	--	< 0.1 percent
	ASTM C289	--	--
	ASTM C295	--	--
Abrasion resistance	ASTM C779 Procedure A	0.004 to 0.1 in. (0.1 to 2.5 mm) at 30 min.	--

Description	Test Method	Typical Value	Recommended Value
		0.008 to 0.2 in. (0.2 to 5.1 mm) at 60 min.	
Sulfate resistance	ASTM C1012	0 to 0.2 percent	< 0.1 percent

Notes: "--" indicates value not provided in the reference document.

- Constructability. Depending on the repair method and location, the constructability of the repair material can influence its success. For an overhead repair, a cohesive repair material is preferred where the repair material must adhere to the repair cavity. For a pumping application, the viscosity of the concrete mix is important to allow for ease of pumping and for the concrete to fill the formwork without segregation. Working time of the repair material can vary with external environmental considerations such as wind and temperature. Repair materials are also chosen for their aesthetic properties in certain situations. The surface texture and the color of the finished surface should generally match the surrounding concrete in these circumstances.
- Durability. Several durability-related properties of the repair materials, such as resistance to freezing and thawing, susceptibility to alkali-aggerate reactions, resistance to chloride ingress or chemical attack, can be crucial for a successful long-term repair. In addition, consideration should be given to the soundness of the repair materials, particularly fast setting repair materials. These materials can include excess gypsum, which if not consumed before the repair material sets, may react with moisture at later ages and expand, causing cracking (Papas, S. 2014)

A.2.1.3 Additional Requirements for Properties of Hand-Applied and Formed-and-Cast Repair Materials

A.2.1.3.1 Concrete patching – Hand-applied

Typical-hand applied patch materials are fine-grained cementitious mortars with a consistency which limits sag when applied in VOH applications. These repair materials are commercially sold as prebagged/prepackaged mixes.

A.2.1.3.2 Concrete patching – Formed and cast

For formed and poured and form and pumped applications, the repair material used is typically either a packaged repair material that includes or is extended with coarse aggregate or a ready-mixed concrete. The repair material needs high workability to allow for complete filling of the formwork. Use of high range water reducing admixtures is a more common approach to achieve this workability than increasing the water-cement ratio (w/c); a w/c < 0.40 is recommended by ACI RAP Bulletin 4.

The maximum size of aggregate used is limited by the size of the gap the repair material has to pass through considering the formwork, reinforcement, and substrate. ACI RAP Bulletin 4 limits the maximum aggregate size to be no greater than 25% of the space between the formwork and the substrate, or 50% of the gap between the substrate and reinforcement, whichever is smaller. For applications where the repair material is pumped, the type of pump used can also lead to restrictions on the maximum aggregate size. Consideration should be given to using the largest maximum aggregate size possible, since it reduces shrinkage.

A.2.2 Concrete Removal and Surface Preparation

Surface preparation is an important step for a successful VOH repair. The surface of the repair (substrate) is prepared by removing unsound or contaminated concrete, roughening, cleaning, and moisture saturating it (except that surface must be dry for polymer concrete repair materials) prior to application of the repair material. Any reinforcing steel present within the repair area is also cleaned to remove corrosion products and contaminants.

A.2.2.1 Concrete removal and edge conditioning

Sounding is commonly used to identify the extent of delaminated/loose concrete to be removed prior to repairs. The geometry of the concrete removal is kept simple (square or rectangular), with sawcut edges (typically 0.5-inch deep), which are perpendicular to the substrate. All unsound (loose, delaminated) concrete is removed by one or more methods including but not limited to: chipping hammers or other types of concrete breakers (15-lb hammers are commonly used, larger hammers may cause damage to substrate and reinforcement), hydro demolition, and needle scaling. The surface profile achieved depends heavily on the method used for the removal of concrete. ICRI Technical Guideline No. 310.2R-2013 details various surface preparation methods and their applicability.

If evidence of reinforcement corrosion is present, concrete is removed along the reinforcement and adjacent area, including behind the steel. ACI RAP Bulletin 5 recommends a removal to achieve a clearance behind the steel not less than either ¾ inch or ¼ inch greater than the largest aggregate size of the repair material. In cases of advanced section loss in the reinforcing steel, supplemental steel is lapped on existing steel or doweled into the concrete at the perimeter of the repair. ICRI Technical Guideline No. 310.1R-2008, provides guidelines on surface and reinforcing steel preparation.

A.2.2.2 Surface cleaning

Secondary removal or surface cleaning is done to remove fractured concrete and remove debris, residual dust, or other contaminants. This is done to ensure a good bond between the substrate and the repair material. Dry or wet abrasive blasting or low-pressure water-jet blasting (minimum 3000 psi) is commonly used for this purpose (ACI RAP Bulletin 6 & Evaluation and repair of concrete structures, U.S. Army Corps of Engineers (1995)).

Following this, the repair surface is blown with oil-free compressed air or vacuumed to remove all dust. The texture of the substrate should be rough and match the specified Concrete Surface Profile (CSP) (ICRI Technical Guideline No. 310.1R). A CSP of 6 or greater is recommended for good bonding of the repair material to the substrate (ACI RAP Bulletin 6).

A.2.2.3 Exposed reinforcement

The reinforcing steel is cleaned by abrasive blasting or high-pressure water blasting to remove all loose corrosion product, scale, and concrete attached to it. For smaller areas, the reinforcement can be cleaned by using a wire brush.

Where corrosion is the primary driver of the distress being addressed by the repairs, the life of the repairs may be increased by taking steps to mitigate corrosion of the reinforcing steel. This could include the use of epoxy or zinc-rich coating on the bars within the repair, and/or the installation of embedded galvanic anodes (ACI RAP Bulletin 6).

A.2.2.4 Substrate saturation

A saturated surface-dry (SSD) condition is recommended by most portland cement-based repair material manufacturers to prevent the loss of moisture from the repair material into the substrate after the repair material is installed (ACI RAP Bulletin 6). The SSD condition is typically achieved by soaking the substrate, followed by removing any surface water or puddles shortly before repair material installation.

A.2.3 Repair Material Installation

The choice of repair material and method for VOH repairs is usually based on the anticipated efficiency and efficacy, the nature of the distress to be repaired, site constraints, and the quantity of repairs. The success of VOH repairs depends on good installation practices. Manufacturer recommendations for repair materials vary but should be followed.

A.2.3.1 Concrete patch – Hand applied

A thin bond coat is first applied to the SSD substrate. The bond coat may be a bonding agent by a repair product manufacturer or a thin layer of the repair material (less than 1/8 inch). The bond coat is applied to ensure a good contact and to reduce the sagging of repair material on VOH surfaces (RAP Bulletin 6). The repair material is placed by firmly pressing it against the bond coat before it dries or sets. If a second lift is required, the first lift (typically 1.5 to 3 inch) is scored to create a surface profile to provide an improved mechanical bond between the lifts. The repair material is finished to match the surrounding concrete. Repair materials used for VOH patching by hand application are stiff and have no bleed water. The use of evaporation retarder and initiation of curing immediately after placement is crucial to prevent moisture loss at early ages. Curing procedures recommended by repair material manufacturers or in accordance with ACI 308R are typically followed.

A.2.3.2 Concrete patch – Formed and Cast

For formed repair, design and erection of formwork must be such that it accommodates the mass and pressure of the repair material. For concrete pumped into the formwork, ACI RAP Bulletin 5 recommends the design of formwork to withstand a form pressure of 14 psi. The formwork is attached directly to the concrete surface such that it is tight against the surface, using expansion anchors or form ties. Openings or chutes at the top of the formwork are required to prevent entrapping air at the top of the repair for pumped repairs. Overhead repair placements done through openings made in the slab above do not need these openings in the formwork.

When concrete is being placed, the use of internal or external vibration is often necessary to ensure complete filling of the form, though this may be used sparingly to avoid segregation if a self-levelling (self-consolidating) repair material is used. For large vertical repairs (greater than 10 ft in height), placement should be done in multiple lifts to reduce segregation due to free-fall and to reduce formwork pressure (ACI RAP Bulletin 4).

For concrete being pumped into a vertical repair, ACI RAP Bulletin 5 recommends the concrete is filled in to the formwork starting at the lowest point to prevent entrapment of air. Openings in the form (or ports for pump line attachment) are spaced every 3 to 4 ft. Concrete is pumped from a port/opening till material flows out of adjacent openings to ensure all air is expelled. For overhead placement, the concrete placement is done from an extremity, displacing air radially away from the injection port. Similar to vertical placement, concrete is pumped till it flows out of adjacent openings to ensure the expulsion of all air.

The formwork is ideally left in place for the recommended duration of curing. Defects in the repair material surface may be trimmed, cleaned and dry-packed. Application of a curing compound immediately after formwork removal is recommended (ACI RAP Bulletin 4).

A.2.4 Curing

Curing of patch repair material is typically carried out per the guidelines provided by ACI 308R and include methods such as sprinkling water, plastic films or the application of curing compounds. Curing of repair material is especially important due to its high susceptibility to shrinkage. Improper (or lack of) curing can cause the repair material to have lower strength, higher porosity, and reduced long-term durability.

Patch repairs can be highly susceptible to loss of moisture since they usually have a high surface-to-volume ratio and the repair material is installed in contact with old concrete which can absorb moisture from the repair mix if the substrate is not at SSD. Curing, especially water curing, is recommended to combat early age shrinkage of portland cement-based repair materials. Leaving formwork in place, placement of a wet burlap, or application of a curing compound are other common curing methods.

If proprietary repair materials are used, curing procedures prescribed by the manufacturer are typically followed.

A.2.5 Quality Control Procedures

Several best practices regarding quality assurance and quality control (QA/QC) are prescribed for a successful patch repair in ACI RAP Bulletin 4 and 6.

Addition of water to the repair material should be closely monitored. Depending on the repair type, either withholding water (trowel-applied) or addition of excess water (form-and-pour) to help with workability can affect the long-term properties of the repair. Lowering the water content can cause underhydration while increasing the water content can increase shrinkage, lower strength and increase the risk of material segregation.

A preconstruction meeting is recommended by ACI RAP Bulletin 4 before a repair is installed. This includes all the parties involved with the repair (contractor, materials manufacturer, engineer, and owner) to discuss the means, methods, materials, and other pertinent details related to the repair.

The repair should be photographed before and after each step. This allows for documentation of the concrete removal, surface preparation, and finishing. The area and volume of the repair should be documented. The cured hardened repair material should be sounded to identify debonding of the repair material from the substrate. In-place direct tensile bond strength can be measured to quantify the strength of the bond between the repair material and the substrate and also identify the weak link in the system (e.g. substrate, interface, or repair material).

Material used for the repair should be tested by a qualified testing agency for specified properties (typically compressive strength) for acceptance of the patch.

A.3 Vertical and Overhead Repair Practices by State Transportation Agencies

A.3.1 Use of Repair Strategies by State Transportation Agencies

Documents from select transportation agencies, including bridge design manuals, standard specifications, special provisions, qualified material lists, and other manuals were reviewed relative to repair materials and methods used for vertical and overhead concrete repairs. This review considered state agencies from the Midwest, Canadian provinces bordering Wisconsin, and select states from across the country. Table A.3 lists all the reviewed agencies and their select published literature. Table A.4 lists the repair types for VOH repairs defined in these documents broken down by agency. WisDOT does not have a document that specifically applies to VOH repairs, but their Standard Specifications (SS) for Highway and Structure Construction Section 509 (SS-509) governs concrete overlay and structure repair, which governs concrete repairs in general.

Table A.3. State Transportation Agencies and Manuals, Specifications, or Other Documents that were Reviewed

Region	State agency	Documents Reviewed
Midwest	Illinois DOT	Illinois DOT Bridge Manual 2023 Illinois DOT Standard Specifications for Road and Bridge Construction (2022) Illinois DOT Guide Bridge Special Provisions (GBSP) 53 - Structural Repair of Concrete Illinois DOT Qualified Product List - Packaged, Dry, Rapid Hardening Cementitious Materials for Concrete Repairs
	Iowa DOT	Iowa DOT LRFD Bridge Design Manual 2024 Iowa DOT Standard Specifications for Highway and Bridge Construction 2023 Iowa DOT Instructional Memorandum (I.M): I.M 447 Packaged, Dry, Combined Materials for PC Concrete; I.M 491.20 Rapid-setting Concrete Patching Materials
	Kansas DOT	Kansas DOT Bridge Construction Manual (2012) Kansas DOT Standard Specifications for State Road & Bridge Construction (2015) Kansas DOT Special Provision – Section 2009 Rapid Hardening Hydraulic Cement Kansas DOT List of Prequalified Rapid-set Concrete Patching Material Kansas DOT List of Prequalified Rapid Hardening Hydraulic Cement
	Michigan DOT	Michigan DOT Bridge Design Manual Michigan DOT Construction Manual Michigan DOT Standard Specifications for Construction (2020) Michigan DOT Capital Scheduled Maintenance Manual (2010) Michigan DOT Special Provision for Concrete Beam Repair Preparation Michigan DOT Special Provision for Shotcreting Vertical and Overhead Structure Repair Michigan DOT Special Provision for Column Wrapping with Fiber Reinforced Polymer Sheets Michigan DOT Materials Source Guide – Prepackaged Hydraulic Fast Set Mortar
	Missouri DOT	Missouri DOT Bridge Design Manual (2010) 2024 Missouri Standard Specifications for Highway Construction Missouri DOT Job Special Provision (JSP) – Rapid Set Concrete Patching Material – Vertical and Overhead Repairs JSP-02-01

Region	State agency	Documents Reviewed
		Missouri DOT Materials Qualified List - Qualified Rapid Set Concrete Patching Material (Vertical & Overhead) FS-704
	Ohio DOT	Ohio DOT Bridge Design Manual (2020) Ohio DOT Construction and Material Specifications (2023) Ohio DOT Supplemental Specification 843 – Patching Concrete Structures with Trowelable Mortar
	Indiana DOT	Indiana DOT Standard Specifications (2024) Indiana DOT Qualified Lists & Qualified Source Lists – Rapid Setting Patch Materials
	Minnesota DOT	Minnesota DOT Standard Specifications for Construction 2020
	Nebraska DOT	Nebraska DOT Standard Specifications for Highway Construction (2017) Nebraska Dot Concrete Repair Manual
	North Dakota DOT	North Dakota DOT Standard Specifications for Road and Bridge Construction (2024)
	South Dakota DOT	South Dakota DOT Standard Specifications for Roads and Bridges (2015)
	Wisconsin DOT	Wisconsin DOT Bridge Manual (2022) Wisconsin DOT Standard Specifications for Highway and Structure Construction (2024) Wisconsin DOT Prequalified Products – Rapid set concrete repair materials
Canadian Province Neighboring Wisconsin	Ministry of Transportation of Ontario	Ontario Provisional Standard Specification – Construction Specification for Structure Rehabilitation – Concrete Patches, Refacing, and Overlays
East	New York State DOT	New York State DOT Bridge Manual (2021) New York State Dot Standard Specifications (2024) New York State DOT Materials – Approved List – Concrete Repair Materials – Vertical and Overhead Patching Materials (701-08)
South	Texas DOT	Texas DOT Bridge Design Manual – LRFD (2024) Texas DOT standard Specifications for Construction and Maintenance of Highways, streets, and Bridges (2014) Texas DOT Concrete Repair Manual (2021) Texas DOT Departmental Materials Specification (DMS) – DMS-4655 Concrete Repair Materials Texas DOT Concrete Repair Materials – Material Producer List
West	Washington State DOT	Washington State DOT Bridge Design Manual LRFD (2024) Washington State DOT Standard Specifications (2024) Washington State DOT Construction Bulletin – Structural Repairs (2018) Washington State DOT Maintenance Manual (2020) Washington State DOT Qualified Products List

Table A.4. VOH Repair Strategies Defined in Readily-available Documents Published by State Transportation Agencies

State	Coating rebar without patching	Hand-applied	Form and pour	Form and pump	Shotcrete	FRP wrap
Illinois	N/A[1]	Not permitted.	Defined for vertical only; not for overhead.	N/A[1]	Defined. Wet-mix only.	N/A[1]
Indiana	N/A[1]	N/A[1]	N/A[1]	N/A[1]	N/A[1]	Defined for repair of deteriorated bridge components.
Iowa	N/A[1]	Defined for shallow repair; 3/4 inch to 1 1/2 inch in depth.	Defined with min. depth of 1-1/2 inch or 3/4 inch behind an unbonded reinforcing bar.	N/A[1]	Defined. Dry mix process only. May use shotcrete mortar or shotcrete concrete.	For concrete containment of collision damaged pretensioned prestressed concrete beams (per Developmental Specifications).
Kansas	N/A[1]	Defined if specified by the Engineer.	Defined.[2]	Not permitted.	Defined. Wet or dry process is permitted.	N/A[1]
Michigan	N/A[1]	Defined for spalls <1 inch deep.	Defined.[2]	N/A[1]	Defined for waterproofing using latex modified Portland cement and fine aggregates.	Defined when slight to moderate deterioration exists in columns.
Minnesota	N/A[1]	N/A[1]	N/A[1]	N/A[1]	N/A[1]	N/A[1]
Missouri	N/A[1]	Defined. Per repair material manufacturer's recommendation.	Defined. Per repair material manufacturer's recommendation.	Defined. Per repair material manufacturer's recommendation.	Defined. Dry Mix process only. May use shotcrete mortar or shotcrete concrete.	Defined.[2]
Nebraska	N/A[1]	N/A[1]	N/A[1]	N/A[1]	N/A[1]	N/A[1]

State	Coating rebar without patching	Hand-applied	Form and pour	Form and pump	Shotcrete	FRP wrap
New York	N/A[1]	Defined for shallow repair (less than 4 ft^2 and 2 inch deep).	Defined.[2]	Defined.[2]	Defined. Wet and dry mix processes allowed.	N/A[1]
North Dakota	N/A[1]	N/A[1]	N/A[1]	N/A[1]	N/A[1]	N/A[1]
Ohio	N/A[1]	Defined. Trowelable mortar only.	N/A[1]	N/A[1]	Defined.	N/A[1]
Ontario	N/A[1]	Defined. On unformed surfaces.	Defined.[2]	Defined.[2]	Used. Wet and dry mix processes allowed.	N/A[1]
South Dakota	N/A[1]	N/A[1]	N/A[1]	N/A[1]	N/A[1]	N/A[1]
Texas	Defined. Neat epoxy is used to coat both exposed steel and concrete, 10 mils minimum thickness (applicable for repair over traffic)	Defined. Epoxy mortar is used for spalls <1 inch deep, <12 ft^2 but not over traffic. Bagged, neat cementitious mortar for spalls <2 inches deep.	Defined.[2]	N/A[1]	Defined. Wet and dry mix processes allowed.	Defined. Used to confine repair over traffic.
Washington	N/A[1]	N/A[1]	Defined.[2]	Defined.[2]	N/A[1]	N/A[1]
Wisconsin	N/A[1]	N/A[1]	N/A[1]	N/A[1]	N/A[1]	Defined. Used for non-structural applications.

[1]: N/A: Not applicable (i.e. no information available regarding VOH repairs.)

[2]: Repair strategy used/allowed for VOH repair per documents reviewed but requirements specific to VOH repairs not given.

A.3.2 VOH Concrete Patching Practices by State Transportation Agencies

A.3.2.1 Existing Concrete Surface Preparation

For a given transportation agency, the surface preparation requirements for patching are usually the same irrespective of the repair method being used. Typically, the repair perimeter is saw cut and all unsound concrete is removed using chipping hammers. A 15-lb chipping hammer, operated at a maximum angle of 45° is commonly specified by the transportation agencies to remove loose and unsound concrete. Simple configurations, typically rectangular, are preferred for the removal with squared corners. Typical depth of saw cut at the edges of the repair region is ½ inch. These edges are cut such that they are perpendicular to the concrete surface around the repair area. For removals exceeding 150 mm (5.9 inches), New York state requires the walls of the repair to be at slight angle such that the width at the base of the removal is wider than the width at the surface, forming a key. Washington state requires the top edge of vertical repairs to slope up towards the surface at a 1-vertical-to-3-horizontal slope.

The minimum depth of removal ranges from 1 to 4 inches of concrete (Illinois - 1 inch, Kansas - 2-1/2 inches, Michigan - 3 inches or until reinforcement steel is encountered, and Ohio - 4 inches). Around reinforcement, the minimum depth of concrete removal is typically in the range of ½ to 1 inch beyond existing reinforcement or two times the maximum aggregate size, whichever is greater; some examples are: ½ inch or two times the max. aggregate size (Texas); min. ¾ inch (Kansas, Michigan & Washington), 1 inch (Indiana & Wisconsin), 1 inch but can be reduced to ½ inch if using patching concrete with No. 8 coarse aggregate (Ohio), and 1-5/8 inches (New York, for concrete repair using ready-mixed concrete).

Prior to placing concrete, blast cleaning of the concrete surface is commonly specified by the transportation agencies. Abrasive blasting is the most specified method to remove microcracking in the concrete substrate surface caused by concrete chipping and to clean exposed reinforcing bars, as summarized in Table A.5. Some transportation agencies allow high-(Washington – min. 5,000 psi) or ultra-high-(Ohio – min. 10,000 psi) pressure water blasting instead of abrasive blasting. The use of compressed air to clean the surface after blast cleaning is also commonly seen in the specifications of the various transportation agencies reviewed. The blasted surface is then required to be saturated with water to achieve saturated surface dry condition (except Iowa, which requires the substrate to be dry) prior to installation of the repair material.

Table A.5. Surface cleaning requirements by state

State	Surface Blast Cleaning Requirements
Illinois	Abrasive blasting cleaning required
Indiana	Sand Blasting required
Iowa	Sand Blast and air blast required
Kansas	Sand Blast and compressed air required
Michigan	Dry abrasive blasting required
Minnesota	No information
Missouri	Per engineer
Nebraska	No information
New York	Blast cleaning and air cleaning required

State	Surface Blast Cleaning Requirements
North Dakota	No information
Ohio	Abrasive blasting and air or ultra-high pressure water blasting required
Ontario	Abrasive blast cleaning and compressed air required
South Dakota	No information
Texas	Abrasive blasting, high-pressure water blasting, or other approved methods, followed by high-pressure air blast
Washington	Abrasive blasting or high-pressure (minimum 5,000 psi) water blasting.
Wisconsin	Blast* cleaning required for deck overlays and deck full depth repair (WisDOT SS-509.3.4 and 509.3.8). but not for concrete surface repair (WisDOT SS-509.3.7)

** Blast method not specified in WisDOT Standard Specifications; WisDOT Bridge Manual indicates shot blast, sand blast, and water or air blast may be used for overlay repairs.*

If section loss of reinforcing steel is seen within the repair area, transportation agencies require supplemental steel be placed. For example, Illinois requires the addition of supplemental steel with a minimum lapping of 32 bar diameters to existing bars, if >25% of original cross-sectional area is lost. Texas also uses a 25% loss in cross section as a threshold to add additional reinforcement, while Indiana uses 50% section loss as a threshold. Some transportation agencies (Illinois, Ontario, Ohio, and Texas) require the placement of dowels, expansion bolts, and/or welded steel wire fabrics within the patch repair areas. This is typically required by the transportation agencies when the repair area does not contain any steel reinforcement. The spacing requirement for these mechanical ties varies from 6 to 18 inch.

A.3.2.2 Repair Material Installation

Most transportation agencies specify the use of pre-qualified packaged repair materials, especially for hand-applied patches. For larger repairs that involve the use of formwork, packaged repair materials or ready-mixed concrete mixes are used. Packaged repair materials are often allowed to be extended by the addition of aggregates for formed repair. When packaged repair materials are used, transportation agencies frequently rely on the manufacturer's recommendations for the installation of the repair.

For hand-applied repair material, application of a bond coat is commonly required by the product manufacturer and is specified by Iowa and Texas. The bond coat, also known as primer or bonding grout, is scrubbed or painted on to the saturated surface dry substrate to fill pores on the substrate and ensure a good contact of the repair material with the substrate. It also helps to prevent sagging of the repair material on VOH surfaces.

Transportation agencies also limit the type of the repair based on size of the patch, for example trowel-applied patches are only allowed when the repair is between ¾ inch to 1-1/2 inches deep by Iowa; less than 3 inches deep by Texas; smaller than 4 ft^2 in area and 2 inches in depth by New York. Form and place methods are used for patches larger or deeper than the specified maximums for a trowel-applied repair.

Some states have performance requirements listed for pre-qualifying packaged repair materials. These requirements where available are summarized in Table A.6.

Table A.6. Performance requirements for prequalification of packaged repair materials, by state (where available).

State/ Specification	Type	Bond Strength by Slant Shear, psi (minimum) [ASTM C882/C928]			Linear Coefficient of Thermal Expansion (in 10^{-6} in/in/ °F) [ASTM C531]	Resistance to Rapid Freezing and Thawing [ASTM C666]	Compressive Strength, psi (minimum) [ASTM C39]				Length Change* (maximum) [ASTM C157]	Other tests	Color
		24 hours	7 days	28 days			3 hours	24 hours	7 days	28 days			
Missouri Rapid Set Concrete Patching Material - Vertical and Overhead Repairs JSP-02-01	Cementitious concrete	1000	1500	n/a	n/a	80% minimum (Procedure B, 300 cycles) [2]	1500	3000	n/a	n/a	Water Storage, +0.15 Air storage, -0.15	Rapid chloride Permeability [ASTM C1202]: 1000 coulombs at 28 days	Gray
	Polymer-modified concrete	n/a											
	Polymer Concrete	1000	1500	n/a	4 to 8	n/a	n/a				n/a		
Ohio Supplemental Specification 843	n/a	n/a	n/a	1500	n/a	n/a	n/a	1500	3000	5000	Min 0.0% to max. +0.3% at 28 days	Modulus of Elasticity [ASTM C469]: 3500 to 4000 ksi at 28 days	Not available
New York [1] Section 701-08	n/a	200	n/a	n/a	n/a	Max. 1% loss after 25 cycles	n/a	n/a	4000	5000	Contraction 0% Expansion 0.4%	Initial set: Min. 15 minutes Total Chloride content (% by weight): Max. 0.05 Total Sulfate content (% by weight): Max. 5	Munsell Neutral Scale 4.0 to 8.5
Texas Department Materials Specification (DMS-4655)	Type C - Vertical and Overhead Repair Materials	n/a	n/a	1750 [3]	Informational [4]	n/a	n/a	n/a	n/a	3600 [5]	Air storage[6], Max. 0.07% at 28 days	Min. Splitting tensile strength [ASTM C496]: 350 psi at 28 days Modulus of Elasticity [ASTM C469]: Informational	Not available

State/ Specification	Type	Bond Strength by Slant Shear, psi (minimum) [ASTM C882/C928]			Linear Coefficient of Thermal Expansion (in 10^{-6} in/in/ °F) [ASTM C531]	Resistance to Rapid Freezing and Thawing [ASTM C666]	Compressive Strength, psi (minimum) [ASTM C39]				Length Change* (maximum) [ASTM C157]	Other tests	Color
		24 hours	7 days	28 days			3 hours	24 hours	7 days	28 days			
Iowa [Materials IM 491.08]	n/a	1000	n/a	n/a	n/a	70% minimum (after 14-day moist cure and 300 cycles) [7]	n/a	2000 [8]	n/a	n/a	28 days in water, +0.15% 28 days in air, -0.15% [9]	Direct Tension [ASTM C1583]: Min. 260 psi at 28 days Resistivity [AASHTO T358]: Min. 29 k-Ω-cm; 28-day moist cure Rapid chloride Permeability [AASHTO T277]: Max. 1500 coulombs at 28 days; 28-day moist cure	Not available
Washington [Construction Bulletin – Structural Repairs]	n/a	n/a	n/a	n/a	n/a	90% minimum after 300 cycles	n/a	n/a	n/a	6000	+0.05% [10]	Bond Strength [ASTM C1583]: Min. 250 psi at 28 days Rapid chloride Permeability [AASHTO T277]: Max. 2000 coulombs at 28 days	Not available

Source: [*] Curing and drying conditions/duration unclear. [1] Test methods not specified; [2] Procedure A may be used in lieu of Procedure B; [3] Substrate: Max. w/c 0.45, Max. nominal agg. 0.75", Comp. Str. at 28 days 5 to 6 ksi; [4] Test per Tex-428-A; [5] 3 × 6 in. cylinders; [6] Air drying after demolding at 1 day; [7] AASHTO T161, Method A or B; [8] AASHTO T22 or T106; [9] AASHTO T160; [10] modified per ICRI 320.3R

A.3.2.3 Curing

Transportation agencies commonly specify curing per manufacturer recommendations (Ohio, New York, Texas, Washington, and Indiana). Moist curing for 1 to 4 days, application of curing compound immediately after finishing, and curing till the repair material attains a compressive strength of 1500 psi are the other requirements seen in the transportation agencies' specifications reviewed (Illinois, Iowa, Michigan, Missouri, Ohio, Ontario, Texas, and Indiana).

A.3.2.4 Inspection

Acceptance of the patch repairs are typically done by sounding the patch for delamination. Acceptance criteria of the repair can also include minimum compressive strength or other properties such as tensile bond strength or hardened air void distribution.

A.4 Previous Laboratory Studies on Performance of Concrete Patches

WJE performed a review on several past research studies aiming at evaluating performance of repaired concrete members using lab-scale experiments. A summary of the reviewed studies is provided in Table A.7. Repaired specimens were typically slabs or small beams subjected to either environmental exposure or mechanical loading. A notable study evaluating cracking of patches under different field environmental conditions was conducted by Emmons et al. (1998) for the U.S. Army Corps of Engineers. Reinforced concrete slabs of 7 x 25 x 79 inches were repaired using different materials and exposed to field conditions at three sites in Illinois, Florida, and Arizona. The cracking condition of the patches were periodically documented, and the repair materials were rated in terms of workability and potential for cracking.

Repaired slab specimens of different sizes subjected to cyclic mechanical loadings have been evaluated in several studies. Paramasivam et al. (1995) studied repaired reinforced concrete slab specimens of 3 x 12 x 24 inches under 100,000 cycles of loading at several different stress levels. Degradation of flexural rigidity, development of cracks, and ultimate strength of repaired slabs were evaluated. A similar study was performed by Lemieux et al. (2005) using larger slab specimens of 8 x 39 x 130 inches repaired using a concrete overlay subjected to 500,000 cycles of loading. Smaller, unreinforced concrete prisms (3 x 4 x 16 inches) repaired with a concrete patch were studied by Wang and Gupta (2021) to evaluate fatigue life of the patches in tension and degradation of dynamic modulus of elasticity (MoE) with cyclic loadings. While these small concrete specimens were convenient to facilitate testing of a large number of specimens in different conditions, they are small and do not represent behavior of patches in reinforced or prestressed concrete structures.

Table A.7. Summary of previous work on performance of concrete repair utilizing lab-scale specimens

Reference	Specimen[1]	Type of Test	Measurements
Paramasivam et al., 1995	Repaired reinforced concrete slab: 3 x 12 x 24 x inches	Cyclic loading, various stress ranges, 100k cycles	Flexural rigidity. Crack observation. Ultimate flexural resistance; failure mode.
Emmons et al, 1998	Repaired reinforced concrete slab: 7x 25 x 79 inches	Field condition exposure (Illinois, Florida, Arizona)	Cracking rating.

Reference	Specimen[1]	Type of Test	Measurements
Lemieux et al., 2005	Repaired reinforced concrete slab: 8 x 39 x 130 inches	Cyclic loading, constant stress range, 500k cycles	Flexural rigidity. Ultimate flexural resistance; failure mode.
Wang and Gupta, 2021	Repaired unreinforced concrete beam: 3 x 4 x 16 inches	Cyclic loading, various stress ranges, 100k cycles total	Fatigue life to failure. Endurance limit. Dynamic MoE.

Note: [1] All repairs were horizontally applied

These previous research projects provide some insight into behavior of concrete repairs under either environmental exposures or cyclic loadings; however, all the repairs were horizontally applied from the topside, and thus, the difficulties associated with installation in a vertical or overhead position were not captured. In addition, none of these projects assessed the combined effect of environmental exposures and cyclic loadings, to which repair patches in bridges are typically subjected.

A.5 Survey of WJE Practices on Concrete Patches

The research team performed a brief internal survey of WJE's concrete repair designers focusing on their experiences with performance of various repair materials and their best practices on the use of different surface preparation techniques and supplemental anchorages. The findings of this survey were used to select repair materials and anchorage details for the laboratory investigation (Task 4).

A.6 References

ICRI 320.1R-2019, Guideline for Selecting Application Methods for the Repair of Concrete Surfaces

ACI RAP Bulletin 6, Field Guide to Concrete Repair Application Procedures, Vertical and Overhead Spall Repair by Hand Application

ACI 546R-14, Guide to Concrete Repair

ACI 546.3-23, Materials Selection for Concrete Repair—Guide

Papas, S. "Cementitious Concrete Repair Materials and Grouts: When is Fast Too Fast?," International Institute of Building Enclosure Consultants (IIBEC), 2014.

ACI RAP Bulletin 4, Field Guide to Concrete Repair Application Procedures, Surface Repair Using Form-and-Pour Techniques

ASTM D4580-03 (2007), Standard Practice for Measuring Delamination in Concrete Bridge Decks by Sounding.

ICRI 310.2R-2013, Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, Polymer Overlays, and Concrete Repair

ICRI 310.1R-2008, Guideline for Surface Preparation for the Repair of Deteriorated Concrete Resulting from Reinforcing Steel Corrosion

Evaluation and Repair of Concrete Structures, Department of the Army, U.S. Army Corps of Engineers, 1995.

ICRI 310.2R-2013, Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, Polymer Overlays, and Concrete Repair

ICRI 310.3R-2014, Guideline for the Preparation of Concrete Surfaces for Repair Using Hydrodemolition Methods

ACI RAP Bulletin 5, Field Guide to Concrete Repair Application Procedures, Surface Repair Using Form-and-Pump Techniques

Kurt F. von Fay, Guide to Concrete Repair, Second edition, U.S. Department of the Interior Bureau of Reclamation

P. H. Emmons, A. M. Vaysburd, R. W. Poston and J. E. McDonald, "Performance Criteria for Concrete Repair Materials, Phase II Field Studies," U.S. Army Corps of Engineers , Vicksburg, MS , 1998.

P. Paramasivam, K. C. G. Ong, B. G. Ong and S. L. Lee, "Performance of Repaired Reinforced Concrete Slabs Under Static and Cyclic Loadings," Cement and Concrete Composites, no. 17, pp. 37-45, 1995.

M. Lemieux, R. Gagné, B. Bissonnette and M. Lachemi, "Behavior of Overlaid Reinforced Concrete Slab Panels Under Cyclic Loading—Effect of Interface Location and Overlay Thickness," ACI Structural Journal, 2005.

B. Wang and R. Gupta, "Performance of Repaired Concrete under Cyclic Flexural Loading," Materials, vol. 12, no. 1363, 2021.

APPENDIX B. EVALUATION OF VERTICAL AND OVERHEAD REPAIR PRACTICES IN WISCONSIN

APPENDIX B. EVALUATION OF VERTICAL AND OVERHEAD REPAIR PRACTICES IN WISCONSIN

WJE developed and conducted a survey of WisDOT staff regarding their vertical and overhead (VOH) repair practices. This survey was followed up by virtual meetings with the staff to discuss their responses in greater detail.

The survey questionnaire contained twelve questions on the following aspects of VOH repair:

- Repair strategies used
- Repair materials
- Surface preparation
- Curing
- Differences between repairs over traffic vs not over traffic
- Factors influencing performance of repairs
- Areas where improvements are most valuable

The survey was sent to multiple engineers in each of the five regions[1] within WisDOT and also to the Bureau of Structures (BOS)'s Maintenance and Inspection team. The survey questionnaire and the responses received are provided in the Appendix. A summary of the responses and follow-up discussions is provided Section B.1, followed by an evaluation of the repair practices in Section B.2.

B.1 Summary of Survey Responses and Discussions

Bridge inspection and repair in Wisconsin are managed by the BOS, which has a Structure Inspection & Repair Unit (SIR) in the central office, and by engineers in the five regional offices. The bridge repair may be performed by the SIR unit, a county maintenance crew, or a contractor (let project). Regional engineers coordinate with the SIR and county crews in bridge repair projects. Smaller, routine repairs are typically performed by county maintenance crews, whereas larger, more complex repairs are performed by the SIR unit or via LET project.

In this section, the responses and discussions on each of the aspects of VOH repair listed above are summarized. For the purpose of reporting, the responses from the two members of the BOS and the four members of the Southeast (SE) region that responded were averaged to give one result for each region.

B.1.1 Repair strategies used

The survey asked the respondents to rate how commonly each of the VOH repair strategies listed in Table B.1 are used within their region on a scale of 0 (never) to 3 (commonly). The average rating of each region and the overall average across all regions are tabulated in Table B.1.

[1] North Central (NC), Northeast (NE), Northwest (NW), Southeast (SE), and Southwest (SW)

Table B.1. Survey response to question on various repair strategies used (average of each region).

Repair Strategy	BOS	NW	NC	NE	SW	SE	Average
Coating exposed steel reinforcement with a zinc-rich primer without patching	2.5	2	1	2	0	2.0	**1.6**
Patching with a hand-applied material	2.5	1	2	2	2	3.0	**2.1**
Patching with a form-and-pour material	1.5	2	2	2	3	3.0	**2.3**
Patching with a form-and-pump material	0.5	2	2	1	0	1.0	**1.1***
Shotcrete	1.0	1	1	1	2	1.5	**1.3**
Non-structural FRP wrap	2.0	3	2	1	2	2.3	**2.1**

Note: BOS and SE had more than one response to the survey and their responses were averaged. Empty cells indicate no response. Rating scale: 3= commonly, 2= sometimes, 1= rarely, 0=never.

**Rarely used, installed by a contractor; it was clarified during discussions that most respondents meant pumping of the concrete from a truck to the repair area as opposed to pumping concrete through ports into a sealed formwork with pressure.*

Coating exposed steel reinforcement without patching is typically used under one or more of the following conditions:

- Overhead repair above traffic where spall is left unpatched due to concerns of a failed patch falling on traffic and where the spall is small with difficult access for repair (e.g. spalls at girder ends)
- As a temporary measure to slow corrosion until for the spall can be repaired (typically within a year)

Epoxy coatings as well as zinc-rich primer (ZRP) applied by spraying or brushing have been used for coating the exposed reinforcing steel.

Patching with a hand-applied material or a form-and-pour material was found to be the most common repair strategy. Patching with a hand-applied material is used for repair areas that are small in size or when access does not allow for form-and-pour patching (e.g. overhead patching on the underside of a bridge deck). Patching with form-and-pour material is typically used for large repair areas and when there is access for formwork.

Patching with form-and-pump is rarely used because this method requires special equipment and is expensive. When used, e.g. if access does not allow for form-and-pour method, the repair is typically performed by a contractor. Some respondents indicated the use of form-and-pump method in the survey tabulated in Table B.1. However, they clarified during the follow-up discussions that they actually meant pumping of the concrete from a truck to the repair area, as opposed to the pumping concrete through ports into sealed formwork.

Shotcrete has been used on piers, abutments, and underside of decks where access is challenging for hand-applied or form-and-pour patching and/or where the larger repair quantity made shotcrete cost effective relative to the other repair methods. Recently in Wisconsin, shotcrete has always been performed by a contractor, since it requires special equipment and qualified operators. This has made this method expensive. First-hand experience of the respondents with shotcrete installation and long-term performance is limited. While many respondents expressed a favorable impression on quality of shotcrete repairs, some early failures of shotcrete used for deck underside repairs (within 2 years of installation) were noted. The causes of these failures, whether due to surface preparation, materials, or installation, were not clear. WisDOT standard specifications do not address shotcrete, and, where used, shotcrete repairs have been specified using a special provision on a project basis.

Non-structural fiber reinforced polymer (FRP) wrap installed over a concrete patch has been used to contain patches over traffic to address concerns with potential failed patches falling onto traffic. The wrap provides protection to the repair by sealing it and contains any patch failures from falling on traffic. FRP wrap is typically used as pre-saturated rolls and extend 6 to 12 inches beyond the patch.

FRP wrap is generally believed to improve longevity of the patches; however, performance of patches with FRP wrap is typically not monitored, and delamination in FRP-wrapped patches has been reported.

B.1.2 Repair materials

WisDOT has a qualified product list for horizontal concrete repairs, but these materials may not be appropriate for VOH repairs. When VOH repairs are performed by the SIR Unit or counties, repair materials are generally selected based on experience and/or availability. In some instances, maintenance crews used materials solely because the repair materials were readily available.

Based on the respondents' responses, various repair materials have been used for VOH repairs with varying degrees of success. A list of products used and the general experience of the respondents with performance of the repair materials are summarized in Table B.2.

Experience with performance of the repair materials indicated by the respondents was qualitative and based on consideration of workability and set time of repair materials as well as durability of the repair. Some respondents acknowledged that in some cases, poor performance of the repair was likely due to insufficient surface preparation and/or improper mixing and installation, rather than due to the repair material.

Table B.2. Summary of repair materials used for VOH repairs and respondents' experience with performance of repair materials

Repair Materials	Manufacturer	Total respondents	Respondents - good performance	Respondents - not-good performance	Respondents – mixed performance	Respondents - unknown performance	Comments by Respondents
SikaQuick VOH	Sika	4	4	0	0	0	Girder repairs with & without forms. Either formed and poured or 'wet-packed'
RepCon 928	SpecChem	2	2	0	0	0	Formed deck edge repairs. Girder Repairs with forms
Speccopatch RS	Specco Industries	2	2	0	0	0	Best girder repairs with & without forms.
Speedcrete PM	Euclid Chemical	1	1	0	0	0	Used to patch girder hit by construction vehicle; location not directly exposed to water
Verti-Patch	Unknown	1	1	0	0	0	Easy to use for vertical patch but did not stay in overhead patch.
Quickcrete Rapid road	Quickcrete	1	0	1	0	0	Originally worked, but they have since changed their mix design and it just disintegrates to mush. Used in past for curb/deck patches
Phoscrete-F3-VO	Phoscrete Corporation	1	0	1	0	0	Hard to work with and cracked shortly after placement. Only tried on vertical patch.
Dayton Superior PermaPatch VO	Dayton Superior	1	0	0	0	1	Performance unknown
Sikacrete 211	Sika	1	0	0	0	1	Performance unknown
Ready-mixed concrete[1]	--	3	1	0	1	1	Used for slab edge repairs

[1] *Grade C concrete (WisDOT Standard Specification) typically used*

B.1.3 Surface Preparation

There were no standard repair or surface preparation procedures for VOH repairs reported by the respondents. VOH repairs are typically performed based on experience of staff with consideration of manufacturer's recommendations and WisDOT Standard Specification Section 509.3.7, Concrete Surface Repair.

The survey asked the respondents to rate how often they use the surface preparation methods listed in Table B.3 on a scale of 0 (never) to 3 (commonly) within their region. The average rating of each region and the overall average across all regions are tabulated in Table B.3.

Table B.3. Survey response to question on repair surface preparation methods used (average of each region).

Surface Preparation	BOS	NW	NC	NE	SW	SE	Average
Abrasive blasting of repair cavity and bars	1.5	2	3	1	0	0.8	**1.4**
Wire brushing of repair cavity and bars	2.0	1	3	1	2	2.5	**1.9**
Saw cut and chipping squared edge	2.5	3	2	3	3	3.0	**2.8**
Chipping behind bars	2.0	1	2	2	3	3.0	**2.2**
Coating bars	3.0	0	3	2	3	2.0	**2.2**
Bonding agent	1.5	0	1	0	3	2.0	**1.3**
SSD pre-treatment	1.5	2	1	1	--	3.0	**1.7**
Cleaning with compressed air	3.0	3	3	3	3	2.3	**2.9**
Cleaning with low-pressure water (1,000-5,000 psi)	1.0	0	0	0	2	1.0	**0.7**
Cleaning with high- and ultra-high-pressure water (5,000-45,000 psi)	1.0	0	0	0	0	0.0	**0.2**
Anchorage	1.5	1	2	1	2	1.5	**1.5**
Cathodic protection anodes	1.5	0	1	1	2	2.3	**1.3**

Note: BOS and SE had more than one response to the survey and their responses were averaged. "--" indicate no response. Rating scale: 3= commonly, 2= sometimes, 1= rarely, 0=never.

The responses are discussed for each group of surface preparation components in the subsections below.

B.1.3.1 Concrete Removal

Concrete removal is typically performed by squaring the repair area with saw cutting to a depth of 1/2 to 3/4 inch and chipping concrete with small hammers. WisDOT Standard Specification Section 509 - Concrete Overlay and Structure Repair limits the weight of hammer to be no more than 35 pounds for general chipping and 15 pounds for chipping within 1 inch of reinforcing steel.

Regarding requirements for chipping behind bars, most respondents mentioned WisDOT Standard Specification Section 509.3.7 – Concrete Surface Repair, which requires removing concrete to sound concrete or to 1 inch behind existing bars, whichever depth is greater, at locations shown in the plan or as directed by the engineer. Some respondents mentioned that chipping behind existing bars is also based on judgment; for example, concrete is removed behind reinforcing bars if more than 30% of the surface area has reinforcing bars exposed, the bars are corroded, or unsound concrete extends behind the bars. The challenge of removing sound concrete behind bars was also mentioned. The depth of removal behind bars can also be based on a rule of thumb: it is sufficient if you can put your fingers behind the bar and can grab it. For patching prestressed concrete girders, chipping concrete behind prestressing strands is typically avoided due to concerns about damaging the strands.

B.1.3.2 Surface Cleaning and Conditioning

Sandblasting the substrate concrete and the exposed steel is not consistently performed, varying based on availability of equipment, quantity of repair, and environmental/safety considerations. County crews generally do not have the equipment for abrasive blasting, while the SIR Unit has the capability of doing abrasive blasting. Typically, no containment is used when blasting over land. Containment of the abrasive media is required when performing sandblasting over water bodies. In the Milwaukee area (southeast region), abrasive blasting is typically not performed due to environmental/safety restrictions. Some respondents also questioned if abrasive blasting is necessary for successful repairs.

Other surface preparation methods such as compressed air, low power washing, manual or powered wire brushing, and/or needle scaling have been used for surface preparation. Needle scaling was used for small patches in lieu of sandblasting and was noted to be more effective than wire brushing in removing corrosion products from reinforcing bars. Powered wire brushing is more effective and used more often than manual wire brushing.

Treatment for overhead spalls without patching includes removing loose, delaminated concrete and if reinforcing bars are exposed, coating them with a zinc rich primer, epoxy coating material, or corrosion inhibitor. Reinforcing bars are typically cleaned by wire brushing before coating. In some cases, the exposed bar was cleaned using sandblasting and supplemental steel was welded in place prior to coating.

Compressed air is the most common method of cleaning substrate surfaces as the equipment is readily available. Cleaning with low-, high- and ultra-high-pressure water (1,000-45,000 psi pressure) is not common due to unavailability of equipment. High- and ultra-high-pressure water has been used for hydrodemolition in girder repair.

Application of bonding agents or scrub coats to the substrate surface is sometimes performed prior to installation of the repair material.

Prewetting the substrate to achieve a saturated surface dry (SSD) condition is not common in Wisconsin. Some respondents mentioned that the surface is continuously prewetted for a couple of hours before patching while some other respondents noted that the surface is only wetted and water is blown off right before patching. When the repair is performed by county crews, the substrate surface in some cases was not prewetted at all.

B.1.3.3 Supplemental Anchorage

Supplemental anchorage is sometimes used, based on the responses in Table B.3, to tie the repair material to existing concrete for thin patches that do not encompass existing reinforcing bars. Generally, no anchorage is used if the repair area includes reinforcing bars or strands. Anchors are also not used if the repair is to be wrapped with FRP. The use of supplemental anchorage is generally based on the experience of the repair crews.

The survey additionally asked the respondents to rate how often they use the various anchorage methods listed in Table B.4 on a scale of 0 (never) to 3 (commonly) within their region. The response received is tabulated in Table B.4.

Table B.4. Survey response to question on anchorage methods used (average of each region).

Anchorage Method	BOS	NW	NC	NE	SW	SE	Average
No anchorage	2.0	3	1	3	1	3.00	**2.2**
Tapcon concrete screw anchors with steel wire	0.5	1	2	1	0	1.50	**1.0**
Tapcon concrete screw anchors without steel wire	1.0	1	1	1	3	1.75	**1.5**
Epoxy-doweled bars	0.5	0	1	0	2	0.50	**0.7**
Welded wire mesh	0.0	0	1	0	0	0.00	**0.2**
Other	-	0	-	-	-	1.00*	**0.5**

Notes:

BOS and SE had more than one response to the survey and their responses were averaged. "-" indicate no response.

Rating scale: 3= commonly, 2= sometimes, 1= rarely, 0=never.

** Wedge anchors have been used*

Tapcon concrete screw anchors are the most common anchorage method. Steel wire is sometimes used with the tapcon screws. Screw anchor spacing of 4 inches to 1 foot has been used. Some respondents recommended using stainless steel Tapcon anchors to address concerns with anchor corrosion.

Some respondents preferred using wedge anchors, doweled bars, and nails to Tapcon anchors since the Tapcon anchors are more susceptible to head break-off. Wedge anchors of 3/8- or 1/2-inch diameter, spaced at 2 to 4 feett on centers or closer (1-foot spacing) at splices, have been used on large repairs (e.g. 20 foot x 7 foot x 3 inch deep repair on abutments); in this case, welded wire mesh of 1/8-inch diameter, 6 x 6 inch spacing, was also used, being tied to the wedge anchors. Epoxy-doweled bars are used for large repair areas that have significant section loss of existing reinforcement. An example use of epoxy-doweled bars is for slab edge repair where transverse bars are doweled into the existing deck to provide anchorage for the repair and to support supplemental longitudinal bars (Figure B.1).

Based on the survey responses, welded wire mesh is rarely used. One of the respondents had concerns about corrosion of black steel welded wire in repairs and recommended using stainless steel or coated wire mesh.

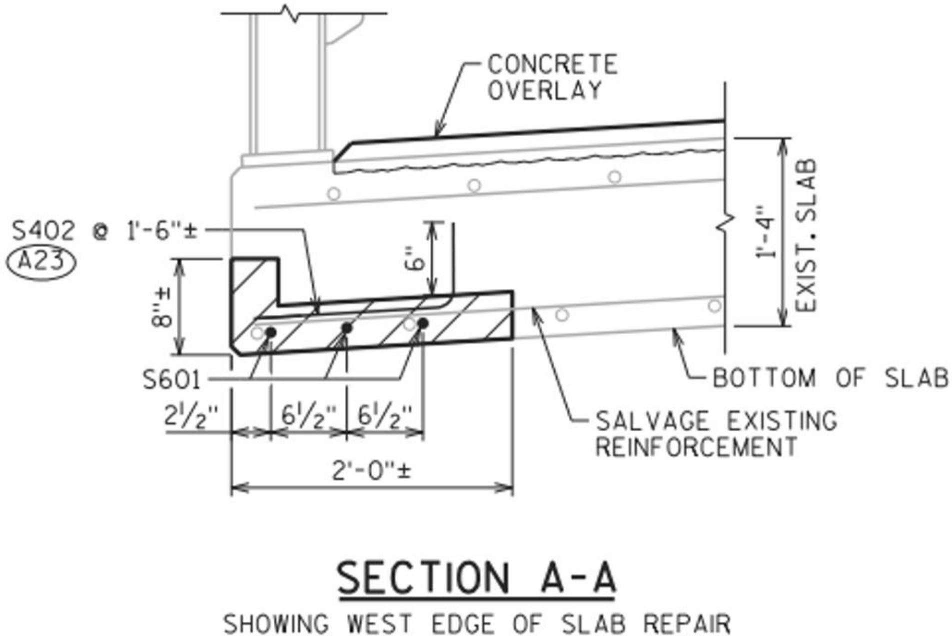

Figure B.1. Use of epoxy-doweled bars as supplemental anchorage for slab edge repair (provided by WisDOT Southeast region)

B.1.3.4 Cathodic protection

Cathodic protection using galvanic anodes is sometimes used by the SIR Unit and in LET projects, but generally not used in repairs by county crews. Some respondents mentioned that galvanic anodes have been used more frequently in recent years.

B.1.4 Curing

The survey asked the respondents to rate how often they use the curing methods listed in Table B.5 for VOH repairs on a scale of 0 (never) to 3 (commonly) within their region. The response received is tabulated in Table B.5.

Table B.5. Survey response to question on curing used for VOH repair (average of each region).

Curing Method	BOS	NW	NC	NE	SW	SE	Average
Curing compound	2	0	1	0	0	1.50	**0.8**
Wet-burlap	0	0	1	1	1	0.25	**0.5**
Plastic sheeting	0	0	1	1	0	0.50	**0.4**
Other	-	0	-	-	0	2.50*	**0.8**

Notes:

BOS and SE had more than one response to the survey and their responses were averaged. "-" indicate no response.

Rating scale: 3= commonly, 2= sometimes, 1= rarely, 0=never.

** For formed repairs, the form provides curing, and no additional curing provided after form is removed*

Based on the survey and interviews, no curing is applied to VOH hand-applied repairs in some regions. However, in other regions, curing compounds are sometimes used on hand-applied repairs and on formed repairs after removal of the form if the form is removed within 1 or 2 days after installation. Respondents from the Southeast region mentioned that it is common that the form is left in place 5 to 7 days or longer, and no additional curing is applied after removal of the form. Some respondents noted that the form was left in place permanently in some instances.

Wet burlap and plastic sheeting are rarely used because they are difficult to be secured in place for VOH repair and need to be removed after completion of curing. Wet burlap and plastic sheeting have been used for curing repair of bridge deck edges where they can be conveniently secured to the top of the deck. When used, the wet burlap was left in place for 3 to 7 days.

On LET projects, information on curing is limited, and curing practice may be different due to contract requirements.

B.1.5 Differences between repairs over traffic and not over traffic

All respondents mentioned that overhead patching for spalled areas above traffic is typically not performed unless non-structural FRP wrap is used to contain the patch due to concerns of failed patches falling onto traffic. When the spalled areas are not patched, loose concrete is removed and the exposed reinforcing steel is coated with a zinc-rich primer, epoxy coating, or corrosion inhibiting coating.

Some respondents mentioned that if a repair is located over traffic (which is not typical), the quality of the repair is important to avoid defects such as honeycombing because patching the voided repair is not an option.

B.1.6 Factors influencing performance of repairs

Surface preparation, material selection, and presence of mechanical anchors were mentioned as the factors having the most influence on the performance and durability of VOH repair.

Some respondents believe that the life of a repair is dependent more on adequate surface preparation and installation and less on repair material. Removal of all unsound concrete (especially behind bars), proper cleaning of reinforcing steel (if present), installing mechanical anchors, and achieving saturated surface dry (SSD) condition of the substrate are critical to improve the longevity of patch repairs.

Using repair materials intended for vertical or overhead applications and following manufacturer's instructions are also important. Some respondents mentioned that repair materials not intended for VOH repairs have been used unknowingly or just because they were locally available, resulting in unsuccessful repairs.

End of life for a repair is defined by the respondents as having a large number of wide cracks and delamination or spalling of the repair. In this context, the expected service life for VOH patching repairs without FRP wrap is typically 5 to 10 years; however, some repairs have been observed to fail within 2 years or installation while others have lasted 12 to 15 years. With FRP wrap, a longer service life is expected, from 10 to 20 years, although this expected service life has not been based on actual monitoring of the performance of the repairs.

B.1.7 Areas where improvements are most valuable

The respondents identified the following as areas where improvements are desired:

- Specification or guidance specifically for VOH repair, which includes surface preparation requirements.
- An approved product list for VOH repair.

B.2 Critical Evaluation of Current VOH Repair Practices in Wisconsin

Based on information collected from the survey and discussions with WisDOT staff (as outlined in Section B.1), the literature review (as outlined in Appendix A), and WJE's experience, a critical evaluation of the VOH repair practices in Wisconsin is provided in this section.

B.2.1 Repair Strategies

The survey of WisDOT indicates that hand-applied and form-and-pour repairs are the most common repair strategies for VOH patching. Most respondents indicated that form-and-pour is the preferred method when access allows for formwork installation, while hand-applied patching is generally limited to small, shallow repairs. This practice by WisDOT is in line with industry best practices as the quality of hand-applied patching is generally less consistent than form-and-pour repairs and can vary widely with surface preparation, installation, and curing and from one repair material to another.

Patching repairs are not typically performed for overhead locations above traffic, unless the patch is subsequently contained by FRP wraps. While the FRP can provide protection to the patch from falling onto traffic, it is expensive. There is little information from the industry and other transportation agencies on the cost effectiveness of using FRP for non-structural purposes. If the right repair material is used with proper surface preparation, anchorage, installation and curing, overhead repair can be durable and may be more cost-effective than using FRP wrap. Further research to evaluate benefits and cost-effectiveness of using FRP wraps to contain concrete patches is needed to assess the value provided by this strategy.

In lieu of patching in areas over traffic, coating of exposed reinforcing steel in the spalled area has been used by WisDOT and others to slow down corrosion of the steel. Surface preparation of the steel surface is typically minimal and may not completely remove chloride-contaminated materials from the steel. Further, it will not address chloride contamination in the surrounding concrete. Thus, corrosion may re-initiate under the coating and develop on the surface or embedded steel adjacent to the exposed and coated steel, resulting in additional delamination and spalling. Zinc-rich primers may be more effective than epoxy or cementitious coatings, since the zinc can provide some level of galvanic protection, in addition to serving as a barrier.

Form-and-pump concrete repair is not common in Wisconsin. Repair materials intended for form-and-pump applications are commercially available, and when applied properly, this method can provide quality repairs in areas where the form-and-pour method is not viable, e.g. underside of bridge decks. However, this method requires special equipment and mix design, and can be expensive, since it requires a contractor with applicable expertise.

While many respondents indicated a positive impression with quality of shotcrete repairs, some failures have been reported on shotcrete repair of bridge deck underside within 2 years of installation where the repair spalled, exposing corroded reinforcing steel. Based on industry and WJE experience, quality VOH repairs can be achieved with shotcrete, but like other repair methods, proper surface preparation is critical for performance of the repair. In addition, shotcrete should be performed by an experienced and qualified contractor using materials specifically designed for this application. Finally, as observed by survey respondents, the cost of mobilizing to perform shotcrete repairs is typically justified only if the repair project is sufficiently large.

B.2.2 Repair materials

WisDOT currently does not have a qualified product list and guidance for material selection for VOH repairs. Repair materials are selected by the maintenance crews, based on their experience and/or availability of repair materials. The survey indicates that various repair materials have been used, but performance of the repairs is not monitored, and there is little information available for comparison of repair materials. Surface preparation and repair material installation also vary among counties and regions, making such a comparison complicated. In some cases, repair materials not intended for VOH applications were reportedly used for VOH repairs just because they were locally available. A wide range of VOH repair compatible materials are available; selection of materials specifically intended for the purpose of the repair can be expected to produce more durable results and easier installation.

B.2.3 Surface Preparation

The SIR Unit generally follows industry best practices in terms of concrete removal and surface preparation. However, practices by counties vary due to experience, knowledge, availability of equipment and environmental regulations, and sometimes deviate from the best practices. One respondent mentioned they have seen many repairs without saw cuts. Saw cuts around edges of the repair are important as they provide anchorage for the patch to the substrate and help reduce debonding along the edges of the repair.

Several respondents mentioned that concrete is not always removed behind exposed reinforcing bars during performance of VOH repairs. The need for removing concrete behind rebars depends on the cause of deterioration. If reinforcing bars are corroded due to chlorides, the concrete around the bar is likely chloride-contaminated, and thus, it is important to completely remove this chloride-contaminated concrete. It is also important to completely remove corrosion products on the reinforcing steel. Otherwise, the chloride left behind in the concrete or on the steel will continue to promote corrosion and reduce the life of the repair. When removing concrete behind bars is needed, the 1-inch clearance in the WisDOT Standard Specification 509.3.7 is consistent with industry standards and can be expected to meet the objective of removing detrimental contaminated concrete. If a concrete spall is not due to corrosion (e.g. vehicle impact) and the remaining concrete is sound, removal behind the bar, which may be difficult or undesired, e.g. removing concrete around prestressing steel is generally not desired because of concerns about damaging the steel and/or changing structural behavior of the member, may not be necessary. However, if the bars are not present to provide anchorage to the repair, an alternate supplemental anchorage should be provided to mechanically tie the patch to the substrate.

The types of supplemental anchorages used in Wisconsin varies among counties and regions. Different types of anchors have been used, including Tapcon screw anchors, wedge anchors, epoxy-doweled bars, and nails, but there are no track records on effectiveness of the anchorage. There is a lack of standard guidelines on anchor details, including type, size and configuration, and thus the anchor details are determined on a project basis based on experience and judgment of the maintenance crews.

Concrete removal for VOH repair is typically done using chipping hammers, which could leave microcracking/bruising in the near-surface substrate. If not removed, the microcracking/bruising will adversely impact the bond between the repair and substrate. Abrasive blasting is one of the most effective methods to remove the weakened substrate surface layer and promote the bond between the repair and substrate. The use of abrasive blasting is inconsistent among the SIR and county crews. Abrasive blasting is typically not used when the repair is performed by county crews since blasting and safety equipment is not available. The SIR Unit has the capability of abrasive blasting, but the use varies depending on size and location of the repair and environmental restrictions.

An alternative method to remove microcracking in the substrate is water blasting at high- or ultra-high pressure (5,000 to 45,000 psi) (ICRI-310.2R-2013); however, none of the survey respondents reported the use of high- or ultra-high pressure waterblasting for surface preparation since the equipment is not readily available (Note: one survey respondent indicated that high- or ultra-high pressure waterblasting was used for hydrodemolition to remove concrete during girder repair.)

The survey indicates that the substate surface is typically not conditioned to a saturated surface dry (SSD) condition, which would require saturating the substrate for at least several hours and blowing off water from the surface. While the SSD condition is difficult to achieve for VOH repair, the recommendation from most manufacturers is that the substrate be prewetted without standing water prior to placement of the repair material, especially for hand-applied applications in which the repair mortar is highly sensitive to changes in the water content. A dry, hot substrate surface will absorb water from the repair material, and can result in a layer of unhydrated repair material at the interface with the substrate, adversely impacting the bond between the repair and substrate.

B.2.4 Repair Materials Installation and Curing

Repair materials should be installed following manufacturer’s instructions. Some repair materials, especially hand-applied repair mortar, are highly sensitive to changes of water content, and thus, the addition of water should strictly follow values recommended by the manufacturer.

Based on the survey and interviews with WisDOT staff, curing is only “sometimes” or “rarely” applied to VOH hand-applied repairs by the SIR Unit or county crews. Curing is critical, especially for hand-applied mortars, which may be more susceptible to drying shrinkage due to the absence of coarse aggregate and the high paste-to-aggregate ratio. Curing of VOH repairs is important to reduce the risk of cracking, encourage hydration of cementitious repair materials, and improve the durability of repairs. Thin repairs are also more prone to shrinkage cracking.

While wet curing is typically the most effective for curing cementitious repair materials, it may not be practical for hand-applied VOH repairs. In lieu of wet curing, curing compound may be used to reduce the loss of water from the repair. Effectiveness of curing compound may vary with the repair materials, the type and application timing of curing compound; thus, manufacturer's instructions on the use of curing compound should be followed.

For formed repairs, the form provides initial curing for the repair material. The age and/or strength of repair material required before the form is removed may vary with the repair material. Some materials may need additional curing, e.g. curing compound, after removal of the form. Manufacturer's recommendations on curing should be followed.

APPENDIX B1. SURVEY OF WISDOT STAFF – QUESTIONNAIRE

WISCONSIN HIGHWAY RESEARCH PROGRAM – PROJECT NO. 0092-24-05

Vertical and Overhead Concrete Patches

This WisDOT-sponsored research project is being performed by Wiss, Janney, Elstner Inc., aiming at improving vertical and overhead concrete patching repair practices for bridges in Wisconsin.

The purpose of this survey is to collect specific and useful information on past and current concrete patching practices in various regions of Wisconsin. Information collected from this survey and follow-up discussion is intended to support the research team's development of a subsequent laboratory testing program and repair guidelines for WisDOT. After we review your responses, we anticipate requesting a brief virtual meeting to allow you to further explain your comments and resolve any questions, if you (the respondent) are willing. This survey is concerned with vertical and overhead patches only.

Please return the completed survey and any questions or comments to Le Pham, PE at lpham@wje.com. Thank you very much for your time and information.

Your name:

Position:

Department/Region:

Email and phone number:

Are you willing to attend a follow-up virtual meeting?:

1. Please list vertical and overhead repair materials (brand and product), if any, that perform well in your experience for vertical and overhead concrete repairs in the order of better performance first. Indicate the intended installation method for each material.

Response:

2. Please list vertical and overhead repair materials (brand and product), if any, that do not perform well in your experience for vertical and overhead concrete repair in the order of worse performance first. Indicate the intended installation method and the main issues with each material.

Response:

3. If you indicated you used shotcrete in question 1, please describe your experience with shotcrete in terms of repair durability, ease of installation, cost of repair, etc. relative to other installation methods.

Response:

4. Do you have a standard patching repair procedure for vertical and overhead repair that you can share with the research team for vertical and overhead concrete repair? If yes, please include it when returning the completed survey. If not, please briefly describe your typical patching repair procedure and tools/equipment used.

Response:

5. Please rate the components of surface preparation for vertical and overhead repair in the table below based on how commonly they are used in your region **(3 = commonly, 2= sometimes, 1= rarely, 0=never).** For each item, please indicate any specific instances where they may not be used and give the reason(s). Also please provide any additional comments or information you would like to share after the table.

Response:

Surface Preparation	Frequency of Use (0 to 3)	Where not used. Give reason
Abrasive blasting of repair cavity and bars		
Wire brushing of repair cavity and bars		
Saw cut and chipping squared edge		
Chipping behind bars		
Coating bars		
Bonding agent		
SSD pre-treatment		
Cleaning with compressed air		
Cleaning with low-pressure water (1,000-5,000 psi)		
Cleaning with high- and ultra-high-pressure water (5,000-45,000 psi)		
Anchorage		
Cathodic protection anodes		
Other		

Additional comments:

6. Please rate the vertical and overhead repair strategies in the table below based on how commonly they are used in your region **(3 = commonly, 2= sometimes, 1= rarely, 0=never)**. Please indicate whether your own agency forces or an external contractor typically perform the repair and list the conditions when each strategy is used. Also please provide any additional comments or information you would like to share after the table.

Response:

Repair Strategy	Frequency of Use (0 to 3)	Performed by Agency (A) or Contractor (C)	Condition when used
Coating exposed steel reinforcement with a zinc-rich primer without patching			
Patching with a hand-applied material			
Patching with a form-and-pour material			
Patching with a form-and-pump material			
Shotcrete			
Non-structural FRP wrap			
Other			

Additional comments:

7. Please rate the methods of anchorage in the table below based on how commonly they are used for vertical and overhead concrete patches in your region **(3 = commonly, 2= sometimes, 1= rarely, 0=never)**. Please indicate under which conditions each method is typically used in the comment (e.g. is anchorage typical for patches over traffic or for shallow patches not containing reinforcement?) Also please provide any additional comments or information you would like to share after the table.

Response:

Anchorage Method	Frequency of Use (0 to 3)	Condition when used
No anchorage		
Tapcon concrete screw anchors with steel wire		
Tapcon concrete screw anchors without steel wire		
Epoxy-doweled bars		
Welded wire mesh		
Other		

Additional comments:

8. For the two most commonly used combinations of surface prep (cited in Question 4) and repair approach (cited in Question 1), please identify the combinations and indicate the expected life of the repair and what end of life looks like.

Response:

9. For the curing methods in the table below, please indicate how commonly **(3 = commonly, 2= sometimes, 1= rarely, 0=never)** and in what condition they are used, and duration of curing for vertical and overhead concrete patches in your region. Also please provide any additional comments or information you would like to share after the table.

Response:

Curing Method	Frequency of Use (0 to 3)	Condition when used	Duration of Curing
Curing compound			
Wet-burlap			
Plastic sheeting			
Other			

Additional comments:

10. Are there any differences in your practice for vertical and overhead repairs located over traffic versus those not over traffic in terms of repair strategies, materials, installation methods, curing time, etc.? If yes, please describe.

Response:

11. Please describe factors that most influence performance and durability of vertical and overhead concrete patching repairs in your experience (for example: repair material properties, repair depth, repair location, the use of anchorage, construction-related factors, contractor's experience, etc.)

Response:

12. If you have other experiences with vertical and overhead repairs that may be useful to developing guidelines, please describe.

Response:

APPENDIX B2. SURVEY OF WISDOT STAFF – RESPONSES

The responses received from WisDOT representatives to Questions 1, 3, 4, 8, 10, 11, and 12 in the questionnaire are provided below. Responses to the other questions are fully discussed in Appendix B. Note: Responses received have been edited for obvious typos.

Question 1

Table B2.1. Responses to Question 1

WisDOT region	Q1: Please list vertical and overhead repair materials (brand and product), if any, that perform well in your experience for vertical and overhead concrete repairs in the order of better performance first. Indicate the intended installation method for each material. Survey Response
BOS – Respondent #1	Phoscrete: Hard to work with and cracked shortly after placement. Only tried on vertical patch. Vertipatch: easy to use but did not stay in overhead patch. Needed to remove so it didn't fall on vehicles. Shotcrete: worked well on vertical patch but went behind the rebar. Tried overhead but very expensive, equipment was expensive and it didn't perform as expected.
BOS - Respondent #2	Speccopatch RS – Best Girder Repairs with & without Forms. Repcon 928 - Girder Repairs with Forms Sika VOH - Girder Repairs with & without Forms Shotcrete – Only completed last year so I can't rate it on my own use."
NW	Speccopatch RS – vertical and overhead spall fill for FRP wrapping and also vertical concrete surface repairs. Sika VOH – Same applications [as above] Shotcrete-dry mix (contractor mix so I don't have details, but they follow ACI Shotcrete Guidelines) – Used for patching vertical and overhead face of pier caps prior to FRP wrapping RepCon 928 – formed deck edge repairs
NC	Sika VOH Surface patch material for spalls on vertical and overhead surfaces. Overhead seems to work best when it's wrapped with RFP materials; otherwise it tends to sag
NE	Standard PCC Patch – Formed and Poured with birds-mouth 1. Shotcrete through LET projects – I know some other regions have done through Maintenance Contracts 2. Sika VOH – either formed and poured or 'wet-packed'
SW	Speed Crete PM
SE – Respondent #1	In the SE Region, concrete patching and repair has typically been done through LET projects. There is an "approved products list" few – if any – products listed for vertical and overhead. There is a note that contractors should use products for that application, but doesn't give specific products or suppliers. Suppliers usually label their patching materials for vertical and overhead as "VOH". There likely isn't widespread knowledge of the difference among construction inspectors. If they see a manufacturer's name on a bag that matches a name on the approved list, it probably isn't questioned. I was made aware of a project where the contractor had 2 types of patching materials on the job site, but the laborers just used whichever was closest or most convenient rather than specifically using the VOH for patching columns and pier caps. Shotcrete has been used on some projects where large quantities of repairs will be done on 1 bridge or when it is for repairs on the underside of a deck or slab. This is a different item than concrete surface repair and contractors don't substitute its use when concrete surface repair is the item in the project. It is likely inefficient to use for a small area due to set-up needs.

WisDOT region	Q1: Please list vertical and overhead repair materials (brand and product), if any, that perform well in your experience for vertical and overhead concrete repairs in the order of better performance first. Indicate the intended installation method for each material.
	Survey Response
	Milwaukee County has done some vertical and overhead repairs, but not often"
SE – Respondent #2	I am not aware of the exact materials that are used. Typically repairs are done with projects, and I inspect at completion of the project. I will also see past repairs in inspections, though the details of these repairs, good or bad, are not known.
SE – Respondent #3	I've approved sikacrete 211, grade C concrete, and Dayton superior perma patch VO for use, but haven't seen how it performs long term. some products used forms and were hand placed, others were hand placed with no forms. Not sure on any of these products performances – I just know I've approved their use for vertical/overhead patches.
SE – Respondent #4	LET construction projects are required to use the WisDOT Approved Products List (APL), but I don't believe any vertical/overhead patching products are on the list of "rapid set concrete repair materials". That list has a note saying a vertical/overhead product must be used for those applications. I don't know what products that contractors are using on LET projects, other than shotcrete/gunnite which is mainly specified for larger repair areas. Some of the materials on the APL have related "VOH" product if you look at the manufacturer websites, and I believe the VOH products are being used when required. WisDOT pays the various counties to do regular maintenance for our structures, but it is rare that we've needed them to do vertical/overhead patching.

Question 3

Table B2.2. Responses to Question 3

WisDOT region	Q3: If you indicated you used shotcrete in question 1, please describe your experience with shotcrete in terms of repair durability, ease of installation, cost of repair, etc. relative to other installation methods.
	Survey Response
BOS – Respondent #1	Cost was very high, wasn't very easy for a new installer, expensive to equipment and didn't perform in an overhead application as expected
BOS – Respondent #2	My only application with shotcrete was last fall (2023) so I can't speak on durability of this location. But WisDOT has other locations in the SW, SE & NE Region that have been around for a good amount of years and are holding up well. The ease of installation is not possible for County Staff due to specialized equipment and therefore require a contractor to install. The cost of repair is very costly but can be cost effective for large and extensive repairs or limited timeframe due to traffic requirements.
NW	Used shotcrete on one project so far and is not yet a year old. Durability of the repair looks to be very good so far. If you have good access and no environmental concerns, installation is very easy and quick. It is fairly expensive (~$115/sf at a 2″ average cover. We provided concrete cleaning/prep, access, and traffic control) but can be cost effective for large, shallow fill repairs like refacing retaining walls, abutments, piers, etc. Biggest advantages are no formwork is required and applies much quicker than applying repair materials in lifts by hand. I also think you get a better bond and overall cohesion of the concrete patch.
NC	No response
NE	No response
SW	I have not used shotcrete, but contractors have in our area. I don't know much about how they prepped the area or methods of placement but it does seem to be holding up adequately.
SE – Respondent #1	Shotcrete has usually only been used for bridges where there is a large quantity of surface repair to be done on piers, abutments, or undersides of slabs. I don't think we have too many cases where it's been in place a long time. It seems to be done well by contractors who have specialized crews for doing the work. My opinion is that when it has been used that it holds up better than standard concrete patching/repair. This could be because of better prep work or following all instructions for applying the material. If contractors don't follow all the steps specified for concrete surface repair, it won't hold up.
SE – Respondent #2	I have a generally favorable impression of shotcrete, the instances I have seen are good immediately after installation, haven't had a long enough timeframe to see long term results.
SE – Respondent #3	N/A
SE – Respondent #4	Shotcrete has been placed by contractors on LET projects, and in general it seems to perform pretty well, but I haven't been personally involved with its installation. I think it performs well when the surface is properly prepared.

Question 4

Table B2.3. Responses to Question 4

WisDOT region	Q4: Do you have a standard patching repair procedure for vertical and overhead repair that you can share with the research team for vertical and overhead concrete repair? If yes, please include it when returning the completed survey. If not, please briefly describe your typical patching repair procedure and tools/equipment used.
	Survey Response
BOS – Respondent #1	I am not aware of one since we stopped doing overhead patches for many years unless wrapped in fiber.
BOS – Respondent #2	Do not have a standard patching repair procedure for VOH repairs. Typical procedure is sawing an edge along the repairs. Removing all loose and unsound concrete. Then sandblasting the exposed rebar clean and repainting rebar. Then installing a VOH repair with or without forms depending on size and location.
NW	No standard procedure. Typically, we square off repair area with ~¾" score cut and remove poor concrete with small chipping hammers. Any exposed reinforcing steel we like to sand blast. Prefer to use formwork if at all possible, rather than installing by hand lifts.
NC	Typically make square edges around the limits of the patch location. Form and place patch material. Sika VOH is very water-responsive, so having measuring pails on site helps to get the correct consistency.
NE	LET side would follow standard spec 509.3.7 which has limited procedure. No official standard procedure on the Maintenance side. Typically limits are scored, and removal of loose/delam material to sound concrete. It's about 50/50 on whether sand blasting is then done, depending on capability/equipment of County we're working in. Cathodic protection is not commonly employed. Form and pour. On rare occasion, curing (typically wet burlap) is used if patch is larger in size and accessibility is not an issue.
SW	I have only had a couple of overhead repairs that I was a part of in the counties that I am in charge of so I wouldn't say anything is standard, but the following is what we did. 1. Remove all deteriorated concrete. 2. Clean the remaining concrete to the best of our abilities, counties don't have sandblasting equipment, so no abrasive cleaning. 3. Formed area to be patched. 4. Placed bonding agent. 5. Poured concrete. 6. After 28 days (cure time) I had the county go out and place an epoxy crack sealer on the construction joint.
SE – Respondent #1	1. Take caution to preserve existing reinforcing steel 2. Remove concrete to sound concrete or to one inch behind the reinforcing steel, whichever is greater 3. Make a ½" deep saw cut at the limits of the concrete surface repair before removing deteriorated concrete 4. Clean the surface where new concrete is to be placed to remove loose particles and dust, and keep continuously wet for a period of 2 hours before placing new concrete"
SE – Respondent #2	Done by projects, or sometimes counties, which each have their own methods

WisDOT region	Q4: Do you have a standard patching repair procedure for vertical and overhead repair that you can share with the research team for vertical and overhead concrete repair? If yes, please include it when returning the completed survey. If not, please briefly describe your typical patching repair procedure and tools/equipment used.
	Survey Response
SE – Respondent #3	Yes – standard specification 509.3.7 (no different than horizontal patching); the only difference is the product must be specified by the manufacturer to be acceptable for vertical/overhead use
SE – Respondent #4	The VOH products should be placed according to the manufacturer's directions. In general, the delaminated areas need to be removed, the edges of the patch defined by a ½" sawcut, chipping to 1" below exposed rebar, wet/SSD surface or possibly a bonding agent applied immediately prior to placing the material, and then different curing requirements (or no curing requirements). Note that in the winter months, temperature can be a problem- the patching surface may be below freezing so SSD is difficult to achieve, or the patch material isn't rated for the low air temp. In some cases, the counties have used propane weed burner torches to warm up the patching surface prior to placing the material.

Question 8

Table B2.4. Responses to Question 8

WisDOT region	Q8: For the two most commonly used combinations of surface prep (cited in Question 4) and repair approach (cited in Question 1), please identify the combinations and indicate the expected life of the repair and what end of life looks like. Survey Response
BOS – Respondent #1	Wire brush clean and just zinc paint.
BOS – Respondent #2	I would expect a life expectancy of at least 5 – 10 years. Girders that were repaired in 2015 using Speccopatch RS are starting to need to be repaired. The end of life is the patch starts to delaminate from the existing girder or the adjacent girder material deteriorates.
NW	No response
NC	Un-wrapped expectancy ~3-10 years depending on chloride applications. Wrapped ~10-20 years depending on conditions; i.e. sunlight exposure, salts, surface prep, etc.
NE	Most common is PCC patch with minimal surface prep (compressed air blow out). Expected service life ~5-10yrs typically. Seems mostly dependent on whether patch has anchorage/existing rebar to nit to. End of life will see spider cracking within patch, delam and then failure. Have seen patches without anchorage spall out after 2 Yrs. Life expectancy or patch also driven by understanding and correcting root causes in some cases (i.e. sealing a leaking joint, providing for expansion etc).
SW	Surface prep for the Speed Crete PM product was wire brushing the spalled area then placing the Speed Crete. Life expectancy is 10-15 years. This was done 8 years ago and looks like the day it was placed. The drip edge repairs the surface prep consists of removing all bad concrete and cleaning the area with low pressure water. Life expectancy is 5-10 years. Some look poor two years later and some look great 10 years later. I believe this is due to the mix design of the material being poured.
SE – Respondent #1	If the repair is done correctly, maybe 10 to 12 years. There are too many cases were proper prep isn't done. I've seen patches that developed cracks within 2 years of placement. If the patch isn't anchored with rebar or other specific anchorages, it is almost guaranteed to fail. The halo effect also is common where concrete around the patch delaminates from corroded rebar.
SE – Respondent #2	Typical 509.3.7 concrete surface repair is most commonly done in projects. 7-15 year life in my opinion, not sure what designers expect. Patches typically develop map cracking, then delaminate, along with additional halo delamination around the edges.
SE – Respondent #3	1) Sawcut edges of repair, chip the repair to sound concrete minimum 1" behind rebar, clean steel with wire brush, blow off repair area, wet area for a few hours, install anodes, patch with a repair material (not a grade C or E concrete); I do not know expected life or end of like visual 2) Sawcut edges of repair, chip the repair to sound concrete (not behind rebar), clean steel with wire brush, install additional anchorage – tapcons or stainless anchors, blow off repair area, wet area for a few hours, install anodes, patch with a repair material (not a grade C or E concrete); I do not know expected life or end of life visual"
SE – Respondent #4	Not sure I fully understand the question. I'd expect 5-10 years of life, maybe less if surface isn't cleaned properly or delams are not fully removed or if patch material is mixed too wet resulting is immediate shrinkage cracking. Failure often starts with map cracking of the patch material

WisDOT region	Q8: For the two most commonly used combinations of surface prep (cited in Question 4) and repair approach (cited in Question 1), please identify the combinations and indicate the expected life of the repair and what end of life looks like. Survey Response
	and/or delaminations beyond the patch edges that creep into the patch. Patch then delaminates and fails, often as underlying rebar starts to rust and pop the concrete patch out.

Question 10

Table B2.5. Responses to Question 10

WisDOT region	Q10: Are there any differences in your practice for vertical and overhead repairs located over traffic versus those not over traffic in terms of repair strategies, materials, installation methods, curing time, etc.? If yes, please describe.
	Survey Response
BOS – Respondent #1	If patch in needed and over traffic, we now fiber wrap. If not over traffic, we sometimes patch with now fiber and sometimes we patch and use fiber. Not sure why we use fiber or not use it. Personally, I wouldn't use fiber when not over traffic. I would hope there is a way to just do the patch properly, so we don't need fiber to hold it.
BOS – Respondent #2	VOH repairs over traffic are covered with a non-structural FRP to minimize the potential for the concrete patch to fall on live traffic.
NW	No
NC	Over traffic repairs must be fiber wrapped.
NE	We are working towards adopting a best practice of FRP wrapping repaired girder damage as added encapsulation over traffic lanes. More commonly employed when State Crews assist with performing repairs but their availability is limited.
SW	No
SE – Respondent #1	Undersides of decks or slabs are usually not patched due to potential failure of patch material. Loose concrete is removed and sometimes the reinforcing steel is coated with a zinc-rich primer. Shotcrete has been used on undersides of some decks/slabs. Patching on girders after a bridge hit has been done, but is usually protected with non-structural FRP to help contain it.
SE – Respondent #2	We are recently avoiding placing patches in decks over traffic due to concern the patch will fall and create a hazard. Cleaning and treating with epoxy, zinc primer, or migrating corrosion inhibitor is spec'd in these situations. For prestressed concrete girder repairs over traffic, typically bottom flange repairs due to bridge hits, a non-structural FRP wrap is used around the patch to protect and support it.
SE – Respondent #3	Only difference is when approving a material to use the spec sheet must specifically say it is a product for use in vertical and overhead applications For overhead repairs over traffic special attention must be given to ensure the patch is completely filled. I.e. we absolutely cannot have honeycombing after pulling the form off – using a mortar mix to rub the patch after is not a great idea as those areas would be susceptible to falling off. Get the patch filled properly – no extra filling after form removal. Also some decisions must be made on means/methods strategies based on how the project is staged. Am I only allowed daily lane closures? are there vertical clearance issues? Can I leave forms on for the full 5-7 day cure? Do I have to access using a snooper truck? Manlift? Etc. those constraints may forces certain means/methods regarding the patch."
SE – Respondent #4	Leaving the spall but cleaning the rebar and coating with zinc primer or corrosion inhibitors is done to prevent possible hazard of future failing patches. Also commonly use FRP wrap to contain patches on prestressed concrete girders.

Question 11

Table B2.6. Responses to Question 11

WisDOT region	Q11: Please describe factors that most influence performance and durability of vertical and overhead concrete patching repairs in your experience (for example: repair material properties, repair depth, repair location, the use of anchorage, construction-related factors, contractor's experience, etc.)
	Survey Response
BOS – Respondent #1	Not sure because we moved away from overhead patching because they weren't working. We now just fiber wrap the area, so it really doesn't matter the performance and durability per say. Getting behind the rebar on vertical patches seem to perform the best.
BOS – Respondent #2	Properly mixing of the repair materials, using a quality product, and proper cleaning of the unsound concrete and especially cleaning on the steel to minimize future corrosion.
NW	From what limited amount I have seen, it seems that surface prep and repair materials seem to be the 2 biggest factors in performance.
NC	Best to do: mechanical anchors of some sort – rebar, tapcons, wedge anchors, etc – fiber wrapping will increase longevity of repair.
NE	As far as material specific I'd say mix quality is the biggest driver – especially for bag mix products. Repair depth and use or lack of anchorage is a driver also to patches staying in place – this comes in to play with specific county crew experience (County's do most of our maintenance work and turnover is an issue with their crews).
SW	I would say surface preparation.
SE – Respondent #1	"Proper material used – VOH; proper prepping of the area to be patched: enough concrete removed, sawcutting edges, wetting the area before material is applied; cleaning the rebar before patch material is applied; ensuring there is something to anchor the patch.
SE – Respondent #2	I feel contractors know what should be done but will cut corners if no one is watching or if inspector doesn't know what spec is or doesn't enforce it."
SE – Respondent #3	I am not present for many actual repairs, but see the preliminary prep work and the final product. I don't think rebar is getting cleaned adequately, and I see too many patches that didn't have sawcut edges. The spec 509.3.7 does not have many requirements, seems a basic one would be to follow manufacturers instructions. Surface prep and workmanship are probably the biggest factors.
SE – Respondent #4	The most important factors are material and substrate prep. Material must be designated for vertical/overhead applications and the substrate must be clean, SSD, and have something the patch can bite.
BOS – Respondent #1	Full removal of all delamination is often not done properly when the delam depth is deep into the rebar (difficult to hammer out so it doesn't get done). SSD condition often not obtained according to manufacturer instructions which often says SSD for several hours- crews just wet the patch and blow out the excess water immediately before the patch is placed.

Question 12

Table B2.7. Responses to Question 12

WisDOT region	Q12: If you have other experiences with vertical and overhead repairs that may be useful to developing guidelines, please describe. Survey Response
BOS – Respondent #1	No response
BOS – Respondent #2	See email with other word document.
NW	No response
NC	VOH products, in my opinion, should not be used on repairs >3" in depth, unless the area of repair is <4ft^2. That would be my limits, personally. And these are somewhat guidelines, not always a hard stop on the repairs, just getting right consistency on these VOH materials is difficult, and placing prior to the end of working time on the material can be difficult as well since they tend to be "hot" mixes.
NE	No response
SW	No response
SE – Respondent #1	In the approved products list, the products for concrete patching should be broken down into different categories and a list of products should be specified for VOH
SE – Respondent #2	No response
SE – Respondent #3	WisDOT spec is not explicitly clear on how surface repairs are to be cured. The concrete surface repair spec references section 502, but I think it should specify curing requirements instead of referencing 502.
SE – Respondent #4	Should be following manufacturer's directions for surface prep and mixing/placement, which varies widely by product. Curing seems to be an afterthought and may not be getting done at all. Shotcrete/gunnite surfaces are often very rough, and can collect deicing chemicals when used in areas too close to the roadway where plowing and salt spray can get to it.

APPENDIX C. LABORATORY INVESTIGATIONS

APPENDIX C1. PHOTOS OF SPECIMEN FABRICATION

APPENDIX C1. SPECIMEN FABRICATION PHOTOS


Figure C1.1. Forms and reinforcing


Figure C1.2. Casting substrate


Figure C1.3. Sawcut edges of repair area

Figure C1.4. Remove concrete with chipping hammer


Figure C1.5. Substrate


Figure C1.6. Sand blasting

Figure C1.7. No anchor


Figure C1.8. Threaded rod U (epoxy embedded)

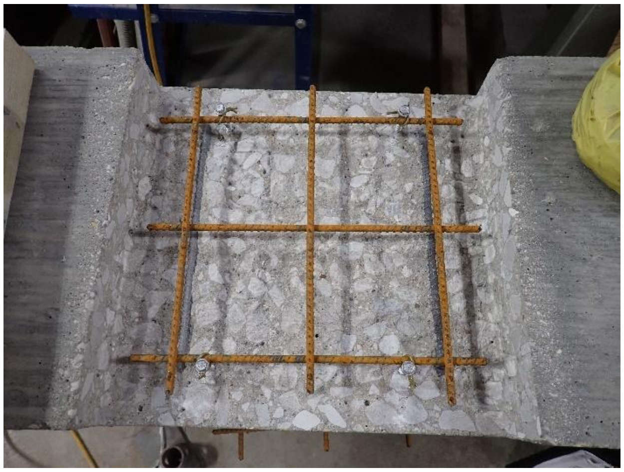

Figure C1.9. Screw anchors and WWR

Figure C1.10. Patch encompassing existing reinforcement

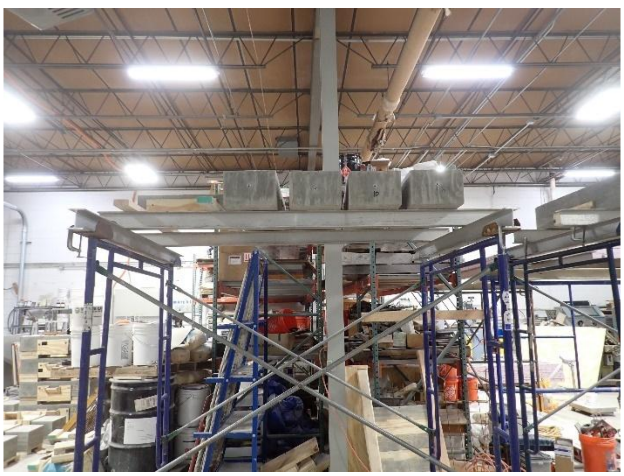

Figure C1.11. Specimens on scaffolding for overhead repair

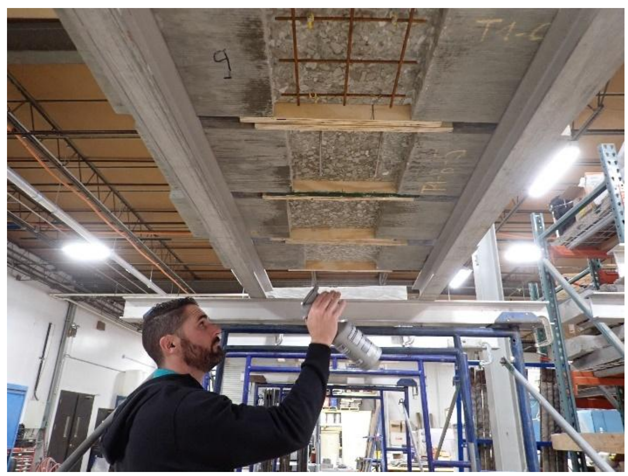

Figure C1.12. Spray substrate surface with water prior to installation of hand-applied repair material

Figure C1.13. Mixing hand-applied repair material

Figure C1.14. Hand-application of repair material

Figure C1.15. Hand-application of repair material using a trowel

Figure C1.16. Hand-applied patching in progress

Figure C1.17. Finishing hand-applied patch

Figure C1.18. Apply curing compound to patch

Figure C1.19. Mixing form-and-pour repair material

Figure C1.20. Slump flow test of form-and-pour material

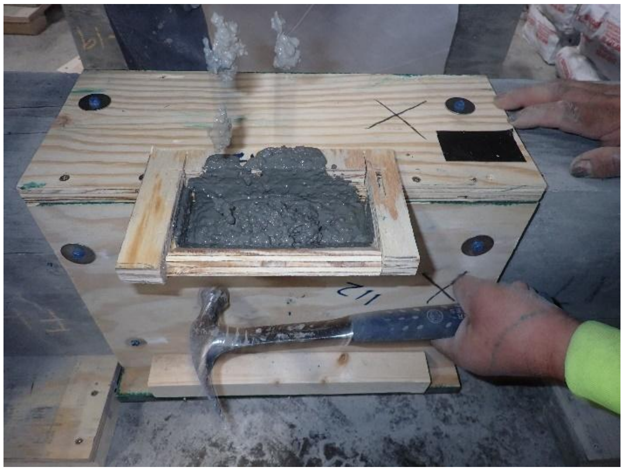

Figure C1.21. Form-and-pour in vertical orientation (patch on the vertical side)

Figure C1.22. Form-and-pour in overhead orientation (patch on the underside)

APPENDIX C2. MATERIALS TEST RESULTS

ASTM C39 Compressive Strength of Concrete Cylinders

Project No: 2023.0069 **Project Coordinator:** L. Pham

Operator: M. Haddad **Date:** 1/3/2025
Checked by: L. Pham **Date:** 1/21/2025

Capping Method
- ☐ Sulfur
- ☐ Lapped
- ☑ End Ground
- ☐ Unbonded

Conditioning
- ☐ As Received
- ☑ Wet
- ☐ Dry

Capping
- ☑ Plane
- ☐ Sound
- ☐ Other

Calipers
- ☐ 12/060107
- ☐ B657697
- ☑ Asset# 2871

Test Machine
- ☑ Test Mark SN# 11005
- ☐ Satec ID: 120HLVC1240
- ☐ Other

Cast Date: 12/6/2024

Sample ID	Capped Length (in.)	Density (lbs/ft³)	Avg. Dia. (in.)	Area (in.²)	Max. Load (lbs.)	Compressive Strength (psi)	L/D	Fracture Type	Sample or Cap Defects	Age of sample (days)
1	7.80	150.5	3.98	12.45	80,280	6,448	1.96	1	None	28
2	7.79	151.1	3.98	12.46	78,460	6,297	1.96	1	None	28
3	7.76	150.2	4.00	12.58	77,930	6,197	1.94	1	None	28
Average	--	**151**	--	--	--	**6,310**	--	--	--	--

The results presented in this test report relate only to the items tested.

Comments: CONCRETE SUBSTRATE

ASTM C39 Compressive Strength of Concrete Cylinders

Project No: 2023.0069 **Project Coordinator:** L. Pham

Operator: M. Haddad **Date:** 2/20/2025

Checked by: L. Pham **Date:** 1/2/2026

Capping Method
- ☐ Sulfur
- ☐ Lapped
- ☑ End Ground
- ☐ Unbonded

Conditioning
- ☐ As Received
- ☑ Wet
- ☐ Dry

Capping
- ☑ Plane
- ☐ Sound
- ☐ Other

Calipers
- ☐ 12/060107
- ☐ B657697
- ☑ Asset# 996

Test Machine
- ☑ Test Mark SN# 11005
- ☐ Satec ID: 120HLVC1240
- ☐ Other

Cast Date: 1/23/2025

Sample ID	Capped Length (in.)	Density (lbs/ft³)	Avg. Dia. (in.)	Area (in.²)	Max. Load (lbs.)	Compressive Strength (psi)	L/D	Fracture Type	Sample or Cap Defects	Age of sample (days)
1	5.79	137.0	3.01	7.13	47,360	6,640	1.92	1	None	28
2	5.72	139.7	3.00	7.09	45,280	6,391	1.91	1	None	28
3	5.92	139.5	2.99	7.02	45,620	6,502	1.98	2	None	28
Average	--	**139**	--	--	--	**6,510**	--	--	--	--

The results presented in this test report relate only to the items tested.

Comments: REPAIR MATERIAL F1

ASTM C39 Compressive Strength of Concrete Cylinders

Project No: 2023.0069 **Project Coordinator:** L. Pham

Operator: M. Haddad **Date:** 2/20/2025

Checked by: L. Pham **Date:** 1/2/2026

Capping Method
- ☐ Sulfur
- ☐ Lapped
- ☑ End Ground
- ☐ Unbonded

Conditioning
- ☐ As Received
- ☑ Wet
- ☐ Dry

Capping
- ☑ Plane
- ☐ Sound
- ☐ Other

Calipers
- ☐ 12/060107
- ☐ B657697
- ☑ Asset# 996

Test Machine
- ☑ Test Mark SN# 11005
- ☐ Satec ID: 120HLVC1240
- ☐ Other

Cast Date: 1/23/2025

Sample ID	Capped Length (in.)	Density (lbs/ft³)	Avg. Dia. (in.)	Area (in.²)	Max. Load (lbs.)	Compressive Strength (psi)	L/D	Fracture Type	Sample or Cap Defects	Age of sample (days)
1	5.76	142.7	3.00	7.06	50,860	7,200	1.92	1	None	28
2	5.76	142.4	3.00	7.09	51,990	7,333	1.92	1	None	28
3	5.90	142.6	3.00	7.06	52,340	7,412	1.97	1	None	28
Average	--	**143**	--	--	--	**7,320**	--	--	--	--

The results presented in this test report relate only to the items tested.

Comments: REPAIR MATERIAL F2

ASTM C39 Compressive Strength of Concrete Cylinders

Project No: 2023.0069 **Project Coordinator:** L. Pham

Operator: M. Haddad **Date:** 2/26/2025

Checked by: L. Pham **Date:** 1/2/2026

Capping Method
- ☐ Sulfur
- ☐ Lapped
- ☑ End Ground
- ☐ Unbonded

Conditioning
- ☐ As Received
- ☑ Wet
- ☐ Dry

Capping
- ☑ Plane
- ☐ Sound
- ☐ Other

Calipers
- ☐ 12/060107
- ☐ B657697
- ☑ Asset# 996

Test Machine
- ☑ Test Mark SN# 11005
- ☐ Satec ID: 120HLVC1240
- ☐ Other

Cast Date: 1/28/2025

Sample ID	Capped Length (in.)	Density (lbs/ft³)	Avg. Dia. (in.)	Area (in.²)	Max. Load (lbs.)	Compressive Strength (psi)	L/D	Fracture Type	Sample or Cap Defects	Age of sample (days)
1	5.83	120.0	3.03	7.19	40,070	5,575	1.93	2	None	29
MOE (A)	5.76	125.6	3.02	7.15	46,510	6,506	1.91	2	None	29
MOE (B)	5.85	124.6	3.03	7.20	45,090	6,262	1.93	2	None	29
Average	--	**123**	--	--	--	**6,110**	--	--	--	--

The results presented in this test report relate only to the items tested.

Comments: REPAIR MATERIAL H1

ASTM C39 Compressive Strength of Concrete Cylinders

Project No: 2023.0069 **Project Coordinator:** L. Pham

Operator: M. Haddad **Date:** 2/26/2025

Checked by: L. Pham **Date:** 1/2/2026

Capping Method
- ☐ Sulfur
- ☐ Lapped
- ☑ End Ground
- ☐ Unbonded

Conditioning
- ☐ As Received
- ☑ Wet
- ☐ Dry

Capping
- ☑ Plane
- ☐ Sound
- ☐ Other

Calipers
- ☐ 12/060107
- ☐ B657697
- ☑ Asset# 996

Test Machine
- ☑ Test Mark SN# 11005
- ☐ Satec ID: 120HLVC1240
- ☐ Other

Cast Date: 1/28/2025

Sample ID	Capped Length (in.)	Density (lbs/ft³)	Avg. Dia. (in.)	Area (in.²)	Max. Load (lbs.)	Compressive Strength (psi)	L/D	Fracture Type	Sample or Cap Defects	Age of sample (days)
1	5.83	132.1	3.02	7.16	50,550	7,062	1.93	1	None	29
MOE (A)	5.80	133.2	3.01	7.13	50,750	7,120	1.92	1	None	29
MOE (B)	5.80	132.5	3.01	7.12	48,050	6,748	1.92	1	None	29
Average	--	**133**	--	--	--	**6,980**	--	--	--	--

The results presented in this test report relate only to the items tested.

Comments: REPAIR MATERIAL H2

ASTM C469 Modulus of Elasticity and Poisson's Ratio

Project No: 2023.0069 **Project Coordinator:** L. Pham

Operator: M. Haddad **Date:** 1/3/2025

Checked by: L. Pham **Date:** 1/21/2025

Capping Method ☐ Sulfur ☒ Lapped ☐ Unbonded ☑ End gound

Conditioning ☐ As Received ☑ Wet ☐ Dry

Capping ☑ Plane ☐ Sound ☐ Other

Calipers ☑ #2871 ☐ B657697 ☐ Other

Test Machine ☑ Test Mark SN# 11005 ☐ Satec ID: 120HLVC1240 ☐ Other

Cast Date: 12/6/2024

Sample ID	Age (days)	Capped Length (in.)	Avg. Dia. (in.)	Area (in.²)	Density (lb/ft³)	Max. Load (lbs.)	Compressive Strength (psi)	L/D	Fracture Type	Sample or Cap Defects
SUBSTRATE 1	28	7.79	3.99	12.49	150.0	79,330	6,350	1.95	1	None

Modulus of Elasticity (psi)	4,800,000
Poisson's Ratio	

Comments:

ASTM C469 Modulus of Elasticity and Poisson's Ratio

Project No: 2023.0069 **Project Coordinator:** L. Pham

Operator: M. Haddad **Date:** 1/3/2025

Checked by: L. Pham **Date:** 1/21/2025

Capping Method ☐ Sulfur ☒ Lapped ☐ Unbonded ☑ End gound

Conditioning ☐ As Received ☑ Wet ☐ Dry

Capping ☑ Plane ☐ Sound ☐ Other

Calipers ☑ #2871 ☐ B657697 ☐ Other

Test Machine ☑ Test Mark SN# 11005 ☐ Satec ID: 120HLVC1240 ☐ Other

Cast Date: 12/6/2024

Sample ID	Age (days)	Capped Length (in.)	Avg. Dia. (in.)	Area (in.²)	Density (lb/ft³)	Max. Load (lbs.)	Compressive Strength (psi)	L/D	Fracture Type	Sample or Cap Defects
SUBSTRATE 2	28	7.83	3.99	12.48	149.5	79,580	6,380	1.96	1	None

Modulus of Elasticity (psi)	4,650,000
Poisson's Ratio	

Comments:

ASTM C469 Modulus of Elasticity

Project No: 2023.0069 **Project Coordinator:** L. Pham

Operator: M. Haddad **Date:** 2/20/2025

Checked by: L. Pham **Date:** 1/2/2026

Capping Method ☐ Sulfur ☒ Lapped ☐ Unbonded ☑ End gound

Conditioning ☑ As Received ☐ Wet ☐ Dry

Capping ☑ Plane ☐ Sound ☐ Other

Calipers ☑ 12/060107 ☐ B657697 ☐ Other

Test Machine ☑ Test Mark SN# 11005 ☐ Satec ID: 120HLVC1240 ☐ Other

Cast Date: 1/23/2025

Sample ID	Age (days)	Capped Length (in.)	Avg. Dia. (in.)	Area (in.²)	Density (lb/ft³)	Max. Load (lbs.)	Compressive Strength (psi)	L/D	Fracture Type	Sample or Cap Defects
F1 (A)	28	5.80	3.01	7.10	138.6	48,380	6,810	1.93	2	None

Modulus of Elasticity (psi)	4,800,000
Poisson's Ratio	

Comments:

ASTM C469 Modulus of Elasticity

Project No: 2023.0069 **Project Coordinator:** L. Pham

Operator: M. Haddad **Date:** 2/20/2025

Checked by: L. Pham **Date:** 1/2/2026

Capping Method
- ☐ Sulfur
- ☒ Lapped
- ☐ Unbonded
- ☑ End gound

Conditioning
- ☑ As Received
- ☐ Wet
- ☐ Dry

Capping
- ☑ Plane
- ☐ Sound
- ☐ Other

Calipers
- ☑ 12/060107
- ☐ B657697
- ☐ Other

Test Machine
- ☑ Test Mark SN# 11005
- ☐ Satec ID: 120HLVC1240
- ☐ Other

Cast Date: 1/23/2025

Sample ID	Age (days)	Capped Length (in.)	Avg. Dia. (in.)	Area (in.²)	Density (lb/ft³)	Max. Load (lbs.)	Compressive Strength (psi)	L/D	Fracture Type	Sample or Cap Defects
F1 (A)	28	5.74	3.01	7.11	138.3	47,290	6,650	1.91	1	None

Modulus of Elasticity (psi)	4,600,000
Poisson's Ratio	

Comments:

ASTM C469 Modulus of Elasticity

Project No: 2023.4664.0

Project Coordinator: L. Pham

Operator: M. Haddad **Date:** 2/20/2025

Checked by: L. Pham **Date:** 1/2/2026

Capping Method
- ☐ Sulfur
- ☒ Lapped
- ☐ Unbonded
- ☑ End gound

Conditioning
- ☑ As Received
- ☐ Wet
- ☐ Dry

Capping
- ☑ Plane
- ☐ Sound
- ☐ Other

Calipers
- ☑ Asset 996
- ☐ B657697
- ☐ Other

Test Machine
- ☑ Test Mark SN# 11005
- ☐ Satec ID: 120HLVC1240
- ☐ Other

Cast Date: 1/23/2025

Sample ID	Age (days)	Capped Length (in.)	Avg. Dia. (in.)	Area (in.²)	Density (lb/ft³)	Max. Load (lbs.)	Compressive Strength (psi)	L/D	Fracture Type	Sample or Cap Defects
F2 (B)	28	5.81	3.02	7.18	140.3	51,540	7,180	1.92	2	None

Modulus of Elasticity (psi)	5,200,000
Poisson's Ratio	

Comments:

ASTM C469 Modulus of Elasticity

Project No: 2023.0069 **Project Coordinator:** L. Pham

Operator: M. Haddad **Date:** 2/20/2025

Checked by: L. Pham **Date:** 1/2/2026

Capping Method ☐ Sulfur ☒ Lapped ☐ Unbonded ☑ End gound

Conditioning ☑ As Received ☐ Wet ☐ Dry

Capping ☑ Plane ☐ Sound ☐ Other

Calipers ☑ Asset 996 ☐ B657697 ☐ Other

Test Machine ☑ Test Mark SN# 11005 ☐ Satec ID: 120HLVC1240 ☐ Other

Cast Date: 1/23/2025

Sample ID	Age (days)	Capped Length (in.)	Avg. Dia. (in.)	Area (in.²)	Density (lb/ft³)	Max. Load (lbs.)	Compressive Strength (psi)	L/D	Fracture Type	Sample or Cap Defects
F2 (B)	28	5.92	3.01	7.13	141.8	52,570	7,370	1.96	1	None

Modulus of Elasticity (psi)	5,225,000
Poisson's Ratio	

Comments:

ASTM C469 Modulus of Elasticity

Project No: 2023.0069 **Project Coordinator:** L. Pham

Operator: M. Haddad **Date:** 2/26/2025

Checked by: L. Pham **Date:** 1/2/2026

Capping Method
- ☐ Sulfur
- ☒ Lapped
- ☐ Unbonded
- ☑ End gound

Conditioning
- ☑ As Received
- ☐ Wet
- ☐ Dry

Capping
- ☑ Plane
- ☐ Sound
- ☐ Other

Calipers
- ☑ 12/060107
- ☐ B657697
- ☐ Other

Test Machine
- ☑ Test Mark SN# 11005
- ☐ Satec ID: 120HLVC1240
- ☐ Other

Cast Date: 1/28/2025

Sample ID	Age (days)	Capped Length (in.)	Avg. Dia. (in.)	Area (in.²)	Density (lb/ft³)	Max. Load (lbs.)	Compressive Strength (psi)	L/D	Fracture Type	Sample or Cap Defects
H1 (A)	29	5.76	3.01	7.14	125.8	46,510	6,520	1.91	2	None

Modulus of Elasticity (psi)	3,050,000
Poisson's Ratio	

Comments:

ASTM C469 Modulus of Elasticity

Project No: 2023.0069 **Project Coordinator:** L. Pham

Operator: M. Haddad **Date:** 2/26/2025

Checked by: L. Pham **Date:** 1/2/2026

Capping Method
- ☐ Sulfur
- ☒ Lapped
- ☐ Unbonded
- ☑ End gound

Conditioning
- ☑ As Received
- ☐ Wet
- ☐ Dry

Capping
- ☑ Plane
- ☐ Sound
- ☐ Other

Calipers
- ☑ 12/060107
- ☐ B657697
- ☐ Other

Test Machine
- ☑ Test Mark SN# 11005
- ☐ Satec ID: 120HLVC1240
- ☐ Other

Cast Date: 1/28/2025

Sample ID	Age (days)	Capped Length (in.)	Avg. Dia. (in.)	Area (in.²)	Density (lb/ft³)	Max. Load (lbs.)	Compressive Strength (psi)	L/D	Fracture Type	Sample or Cap Defects
H1 (B)	29	5.85	3.03	7.20	124.6	45,090	6,260	1.93	2	None

Modulus of Elasticity (psi)	2,875,000
Poisson's Ratio	

Comments:

ASTM C469 Modulus of Elasticity

Project No: 2023.0069 **Project Coordinator:** L. Pham

Operator: M. Haddad **Date:** 2/26/2025

Checked by: L. Pham **Date:** 1/2/2026

Capping Method ☐ Sulfur ☒ Lapped ☐ Unbonded ☑ End gound

Conditioning ☑ As Received ☐ Wet ☐ Dry

Capping ☑ Plane ☐ Sound ☐ Other

Calipers ☑ 12/060107 ☐ B657697 ☐ Other

Test Machine ☑ Test Mark SN# 11005 ☐ Satec ID: 120HLVC1240 ☐ Other

Cast Date: 1/28/2025

Sample ID	Age (days)	Capped Length (in.)	Avg. Dia. (in.)	Area (in.²)	Density (lb/ft³)	Max. Load (lbs.)	Compressive Strength (psi)	L/D	Fracture Type	Sample or Cap Defects
H2 (A)	29	5.80	3.01	7.13	133.2	50,750	7,120	1.92	1	None

Modulus of Elasticity (psi)	4,275,000
Poisson's Ratio	

Comments:

ASTM C469 Modulus of Elasticity

Project No: 2023.0069 **Project Coordinator:** L. Pham

Operator: M. Haddad **Date:** 2/26/2025

Checked by: L. Pham **Date:** 1/2/2026

Capping Method
- ☐ Sulfur
- ☒ Lapped
- ☐ Unbonded
- ☑ End gound

Conditioning
- ☑ As Received
- ☐ Wet
- ☐ Dry

Capping
- ☑ Plane
- ☐ Sound
- ☐ Other

Calipers
- ☑ 12/060107
- ☐ B657697
- ☐ Other

Test Machine
- ☑ Test Mark SN# 11005
- ☐ Satec ID: 120HLVC1240
- ☐ Other

Cast Date: 1/28/2025

Sample ID	Age (days)	Capped Length (in.)	Avg. Dia. (in.)	Area (in.²)	Density (lb/ft³)	Max. Load (lbs.)	Compressive Strength (psi)	L/D	Fracture Type	Sample or Cap Defects
H2 (B)	29	5.80	3.01	7.12	132.5	48,050	6,750	1.92	1	None

Modulus of Elasticity (psi)	4,125,000
Poisson's Ratio	

Comments:

ASTM C109 - Compressive Strength of 2-inch Cubes

WJE Project No.: 2023.0069 **Project Coordinator:** Le Pham

Checked by: L. Pham **Date:** 1/2/2026

Test Machine: ☑ Test Mark Asset #734 ☐ Satec Asset #692 ☐ Other:

Caliper: ☑ Asset # 7073 ☐ Asset # 2871 ☐ Other:

Scale: ☐ Asset #2215 (retired) ☑ Asset #2214 ☐ Other:

Conditioning: ☑ 100% Room ☐ Limewater Tank ☐ Other:

Date Batched: 1/28/2025
Water Content (%): N/A
Flow (%): N/A

Material Tested: H1
ASTM Standard:

Specimen	Height (in.)	Area (in.^{2})	Density (lb/ft^3)	Max. Load (lbf.)	Compressive Strength (psi)	Age at Test (days)
1	2.01	4.10	125.0	25,740	6,280	29
2	2.01	4.09	125.8	25,410	6,220	
3	2.01	4.09	126.6	26,400	6,460	
Average:	--	--	**125.8**	--	**6,320**	--

Comments: REPAIR MATERIAL H1

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ASTM C109 - Compressive Strength of 2-inch Cubes

WJE Project No.: 2023.0069 **Project Coordinator:** Le Pham

Checked by: L. Pham **Date:** 3/19/2026

Test Machine: ☑ Test Mark Asset #734 ☐ Satec Asset #692 ☐ Other: ______

Caliper: ☑ Asset # 7073 ☐ Asset # 2871 ☐ Other: ______

Scale: ☐ Asset #2215 (retired) ☑ Asset #2214 ☐ Other: ______

Conditioning: ☑ 100% Room ☐ Limewater Tank ☐ Other: ______

Date Batched: 1/28/2025
Water Content (%): ______
Flow (%): ______

Material Tested: H2
ASTM Standard: ______

Specimen	Height (in.)	Area (in.^{2})	Density (lb/ft^3)	Max. Load (lbf.)	Compressive Strength (psi)	Age at Test (days)
1	2.01	4.07	131.2	32,290	7,930	29
2	2.00	4.05	131.3	31,390	7,750	
3	2.00	4.08	130.7	30,130	7,380	
Average:	--	--	**131.0**	--	**7,690**	--

Comments: REPAIR MATERIAL H2

ASTM C157 - Length Change of Hardened Hydraulic-Cement Mortar and Concrete

Project Number: 2023.0069 **Lab Coordinator:** L. Pham **Project Manager:** L. Pham

Operator: M. Haddad **Date:** 1/3/2025

Checked by: L. Pham **Date:** 3/5/2026

Mix ID: Substrate concrete

Date Cast: 12/6/2024

Type of Material: ☑ Concrete ☐ Mortar ☐

Specimen Size: ☑ 3 x 3 x 11.25 in ☐ 4 x 4 x 11.25 in ☐

Mix Temp. (°F): 62

Slump (in.): 3

Consolidation: ☐ Rodding ☑ Vibration ☐

Max. Size of Aggregate: ☑ 3/4" ☐ 1/2" ☐

Number of Specimens: 3

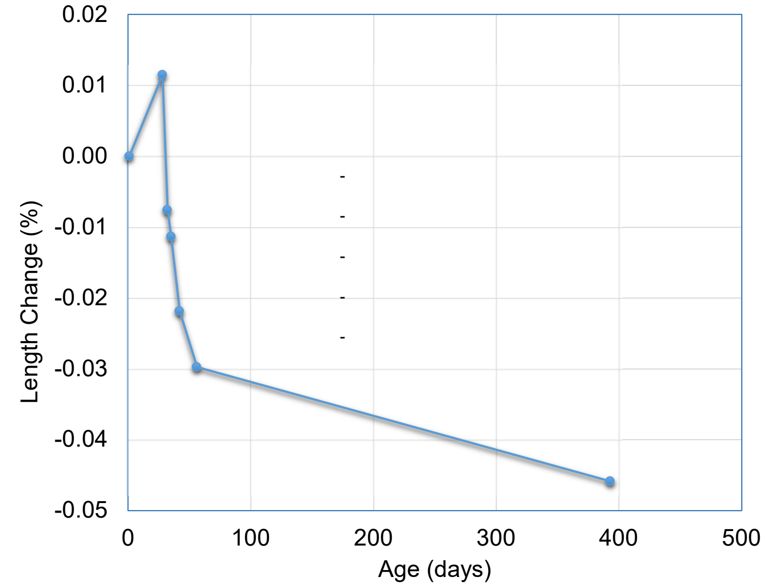
Curing Duration (days): 28

Storage Condition: ☐ Water ☑ Air ☐

Length Comparator: ☐ Asset #1083 ☑ Asset #1084 ☐ Asset #9854

Dial Gage: ☑ #4657 ☑

Reading #	Age (days)	Time of Storage (days)	Average Length Change (%)
0	1	Before cure	0.000
1	28	0	0.011
2	32	4	-0.008
3	35	7	-0.011
4	42	14	-0.022
5	56	28	-0.030
6	393	365	-0.046
7			
8			
9			
10			
11			
12			



ASTM C157 - Length Change of Hardened Hydraulic-Cement Mortar and Concrete

Project Number: 2023.0069 **Lab Coordinator:** L. Pham **Project Manager:** L. Pham

Operator: M. Haddad **Date:** 1/28/2025

Checked by: L. Pham **Date:** 3/5/2026

Mix ID: H1

Date Cast: 1/28/2025

Type of Material: ☐ Concrete ☑ Mortar ☐ ______

Specimen Size: ☑ 3 x 3 x 11.25 in ☐ 4 x 4 x 11.25 in ☐ ______

Mix Temp. (°F): N/A

Slump (in.): N/A

Consolidation: ☐ Rodding ☑ Vibration ☐ ______

Max. Size of Aggregate: ☐ 3/4" ☐ 1/2" ☐ N/A

Number of Specimens: 3

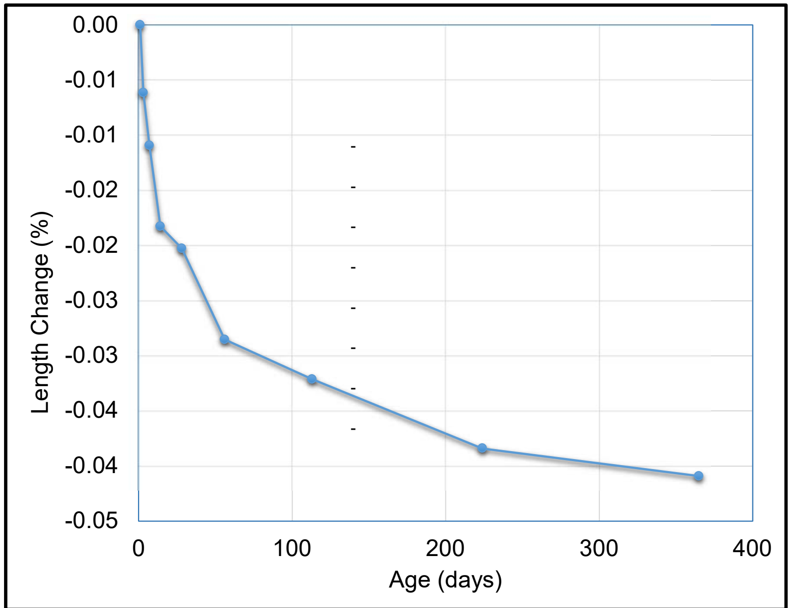
Curing Duration (days): 0

Storage Condition: ☐ Water ☑ Air ☐ ______

Length Comparator: ☐ Asset #1083 ☑ Asset #1084 ☐ Asset #9854

Dial Gage: ☑ #4657 ☑ ______

Reading #	Age (days)	Time of Storage (days)	Average Length Change (%)
0	1	Before cure	0.000
1	3	3	-0.006
2	7	7	-0.011
3	14	14	-0.018
4	28	28	-0.020
5	56	56	-0.029
6	113	113	-0.032
7	224	224	-0.038
8	365	365	-0.041
9			
10			
11			
12			



ASTM C157 - Length Change of Hardened Hydraulic-Cement Mortar and Concrete

Project Number: 2023.0069 **Lab Coordinator:** L. Pham **Project Manager:** L. Pham

Operator: M. Haddad **Date:** 1/28/2025

Checked by: L. Pham **Date:** 3/5/2026

Mix ID: H2

Date Cast: 1/28/2025

Type of Material: ☐ Concrete ☑ Mortar ☐ ____

Specimen Size: ☑ 3 x 3 x 11.25 in ☐ 4 x 4 x 11.25 in ☐ ____

Mix Temp. (°F): NA

Slump (in.): NA

Consolidation: ☐ Rodding ☑ Vibration ☐ ____

Max. Size of Aggregate: ☐ 3/4" ☐ 1/2" ☑ NA

Number of Specimens: 3

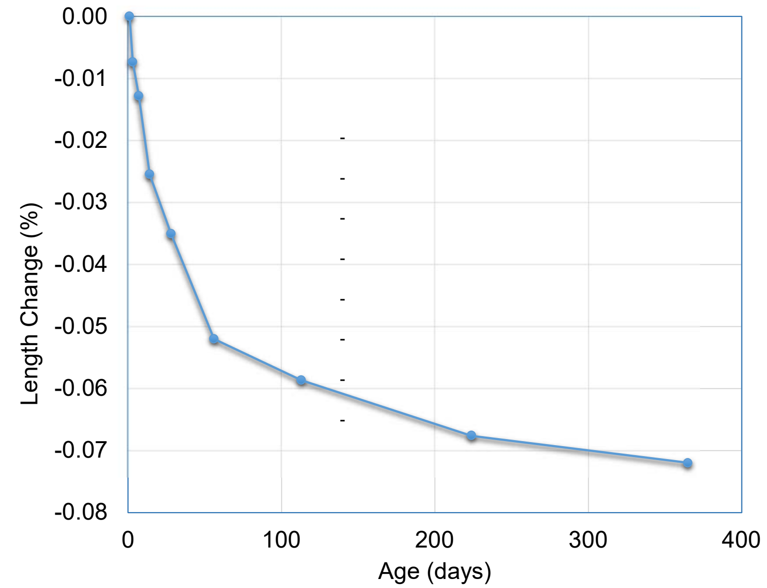
Curing Duration (days): 0

Storage Condition: ☐ Water ☑ Air ☐ ____

Length Comparator: ☐ Asset #1083 ☑ Asset #1084 ☐ Asset #9854

Dial Gage: ☑ #4657 ☑ ____

Reading #	Age (days)	Time of Storage (days)	Average Length Change (%)
0	1	Before cure	0.000
1	3	3	-0.007
2	7	7	-0.013
3	14	14	-0.025
4	28	28	-0.035
5	56	56	-0.052
6	113	113	-0.059
7	224	224	-0.068
8	365	365	-0.072
9			
10			
11			
12			



ASTM C157 - Length Change of Hardened Hydraulic-Cement Mortar and Concrete

Project Number: 2023.0069 **Lab Coordinator:** L. Pham **Project Manager:** L. Pham

Operator: M. Haddad **Date:** 1/26/2025

Checked by: L. Pham **Date:** 3/5/2026

Mix ID: F1

Date Cast: 1/23/2025

Type of Material: ☐ Concrete ☐ Mortar ☑ SCC

Specimen Size: ☑ 3 x 3 x 11.25 in ☐ 4 x 4 x 11.25 in ☐

Mix Temp. (°F): 77

Slump Flow (in.): 30

Consolidation: ☐ Rodding ☐ Vibration ☑ None

Max. Size of Aggregate: ☐ 3/4" ☐ 1/2" ☑ NA

Number of Specimens: 3

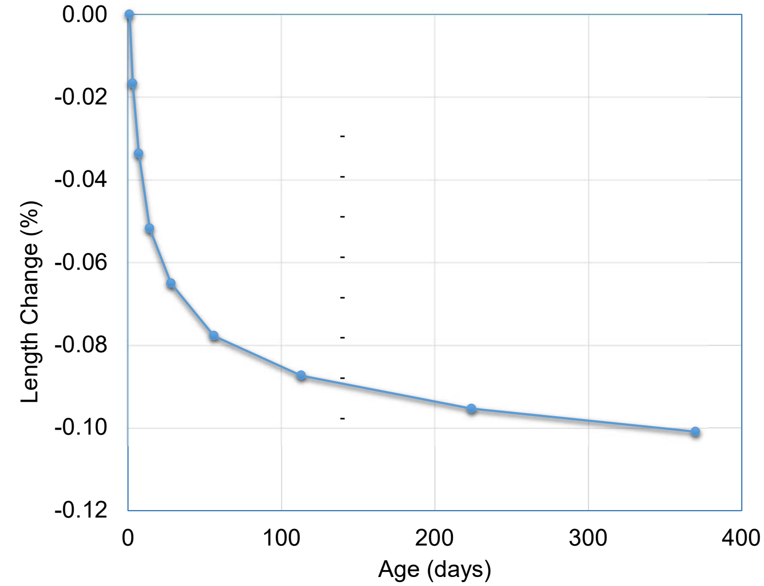
Curing Duration (days): 0

Storage Condition: ☐ Water ☑ Air ☐

Length Comparator: ☐ Asset #1083 ☑ Asset #1084 ☐ Asset #9854

Dial Gage: ☑ #4657 ☑

Reading #	Age (days)	Time of Storage (days)	Average Length Change (%)
0	1	Before cure	0.000
1	3	3	-0.017
2	7	7	-0.034
3	14	14	-0.052
4	28	28	-0.065
5	56	56	-0.078
6	113	113	-0.087
7	224	224	-0.095
8	370	370	-0.101
9			
10			
11			
12			



ASTM C157 - Length Change of Hardened Hydraulic-Cement Mortar and Concrete

Project Number: 2023.0069 **Lab Coordinator:** L. Pham **Project Manager:** L. Pham

Operator: M. Haddad **Date:** 1/26/2025

Checked by: L. Pham **Date:** 3/5/2026

Mix ID: F2

Date Cast: 1/23/2025

Type of Material: ☐ Concrete ☐ Mortar ☑ Pre-extended SC Mortar

Specimen Size: ☑ 3 x 3 x 11.25 in ☐ 4 x 4 x 11.25 in ☐

Mix Temp. (°F): 77

Consolidation: ☐ Rodding ☐ Vibration ☑ None

Max. Size of Aggregate: ☐ 3/4" ☐ 1/2" ☑ NA

Number of Specimens: 3

Slump Flow (in.): 25.5

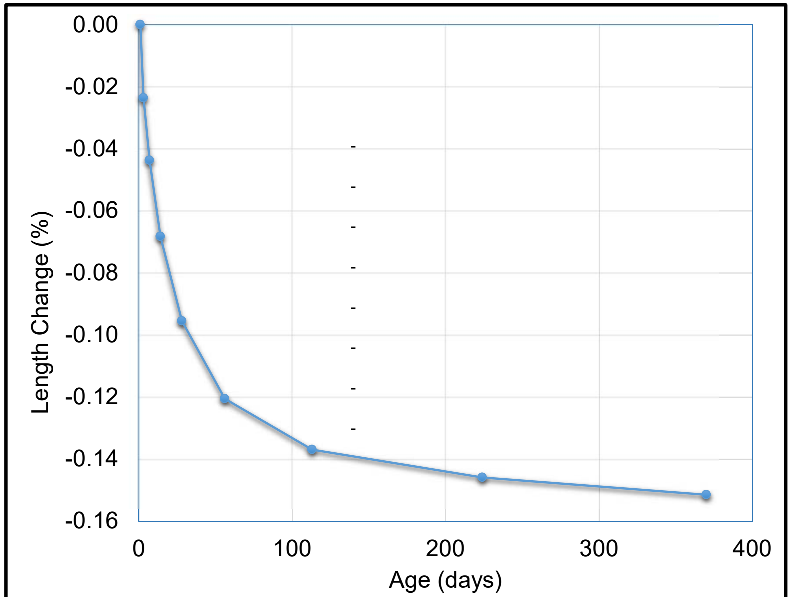
Curing Duration (days): 0

Storage Condition: ☐ Water ☑ Air ☐

Length Comparator: ☐ Asset #1083 ☑ Asset #1084 ☐ Asset #9854

Dial Gage: ☑ #4657 ☑

Reading #	Age (days)	Time of Storage (days)	Average Length Change (%)
0	1	Before cure	0.000
1	3	3	-0.024
2	7	7	-0.044
3	14	14	-0.068
4	28	28	-0.095
5	56	56	-0.121
6	113	113	-0.137
7	224	224	-0.146
8	370	370	-0.151
9			
10			
11			
12			



AASHTO T336 - Coefficient of Thermal Expansion of Hyrdraulic Cement Concrete

Project Number: 2023.0069 **Project Coordinator:** L. Pham

Operator: D. Witte **Test Date:** 1/6/2025

Checked by: L. Pham **Review Date:** 1/6/2026

Mix ID: Substrate

Date Cast: 12/6/2024

Specimen Type: ☑ Cast ☐ Cored ☐ ____

Curing Duration (days): 31

Specimen Age (days): 31

Calibration Sample Material: SS 304
Calibration Sample CTE (10^{-6}/°C): 16.20

Curing Condition ☑ Saturated ☐ ____

Specimen Dia. (in): 4

Verification Sample Material: SS 440C
Verification Sample CTE (10^{-6}/°C): 10.40

Specimen ID	Length (in)	Correction Factor (10-6/°C)	Segment	Start Temperature (°C)	Start LVDT Reading (in.)	End Temperature (°C)	End LVDT Reading (in.)	Measured Length Change, ΔLm (in.)	Length Change of Frame, ΔLf (in.)	Actual Length Change, ΔLa (in.)	Concrete CTE (10-6/°C)	Concrete CTE (10-6/°F)
Sample A	7.011	-0.21	Cooling	50.1	0.015940	10.1	0.013000	-0.002940	5.90E-05	-2.88E-03	**10.26**	**5.70**
			Heating	10.1	0.013000	50.1	0.015910	0.002910	-5.89E-05	2.85E-03	**10.16**	**5.64**
			Sample 2 CTE (Avergage of two segments)								**10.21**	**5.67**

Concrete Mixture CTE (10-6/°C and 10-6/°F, respectively)	**10.2**	**5.7**

AASHTO T336 - Coefficient of Thermal Expansion of Hyrdraulic Cement Concrete

Project Number: 2023.0069 **Project Coordinator:** L. Pham

Operator: D. Witte **Test Date:** 1/3/2025

Checked by: L. Pham **Review Date:** 1/6/2026

Mix ID: Substrate

Date Cast: 12/6/2024

Curing Duration (days): 28

Curing Condition ☑ Saturated ☐

Specimen Type: ☑ Cast ☐ Cored ☐

Specimen Age (days): 28

Specimen Dia. (in): 4

Calibration Sample Material: SS 304
Calibration Sample CTE (10^{-6}/°C): 16.20

Verification Sample Material: SS 440C
Verification Sample CTE (10^{-6}/°C): 10.40

Specimen ID	Length (in)	Correction Factor (10-6/°C)	Segment	Start Temperature (°C)	Start LVDT Reading (in.)	End Temperature (°C)	End LVDT Reading (in.)	Measured Length Change, ΔLm (in.)	Length Change of Frame, ΔLf (in.)	Actual Length Change, ΔLa (in.)	Concrete CTE (10-6/°C)	Concrete CTE (10-6/°F)
Sample B	6.998	-0.21	Cooling	50.1	0.004494	9.9	0.001626	-0.002868	5.91E-05	-2.81E-03	**9.98**	**5.55**
			Heating	9.9	0.001626	50.1	0.004492	0.002866	-5.91E-05	2.81E-03	**9.98**	**5.54**
			Sample 2 CTE (Avergage of two segments)								**9.98**	**5.55**

Concrete Mixture CTE (10-6/°C and 10-6/°F, respectively)	**10.0**	**5.5**

AASHTO T336 - Coefficient of Thermal Expansion of Hyrdraulic Cement Concrete

Project Number: 2023.0069 **Project Coordinator:** L. Pham

Operator: D. Witte **Test Date:** 3/14/2025

Checked by: L. Pham **Review Date:** 1/6/2026

Mix ID: F1

Date Cast: 1/23/2025

Curing Duration (days): 50

Curing Condition ☑ Saturated ☐

Specimen Type: ☑ Cast ☐ Cored ☐

Specimen Age (days): 50

Specimen Dia. (in): 4

Calibration Sample Material: SS 304
Calibration Sample CTE (10^{-6}/°C): 16.20

Verification Sample Material: SS 440C
Verification Sample CTE (10^{-6}/°C): 10.40

Specimen ID	Length (in)	Correction Factor (10-6/°C)	Segment	Start Temperature (°C)	Start LVDT Reading (in.)	End Temperature (°C)	End LVDT Reading (in.)	Measured Length Change, ΔLm (in.)	Length Change of Frame, ΔLf (in.)	Actual Length Change, ΔLa (in.)	Concrete CTE (10-6/°C)	Concrete CTE (10-6/°F)
Mix 3-2 (A)	7.005	-0.21	Heating	10.1	0.008070	50.1	0.011920	0.003850	-5.89E-05	3.79E-03	**13.53**	**7.51**
			Cooling	50.1	0.011920	10.2	0.008040	-0.003880	5.88E-05	-3.82E-03	**13.64**	**7.58**
			Sample 2 CTE (Avergage of two segments)								**13.59**	**7.55**

Concrete Mixture CTE (10-6/°C and 10-6/°F, respectively)	**13.6**	**7.5**

AASHTO T336 - Coefficient of Thermal Expansion of Hyrdraulic Cement Concrete

Project Number: 2023.0069   **Project Coordinator:** L. Pham

Operator: D. Witte   **Test Date:** 2/25/2025

Checked by: L. Pham   **Review Date:** 1/6/2026

Mix ID: F1

Date Cast: 1/23/2025

Specimen Type: ☑ Cast ☐ Cored ☐

Curing Duration (days): 33

Specimen Age (days): 33

Calibration Sample Material: SS 304

Calibration Sample CTE (10^{-6}/°C): 16.20

Curing Condition ☑ Saturated ☐

Specimen Dia. (in): 4

Verification Sample Material: SS 440C

Verification Sample CTE (10^{-6}/°C): 10.40

Specimen ID	Length (in)	Correction Factor (10-6/°C)	Segment	Start Temperature (°C)	Start LVDT Reading (in.)	End Temperature (°C)	End LVDT Reading (in.)	Measured Length Change, ΔLm (in.)	Length Change of Frame, ΔLf (in.)	Actual Length Change, ΔLa (in.)	Concrete CTE (10-6/°C)	Concrete CTE (10-6/°F)
Mix3-2(B)	7.002	-0.21	Cooling	50.2	0.002769	10.3	-0.000851	-0.003620	5.87E-05	-3.56E-03	**12.73**	**7.07**
			Heating	10.3	-0.000851	50.2	0.002779	0.003630	-5.88E-05	3.57E-03	**12.75**	**7.09**
			Sample 2 CTE (Avergage of two segments)								**12.74**	**7.08**

Concrete Mixture CTE (10-6/°C and 10-6/°F, respectively)	12.7	7.1

AASHTO T336 - Coefficient of Thermal Expansion of Hyrdraulic Cement Concrete

Project Number: 2023.0069 **Project Coordinator:** L. Pham

Operator: D. Witte **Test Date:** 3/6/2025

Checked by: L. Pham **Review Date:** 1/6/2026

Mix ID: F2

Date Cast: 1/23/2025

Specimen Type: ☑ Cast ☐ Cored ☐

Curing Duration (days): 42

Specimen Age (days): 42

Calibration Sample Material: SS 304

Calibration Sample CTE (10^{-6}/°C): 16.20

Curing Condition ☑ Saturated ☐

Specimen Dia. (in): 4

Verification Sample Material: SS 440C

Verification Sample CTE (10^{-6}/°C): 10.40

Specimen ID	Length (in)	Correction Factor (10-6/°C)	Segment	Start Temperature (°C)	Start LVDT Reading (in.)	End Temperature (°C)	End LVDT Reading (in.)	Measured Length Change, ΔLm (in.)	Length Change of Frame, ΔLf (in.)	Actual Length Change, ΔLa (in.)	Concrete CTE (10-6/°C)	Concrete CTE (10-6/°F)
Mix 2-A	6.986	-0.21	Cooling	50.1	0.004083	10.0	0.000332	-0.003751	5.88E-05	-3.69E-03	**13.18**	**7.32**
			Heating	10.0	0.000332	50.2	0.004033	0.003701	-5.89E-05	3.64E-03	**12.98**	**7.21**
			Sample 2 CTE (Avergage of two segments)								**13.08**	**7.27**

Concrete Mixture CTE (10-6/°C and 10-6/°F, respectively)	**13.1**	**7.3**

AASHTO T336 - Coefficient of Thermal Expansion of Hyrdraulic Cement Concrete

Project Number: 2023.0069 **Project Coordinator:** L. Pham

Operator: D. Witte **Test Date:** 2/20/2025

Checked by: L. Pham **Review Date:** 1/6/2026

Mix ID: F2

Date Cast: 1/23/2025

Curing Duration (days): 28

Curing Condition ☑ Saturated ☐

Specimen Type: ☑ Cast ☐ Cored ☐

Specimen Age (days): 28

Specimen Dia. (in): 4

Calibration Sample Material: SS 304
Calibration Sample CTE (10^{-6}/°C): 16.20

Verification Sample Material: SS 440C
Verification Sample CTE (10^{-6}/°C): 10.40

Specimen ID	Length (in)	Correction Factor (10-6/°C)	Segment	Start Temperature (°C)	Start LVDT Reading (in.)	End Temperature (°C)	End LVDT Reading (in.)	Measured Length Change, ΔLm (in.)	Length Change of Frame, ΔLf (in.)	Actual Length Change, ΔLa (in.)	Concrete CTE (10-6/°C)	Concrete CTE (10-6/°F)
Mix2-B	6.998	-0.21	Cooling	50.1	0.020030	10.1	0.015970	-0.004060	5.88E-05	-4.00E-03	**14.29**	**7.94**
			Heating	10.1	0.015970	50.2	0.020070	0.004100	-5.88E-05	4.04E-03	**14.43**	**8.01**
			Sample 2 CTE (Avergage of two segments)								**14.36**	**7.98**

Concrete Mixture CTE (10-6/°C and 10-6/°F, respectively)	14.4	8.0

AASHTO T336 - Coefficient of Thermal Expansion of Hyrdraulic Cement Concrete

Project Number: 2023.0069 **Project Coordinator:** L. Pham

Operator: D. Witte **Test Date:** 3/27/2025

Checked by: L. Pham **Review Date:** 1/6/2026

Mix ID: H1

Date Cast: 1/28/2025

Specimen Type: ☑ Cast ☐ Cored ☐ ________

Curing Duration (days): 58

Specimen Age (days): 58

Calibration Sample Material: SS 304
Calibration Sample CTE (10^{-6}/°C): 16.20

Curing Condition ☑ Saturated ☐ ________

Specimen Dia. (in): 4

Verification Sample Material: SS 440C
Verification Sample CTE (10^{-6}/°C): 10.40

Specimen ID	Length (in)	Correction Factor (10-6/°C)	Segment	Start Temperature (°C)	Start LVDT Reading (in.)	End Temperature (°C)	End LVDT Reading (in.)	Measured Length Change, ΔLm (in.)	Length Change of Frame, ΔLf (in.)	Actual Length Change, ΔLa (in.)	Concrete CTE (10-6/°C)	Concrete CTE (10-6/°F)
Mix 1-A	6.981	-0.21	Cooling	50.1	0.005416	9.8	0.000867	-0.004549	5.91E-05	-4.49E-03	**15.96**	**8.86**
			Heating	9.8	0.000867	50.1	0.005342	0.004475	-5.90E-05	4.42E-03	**15.71**	**8.73**
			Sample 2 CTE (Avergage of two segments)								**15.83**	**8.80**

Concrete Mixture CTE (10-6/°C and 10-6/°F, respectively)	**15.8**	**8.8**

AASHTO T336 - Coefficient of Thermal Expansion of Hyrdraulic Cement Concrete

Project Number: 2023.0069 **Project Coordinator:** L. Pham

Operator: D. Witte **Test Date:** 2/22/2025

Checked by: L. Pham **Review Date:** 1/6/2026

Mix ID: H1

Date Cast: 1/28/2025

Specimen Type: ☑ Cast ☐ Cored ☐

Curing Duration (days): 25

Specimen Age (days): 25

Calibration Sample Material: SS 304

Calibration Sample CTE (10^{-6}/°C): 16.20

Curing Condition ☑ Saturated ☐

Specimen Dia. (in): 4

Verification Sample Material: SS 440C

Verification Sample CTE (10^{-6}/°C): 10.40

Specimen ID	Length (in)	Correction Factor (10-6/°C)	Segment	Start Temperature (°C)	Start LVDT Reading (in.)	End Temperature (°C)	End LVDT Reading (in.)	Measured Length Change, ΔLm (in.)	Length Change of Frame, ΔLf (in.)	Actual Length Change, ΔLa (in.)	Concrete CTE (10-6/°C)	Concrete CTE (10-6/°F)
Mix1-B	7.005	-0.21	Cooling	50.3	0.014360	10.1	0.010020	-0.004340	5.91E-05	-4.28E-03	**15.21**	**8.45**
			Heating	10.1	0.010020	50.2	0.014240	0.004220	-5.90E-05	4.16E-03	**14.81**	**8.23**
			Sample 2 CTE (Avergage of two segments)								**15.01**	**8.34**

Concrete Mixture CTE (10-6/°C and 10-6/°F, respectively)	**15.0**	**8.3**

AASHTO T336 - Coefficient of Thermal Expansion of Hyrdraulic Cement Concrete

Project Number: 2023.0069 **Project Coordinator:** L. Pham

Operator: D. Witte **Test Date:** 3/17/2025

Checked by: L. Pham **Review Date:** 1/6/2026

Mix ID: H2

Date Cast: 1/28/2025

Specimen Type: ☑ Cast ☐ Cored ☐

Curing Duration (days): 48

Specimen Age (days): 48

Calibration Sample Material: SS 304

Calibration Sample CTE (10^{-6}/°C): 16.20

Curing Condition ☑ Saturated ☐

Specimen Dia. (in): 4

Verification Sample Material: SS 440C

Verification Sample CTE (10^{-6}/°C): 10.40

Specimen ID	Length (in)	Correction Factor (10-6/°C)	Segment	Start Temperature (°C)	Start LVDT Reading (in.)	End Temperature (°C)	End LVDT Reading (in.)	Measured Length Change, ΔLm (in.)	Length Change of Frame, ΔLf (in.)	Actual Length Change, ΔLa (in.)	Concrete CTE (10-6/°C)	Concrete CTE (10-6/°F)
Mix 4-A	7.01	-0.21	Cooling	50.1	0.005207	10.2	0.001180	-0.004027	5.88E-05	-3.97E-03	**14.18**	**7.88**
			Heating	10.2	0.001180	50.1	0.005213	0.004033	-5.89E-05	3.97E-03	**14.18**	**7.88**
			Sample 2 CTE (Avergage of two segments)								**14.18**	**7.88**

Concrete Mixture CTE (10-6/°C and 10-6/°F, respectively)	14.2	7.9

AASHTO T336 - Coefficient of Thermal Expansion of Hyrdraulic Cement Concrete

Project Number: 2023.0069 **Project Coordinator:** L. Pham

Operator: D. Witte **Test Date:** 2/28/2025

Checked by: L. Pham **Review Date:** 1/6/2026

Mix ID: H2

Date Cast: 1/28/2025

Specimen Type: ☑ Cast ☐ Cored ☐

Curing Duration (days): 31

Specimen Age (days): 31

Calibration Sample Material: SS 304

Calibration Sample CTE (10^{-6}/°C): 16.20

Curing Condition ☑ Saturated ☐

Specimen Dia. (in): 4

Verification Sample Material: SS 440C

Verification Sample CTE (10^{-6}/°C): 10.40

Specimen ID	Length (in)	Correction Factor (10-6/°C)	Segment	Start Temperature (°C)	Start LVDT Reading (in.)	End Temperature (°C)	End LVDT Reading (in.)	Measured Length Change, ΔLm (in.)	Length Change of Frame, ΔLf (in.)	Actual Length Change, ΔLa (in.)	Concrete CTE (10-6/°C)	Concrete CTE (10-6/°F)
Mix4B	6.995	-0.21	Cooling	50.1	0.001820	10.4	-0.002105	-0.003925	5.84E-05	-3.87E-03	**13.91**	**7.73**
			Heating	10.4	-0.002105	50.1	0.001758	0.003863	-5.83E-05	3.80E-03	**13.69**	**7.61**
			Sample 2 CTE (Avergage of two segments)								**13.80**	**7.67**

Concrete Mixture CTE (10-6/°C and 10-6/°F, respectively)	**13.8**	**7.7**

Tensile Pull-off Testing - ASTM C1583 & ICRI No. 210.3R-2013

Job Number:	2023.0069	**Operator:**	M. Haddad	**Location of Tests:**	Lab
Bond Tester SN:	8939	**Date:**	2/19/25 - 2/20/25	**Age of Repair/Overlay:**	28
Adhesive:	Loctite EA 7363	**Curing Time:**	12 plus hrs.	**Disk Type:**	3" Aluminum

Location ID	Ambient Temperature (F)	Surface Temperature (F)	Measured Load (lb.)	Specimen Diameter - 1 (in.)	Specimen Diameter - 2 (in.)	Area (in^2)	Tensile/Bond Strength (psi)	Overlay or Surface (O or S)	ASTM C1583 Failure Mode[1]	Faliure Notes
33A	72	68	2065	3.01	3.01	7.11	290	O	b	Separation predominantly in substrate within 1/16 in. from repair-substrate bond line
33B	72	68	1903	3.02	3.00	7.12	267	O	c/d	Separation 50% in repair; 50% adhesive
33C	72	68	1253	3.01	3.01	7.11	176	O	b	Separation predominantly in substrate within 1/16 in. from repair-substrate bond line
34A	72	68	911	3.01	3.01	7.10	128	O	b	Separation 100% at repair-substrate bond line
34B	72	68	1670	3.03	3.02	7.16	233	O	c	Separation 100% in repair
34C	72	68	1195	3.01	3.01	7.12	168	O	b	Separation 100% at repair-substrate bond line
35A	72	70	1674	3.02	3.02	7.16	234	O	b	Separation predominantly in substrate within 1/16 in. from repair-substrate bond line
35B	72	70	1170	3.01	3.01	7.12	164	O	b	Separation predominantly in substrate within 1/16 in. from repair-substrate bond line
35C	72	70	2138	3.01	3.01	7.11	301	O	b	Separation predominantly in substrate within 1/16 in. from repair-substrate bond line
36A	72	69	782	3.01	3.01	7.13	110	O	b	Separation 100% at repair-substrate bond line
36B	72	69	634	3.01	3.01	7.11	89	O	b	Separation 100% at repair-substrate bond line
36C	72	69	364	3.00	3.01	7.09	51	O	b	Separation 100% at repair-substrate bond line
37A	72	69	1680	3.01	3.01	7.12	236	O	b	Separation 100% at repair-substrate bond line
37B	72	69	1334	3.00	3.00	7.08	189	O	b	Separation 100% at repair-substrate bond line
37C	72	69	1270	3.01	3.01	7.11	179	O	b	Separation 100% at repair-substrate bond line
38A	72	67	728	3.01	3.01	7.10	103	O	b	Separation 100% at repair-substrate bond line
38B	72	67	1046	3.01	3.00	7.07	148	O	b	Separation 100% at repair-substrate bond line
38C	72	67	1780	3.01	3.01	7.11	250	O	b	Separation 100% at repair-substrate bond line
39A	-	-	-	-	-	-	-	O	b	Sample broke during coring at repair-substrate bond line
39B	-	-	-	-	-	-	-	O	b	Sample broke during coring at repair-substrate bond line
39C	-	-	-	-	-	-	-	O	b	Sample broke during coring at repair-substrate bond line
40A	-	-	-	-	-	-	-	O	b	Sample broke during coring at repair-substrate bond line
40B	-	-	-	-	-	-	-	O	b	Sample broke during coring at repair-substrate bond line
40B	-	-	-	-	-	-	-	O	b	Sample broke during coring at repair-substrate bond line

Notes:
[1] Per ASTM C1583: a - Failure in substrate; b - Failure at bond line between substrate and overlay or repair material, c - Failure in overlay or repair material, d - Failure at bond line between overlay or repair material and adhesive

Tensile Pull-off Testing - ASTM C1583 & ICRI No. 210.3R-2013

Sample ID	Repair Material	Installation method	Surface Prep
33A	H1	Hand-applied; Overhead	Sandblasted
33B	H1	Hand-applied; Overhead	Sandblasted
33C	H1	Hand-applied; Overhead	Sandblasted
34A	H2	Hand-applied; Overhead	Sandblasted
34B	H2	Hand-applied; Overhead	Sandblasted
34C	H2	Hand-applied; Overhead	Sandblasted
35A	H1	Hand-applied; Overhead	Not Sandblasted
35B	H1	Hand-applied; Overhead	Not Sandblasted
35C	H1	Hand-applied; Overhead	Not Sandblasted
36A	H2	Hand-applied; Overhead	Not Sandblasted
36B	H2	Hand-applied; Overhead	Not Sandblasted
36C	H2	Hand-applied; Overhead	Not Sandblasted
37A	F1	Form-and-pour; Vertical	Sandblasted
37B	F1	Form-and-pour; Vertical	Sandblasted
37C	F1	Form-and-pour; Vertical	Sandblasted
38A	F2	Form-and-pour; Vertical	Sandblasted
38B	F2	Form-and-pour; Vertical	Sandblasted
38C	F2	Form-and-pour; Vertical	Sandblasted
39A	F1	Form-and-pour; Overhead	Sandblasted
39B	F1	Form-and-pour; Overhead	Sandblasted
39C	F1	Form-and-pour; Overhead	Sandblasted
40A	F2	Form-and-pour; Overhead	Sandblasted
40B	F2	Form-and-pour; Overhead	Sandblasted
40C	F2	Form-and-pour; Overhead	Sandblasted

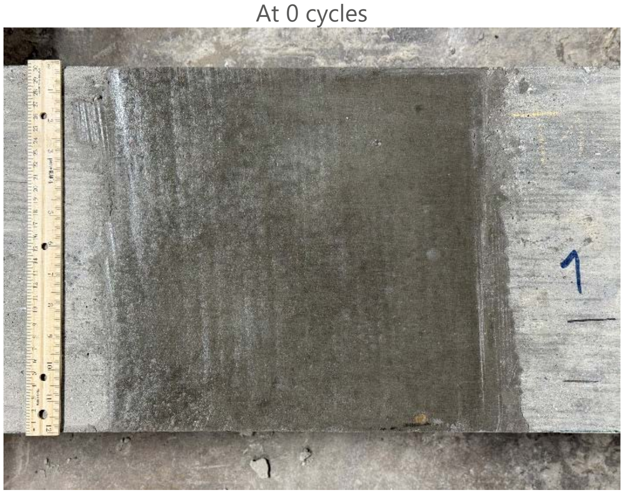
APPENDIX C3. THERMAL TESTING RESULTS

Table C3.1. Cracking in patch before and after thermal testing

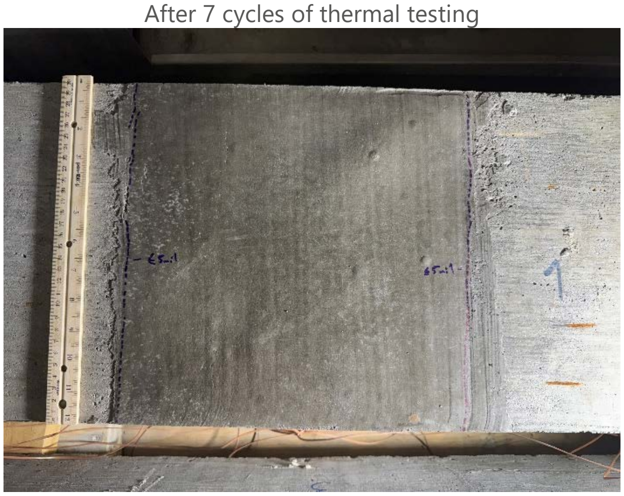
Specimen ID	Crack density (in/in^2)			
	At 0 cycle	Increase between 0 and 7 cycles	Increase between 7 and 28 cycles	Total after 28 cycles
1	-	0.16	-	0.16
2	0.05	0.08	-	0.13
3	0.16	0.16	0.05	0.38
4	0.13	0.18	-	0.31
5	-	0.17	-	0.17
6	-	0.17	-	0.17
7	0.16	0.11	0.13	0.40
8	0.22	0.10	-	0.32
9	-	0.17	0.03	0.20
10	-	0.24	-	0.24
11	0.17	0.18	0.02	0.37
12	0.17	0.16	0.01	0.34
13	-	0.13	0.03	0.16
14	-	0.23	-	0.23
15	0.06	0.02	0.07	0.15
16	0.06	0.12	-	0.18
17	0.13	-	-	0.13
18	-	0.12	-	0.12
19	-	0.16	-	0.16
20	0.15	0.02	-	0.16
21	0.21	-	-	0.21
22	-	-	-	-
23	0.12	-	-	0.12
24	0.11	-	-	0.11
25	0.18	0.02	-	0.20
26	0.02	-	0.06	0.08
27	0.16	0.01	-	0.17
28	0.15	0.01	-	0.16
29	0.09	0.06	-	0.15
30	0.06	0.08	-	0.13
31	0.17	-	-	0.17
32	-	0.12	-	0.12

Notes: "-" indicates that no cracking or not change in crack density was observed

At 0 cycles



After 7 cycles of thermal testing



After 28 cycles of thermal testing

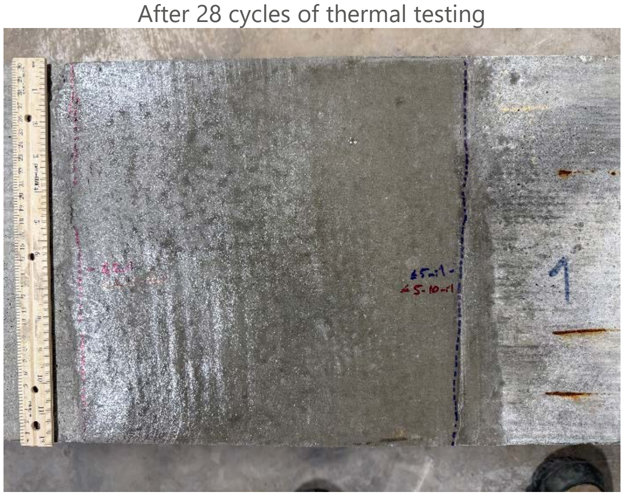
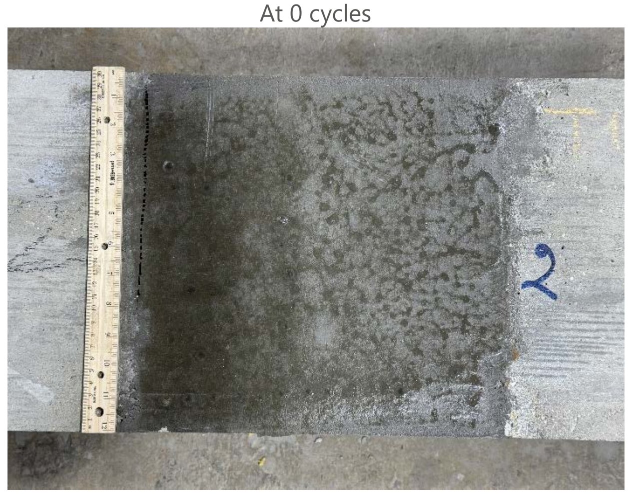


Figure C3.1. Specimen 1

At 0 cycles



After 7 cycles of thermal testing

After 28 cycles of thermal testing

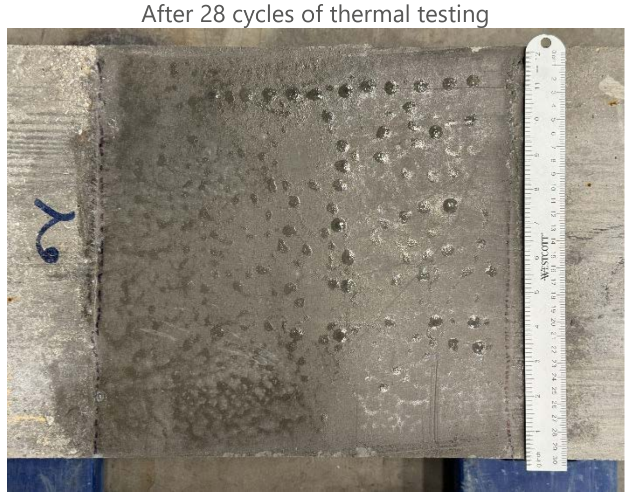
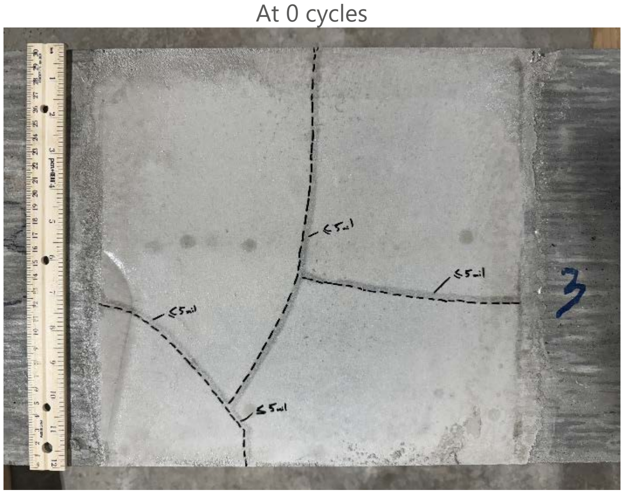


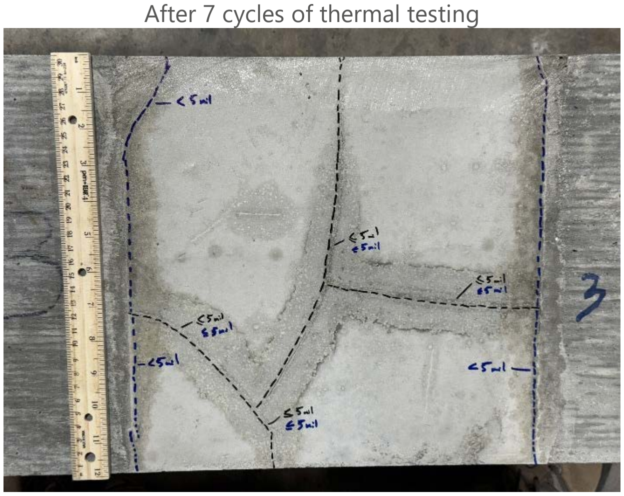
Figure C3.2. Specimen 2

(Marking indicates cracks and crack widths in mils (0.001 inch) within patch or at interface with substrate)

At 0 cycles



After 7 cycles of thermal testing



After 28 cycles of thermal testing

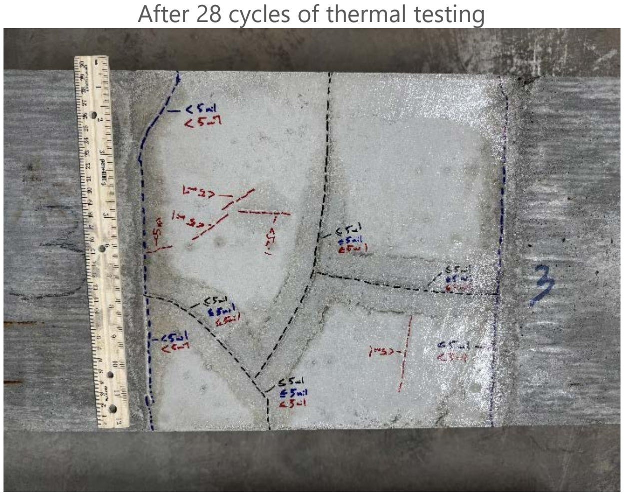
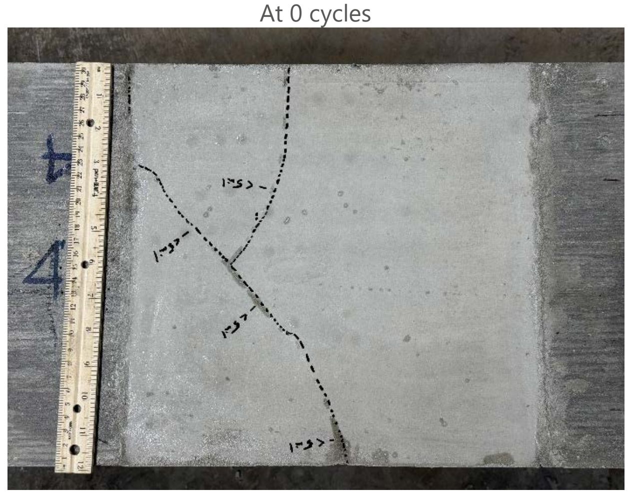
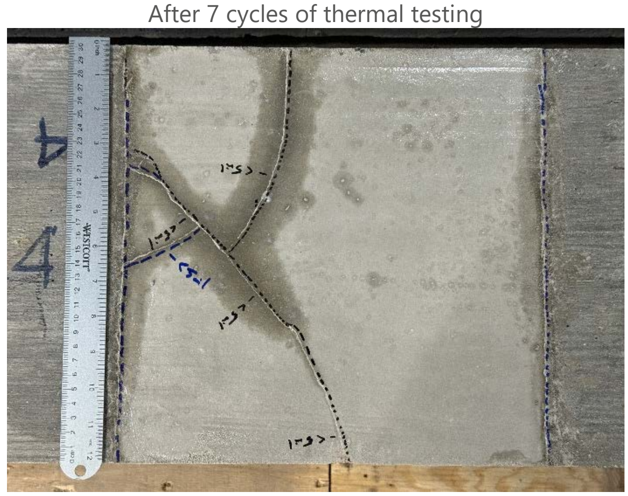


Figure C3.3. Specimen 3

At 0 cycles



After 7 cycles of thermal testing



After 28 cycles of thermal testing

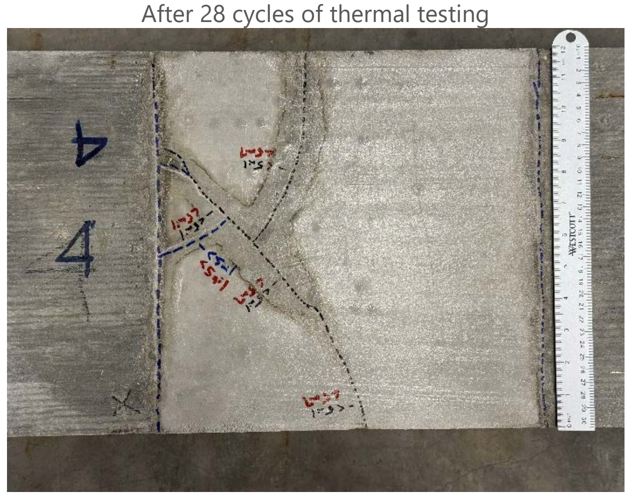
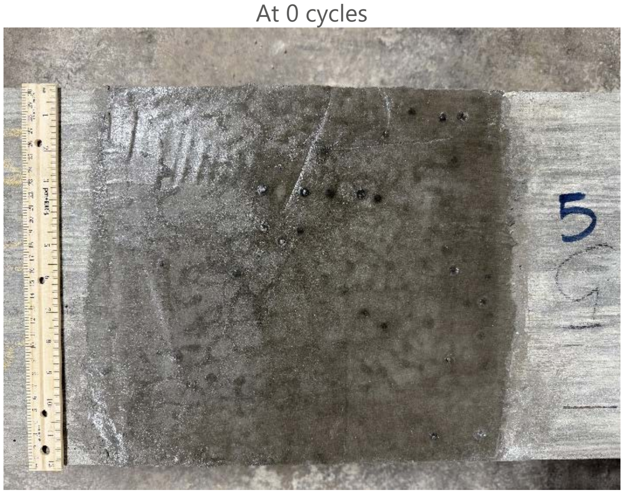


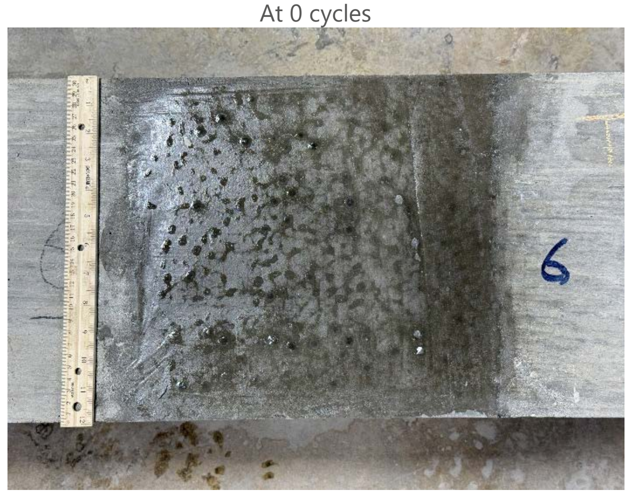
Figure C3.4. Specimen 4

(Marking indicates cracks and crack widths in mils (0.001 inch) within patch or at interface with substrate)

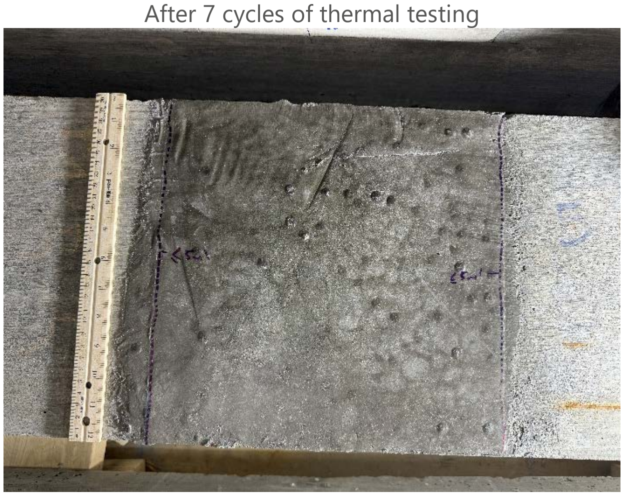
At 0 cycles



At 0 cycles

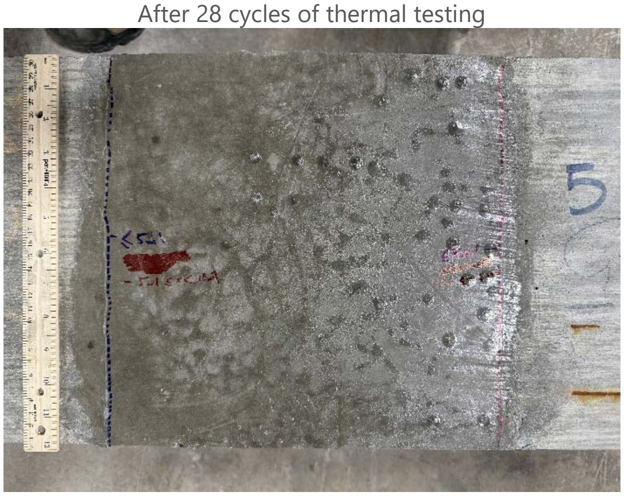


After 7 cycles of thermal testing



After 7 cycles of thermal testing

After 28 cycles of thermal testing



After 28 cycles of thermal testing

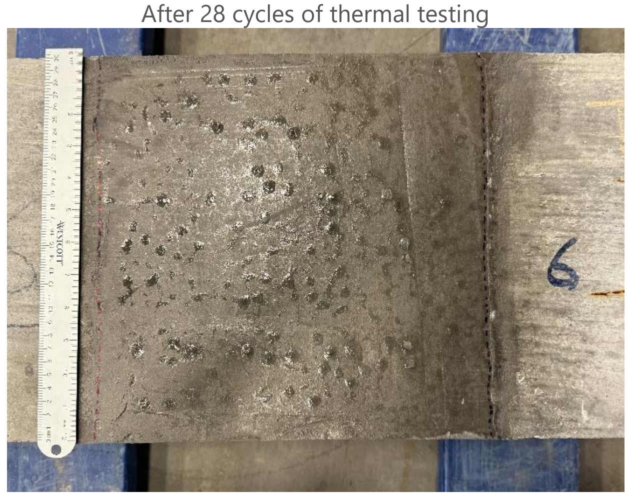
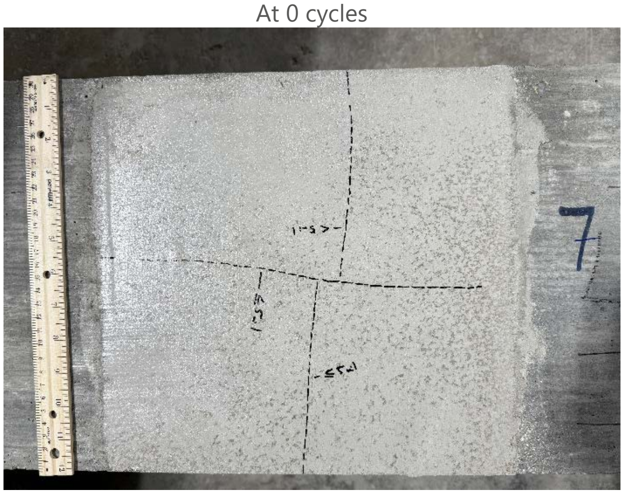


Figure C3.5. Specimen 5

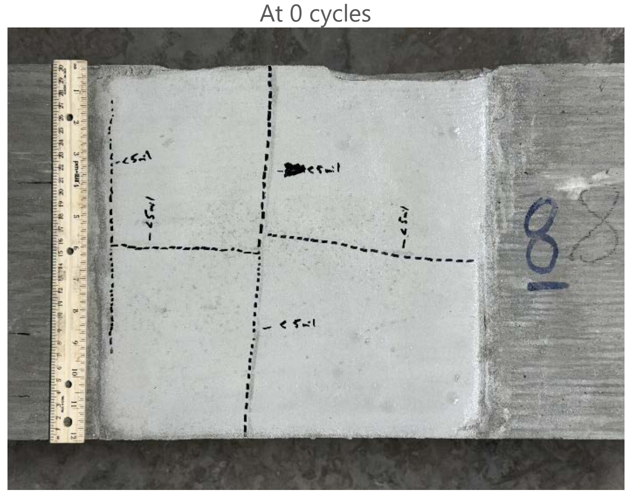
Figure C3.6. Specimen 6

(Marking indicates cracks and crack widths in mils (0.001 inch) within patch or at interface with substrate)

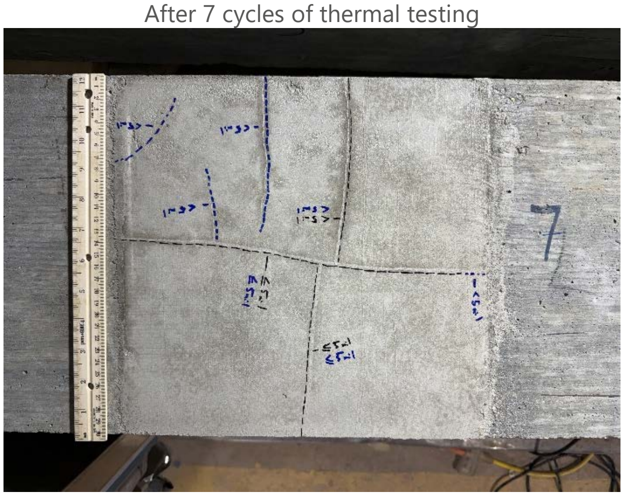
At 0 cycles



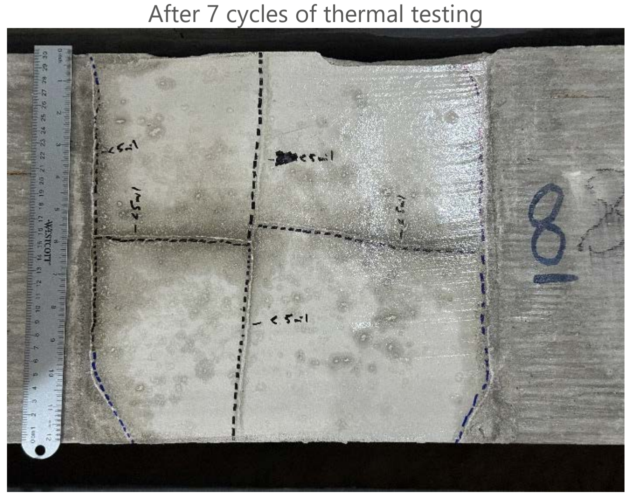
At 0 cycles



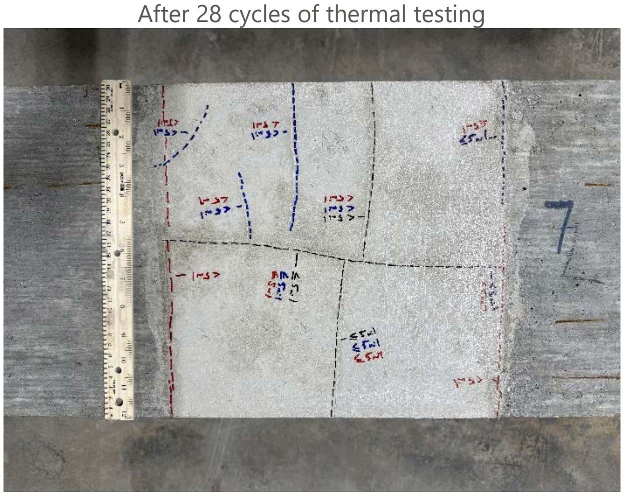
After 7 cycles of thermal testing



After 7 cycles of thermal testing



After 28 cycles of thermal testing



After 28 cycles of thermal testing

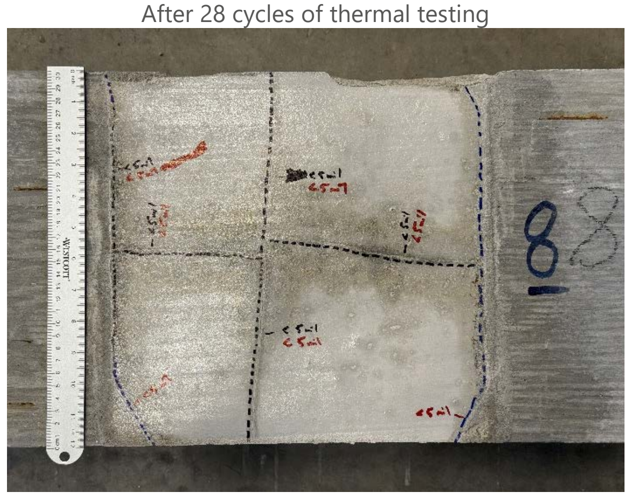
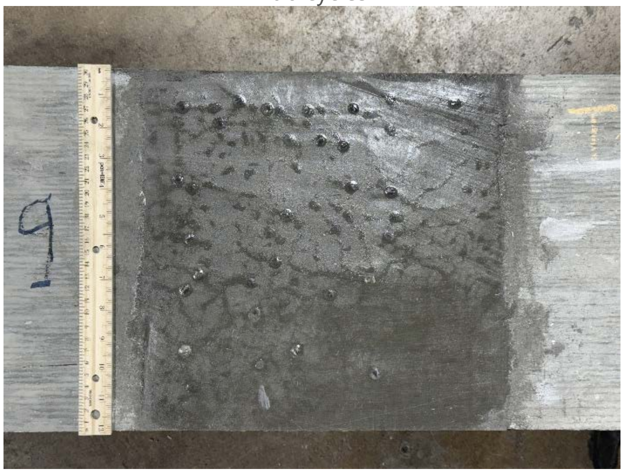


Figure C3.7. Specimen 7

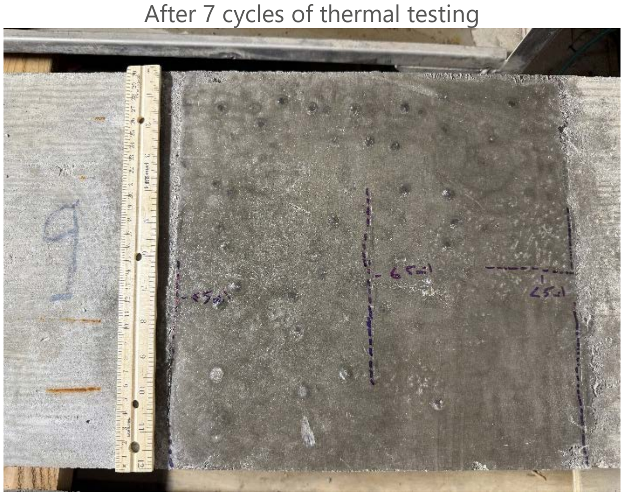
Figure C3.8. Specimen 8

(Marking indicates cracks and crack widths in mils (0.001 inch) within patch or at interface with substrate)

At 0 cycles



After 7 cycles of thermal testing



After 28 cycles of thermal testing

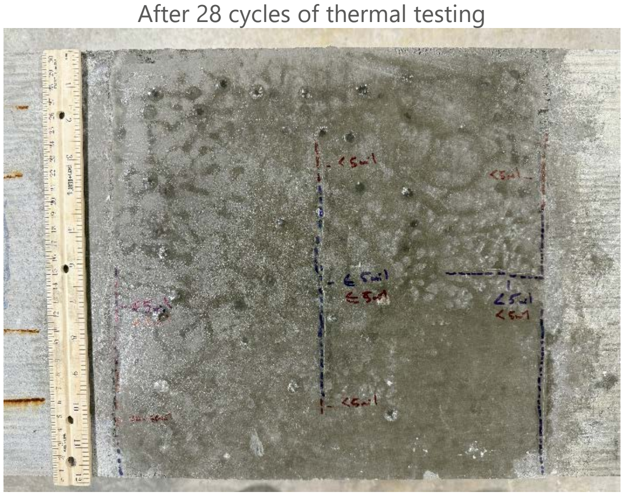
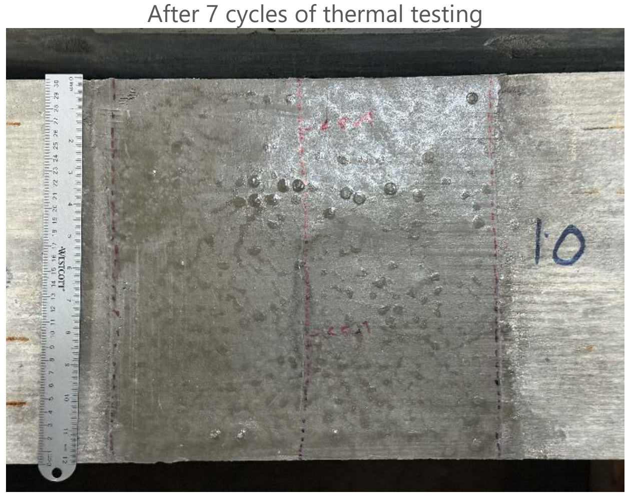


Figure C3.9. Specimen 9

At 0 cycles

After 7 cycles of thermal testing



After 28 cycles of thermal testing

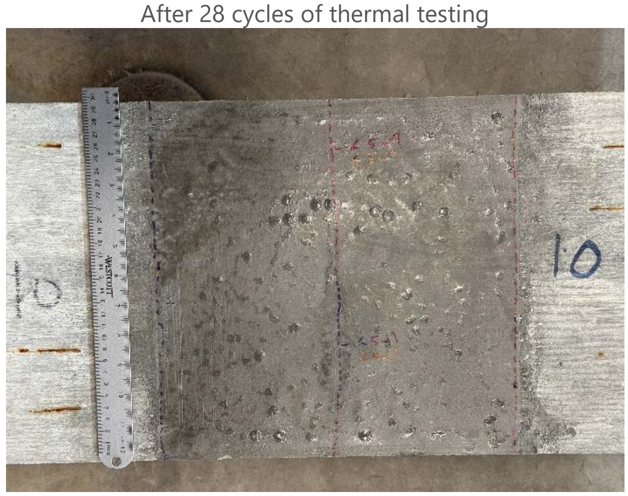
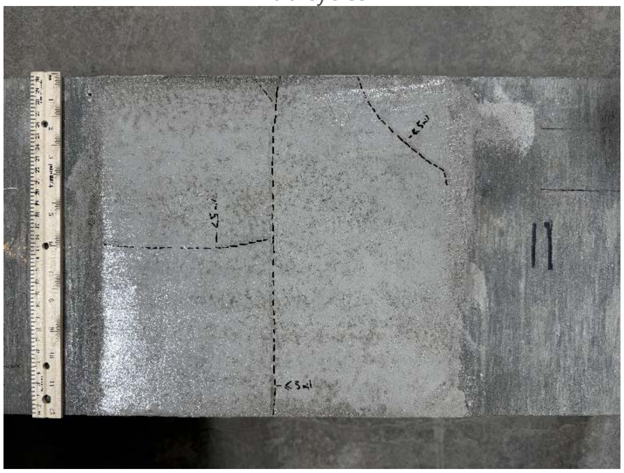


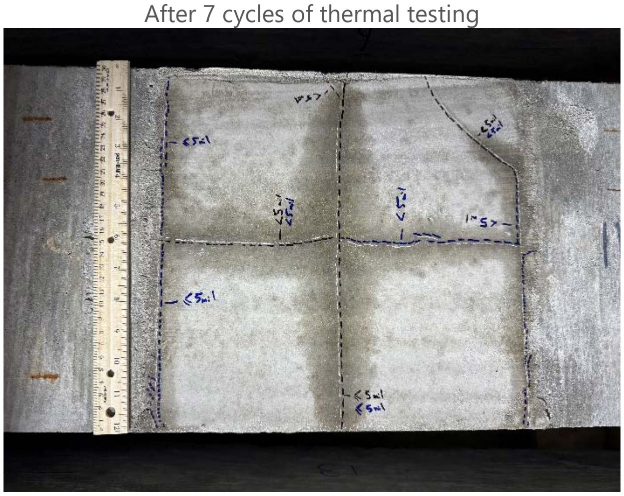
Figure C3.10. Specimen 10

(Marking indicates cracks and crack widths in mils (0.001 inch) within patch or at interface with substrate)

At 0 cycles



After 7 cycles of thermal testing



After 28 cycles of thermal testing

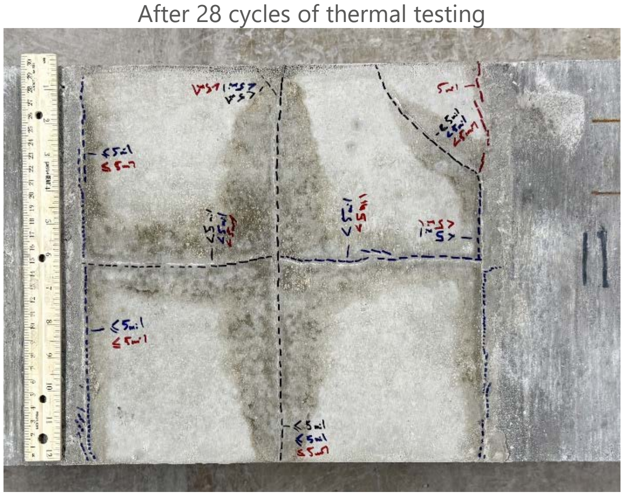
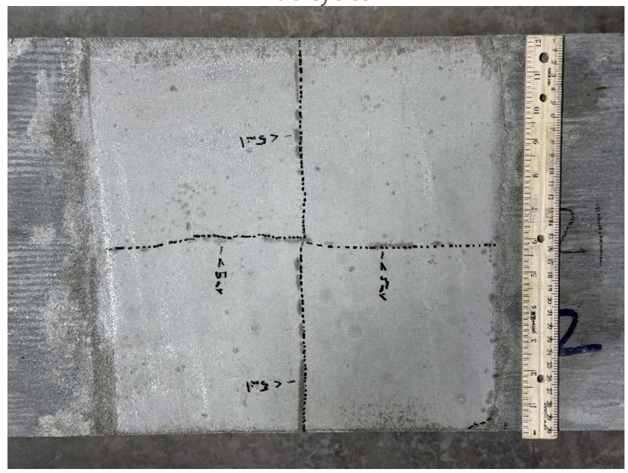
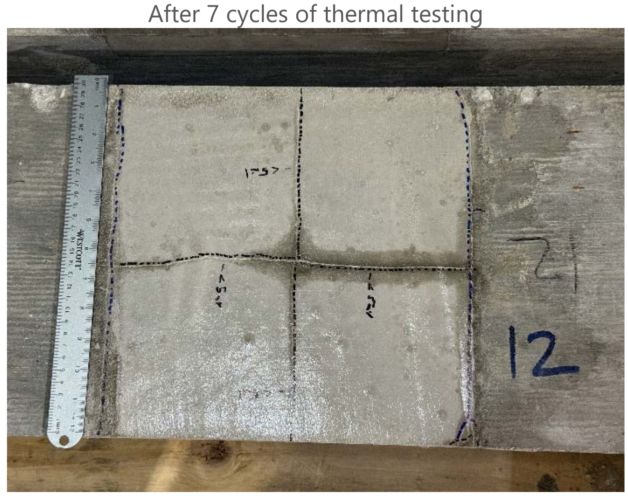


Figure C3.11. Specimen 11

At 0 cycles



After 7 cycles of thermal testing



After 28 cycles of thermal testing

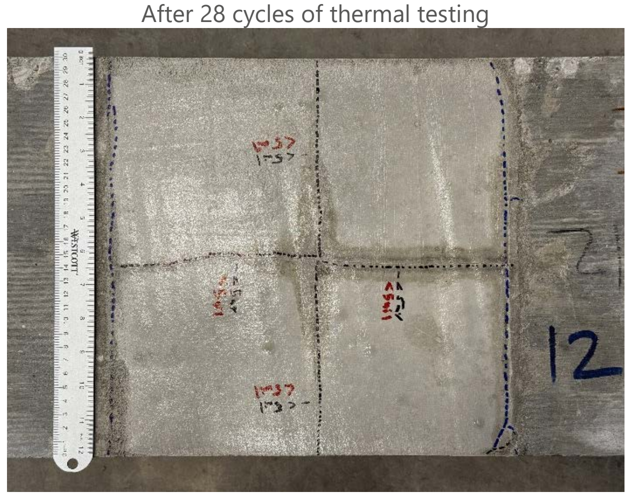
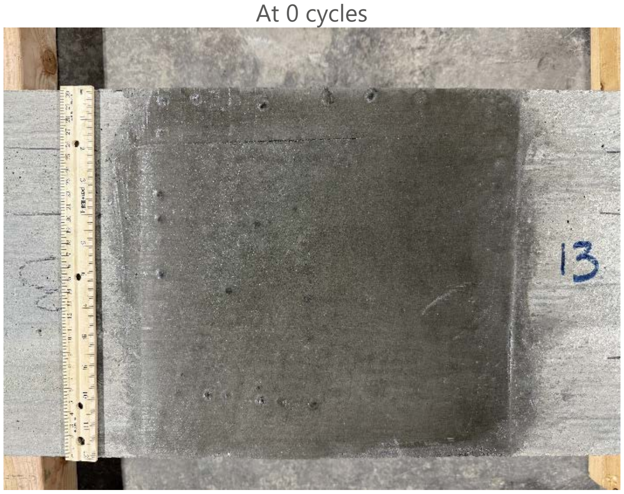


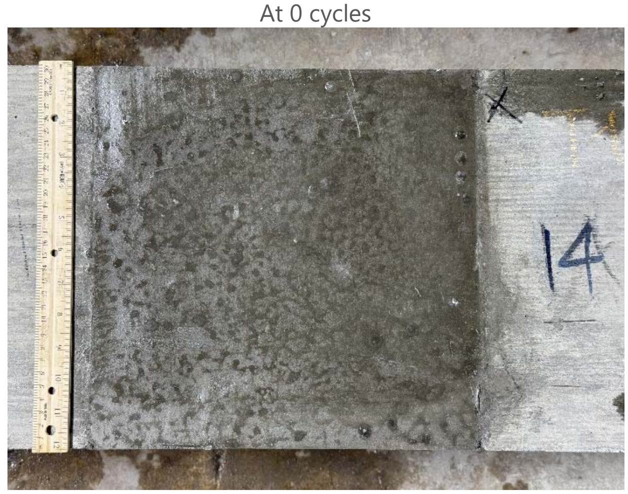
Figure C3.12. Specimen 12

(Marking indicates cracks and crack widths in mils (0.001 inch) within patch or at interface with substrate)

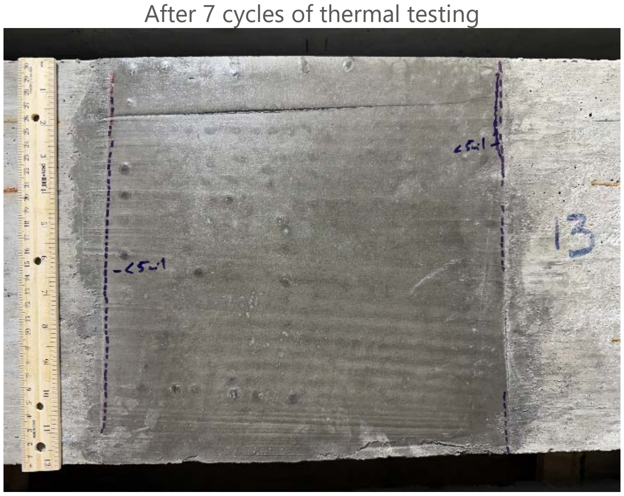
At 0 cycles



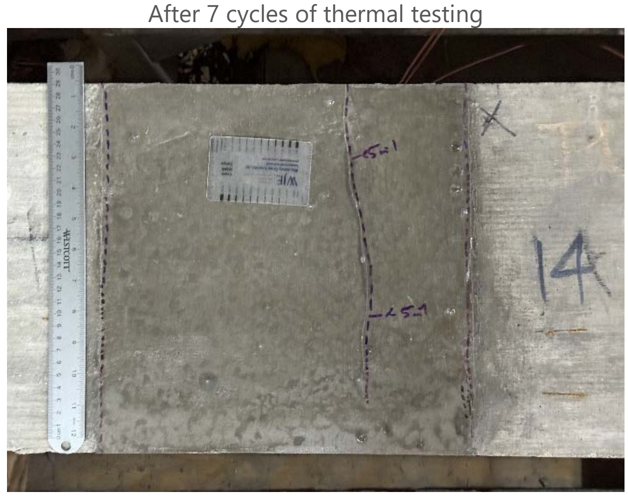
At 0 cycles



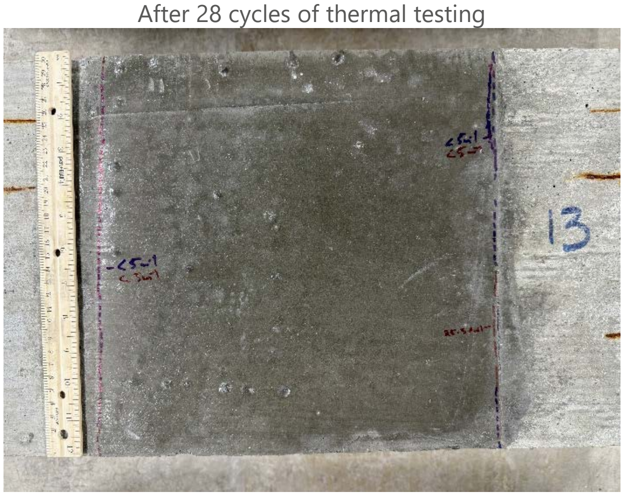
After 7 cycles of thermal testing



After 7 cycles of thermal testing



After 28 cycles of thermal testing



After 28 cycles of thermal testing

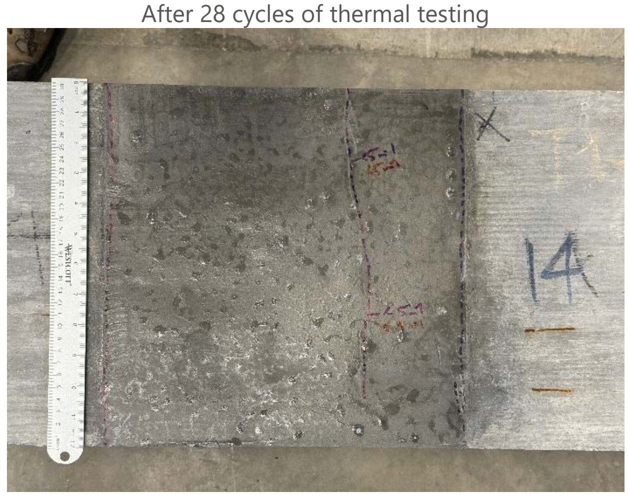


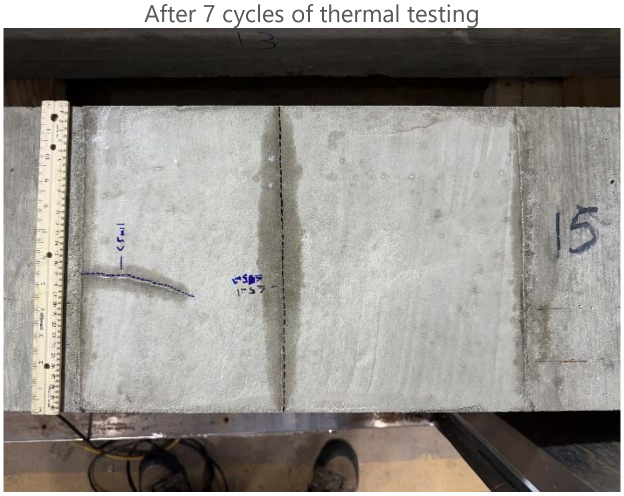
Figure C3.13. Specimen 13

Figure C3.14. Specimen 14

(Marking indicates cracks and crack widths in mils (0.001 inch) within patch or at interface with substrate)

At 0 cycles

After 7 cycles of thermal testing



After 28 cycles of thermal testing

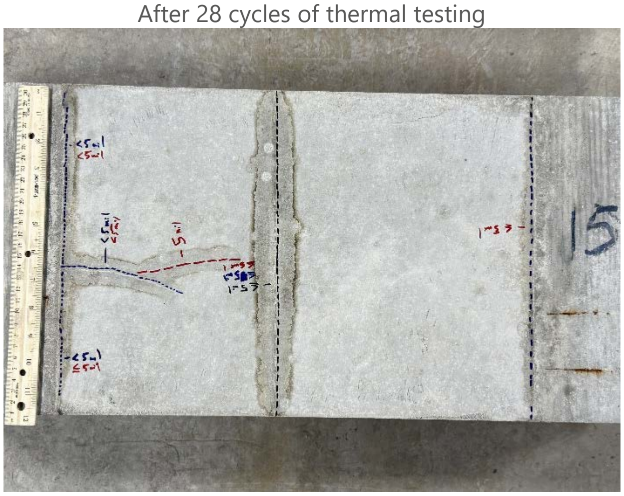
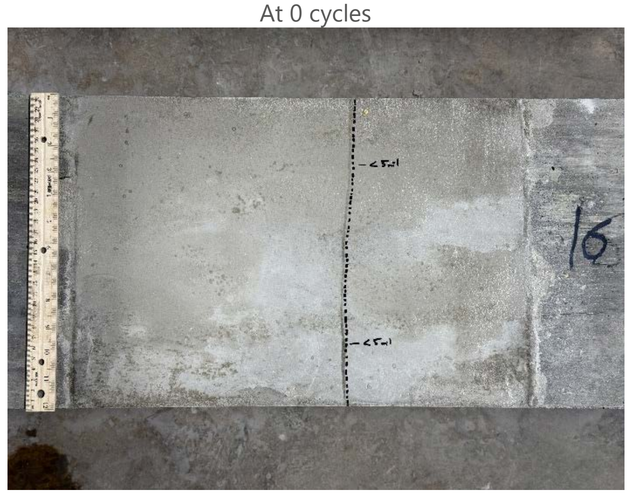
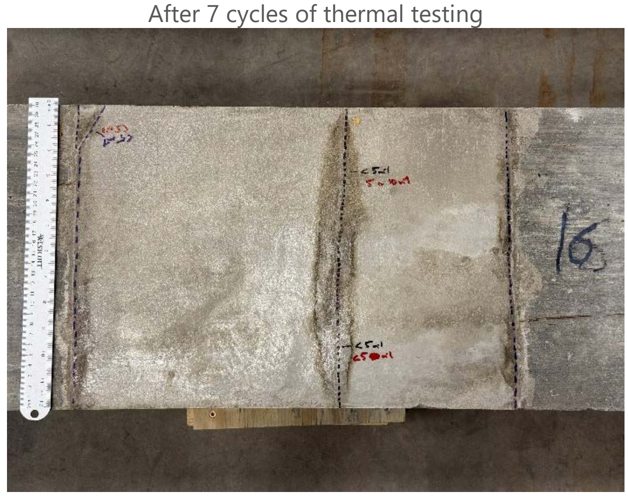


Figure C3.15. Specimen 15

At 0 cycles



After 7 cycles of thermal testing



After 28 cycles of thermal testing

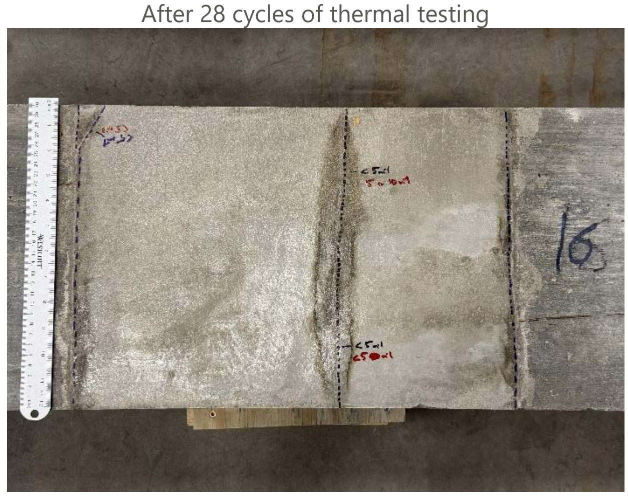
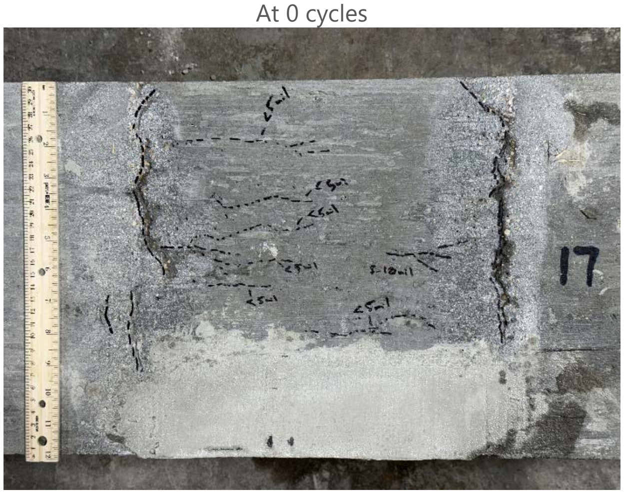


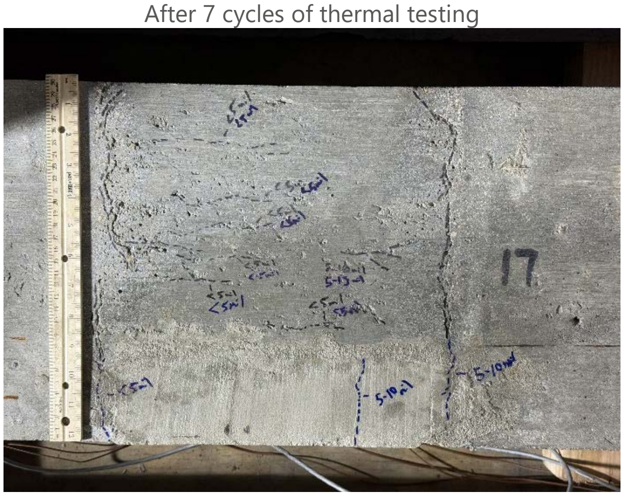
Figure C3.16. Specimen 16

(Marking indicates cracks and crack widths in mils (0.001 inch) within patch or at interface with substrate)

At 0 cycles



After 7 cycles of thermal testing



After 28 cycles of thermal testing

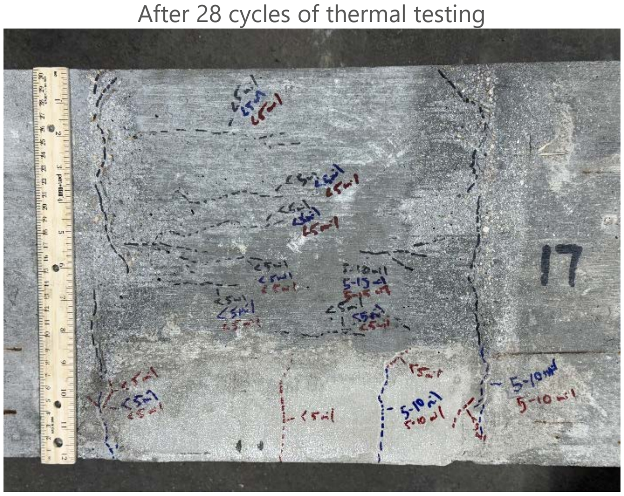
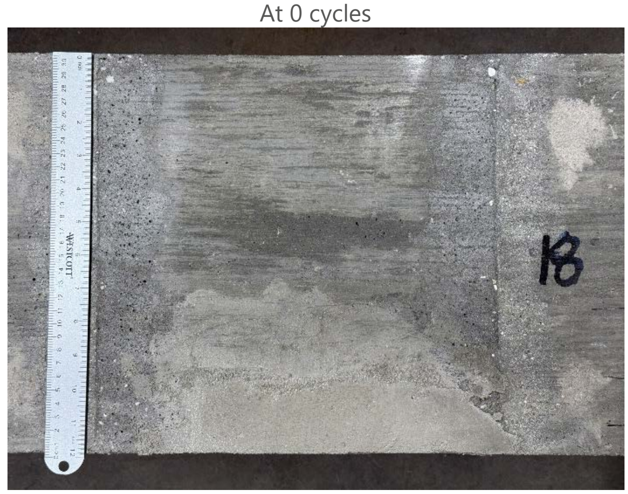
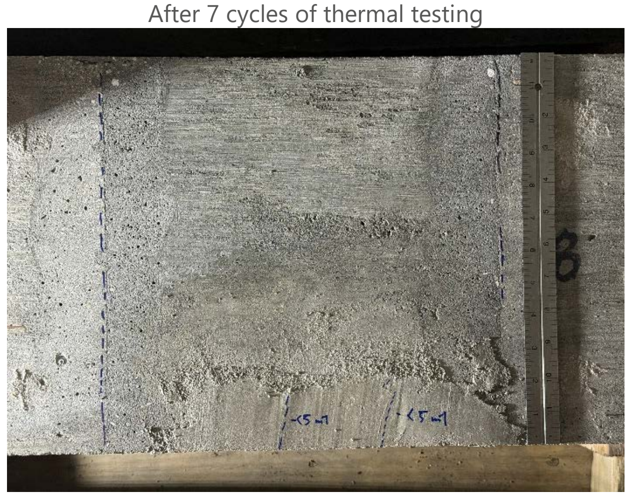


Figure C3.17. Specimen 17

At 0 cycles



After 7 cycles of thermal testing



After 28 cycles of thermal testing

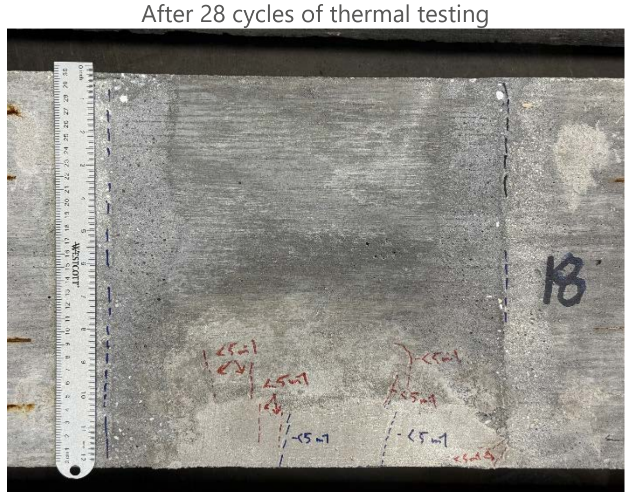
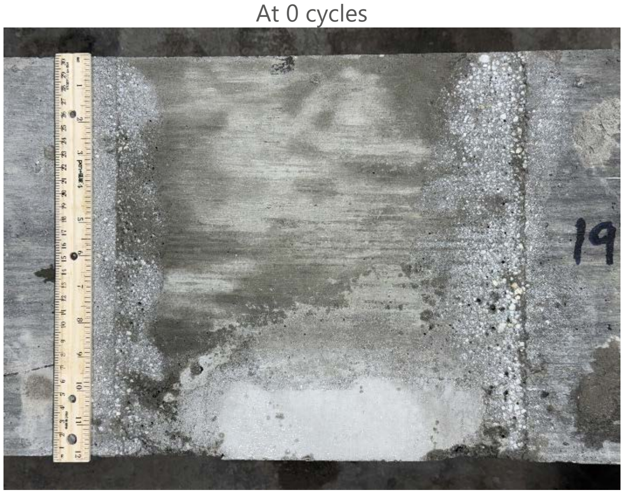


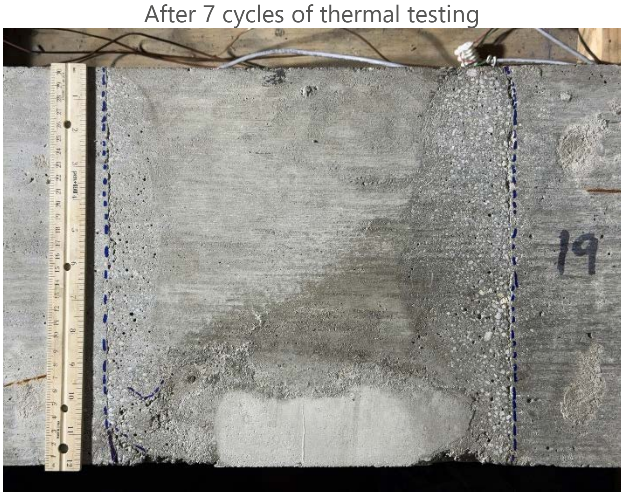
Figure C3.18. Specimen 18

(Marking indicates cracks and crack widths in mils (0.001 inch) within patch or at interface with substrate. Cracks in the repair to the patch and non-crack features were excluded in the analysis)

At 0 cycles



After 7 cycles of thermal testing



After 28 cycles of thermal testing

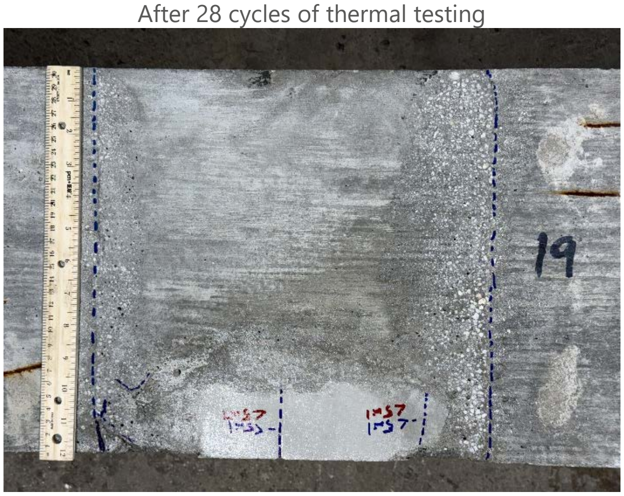
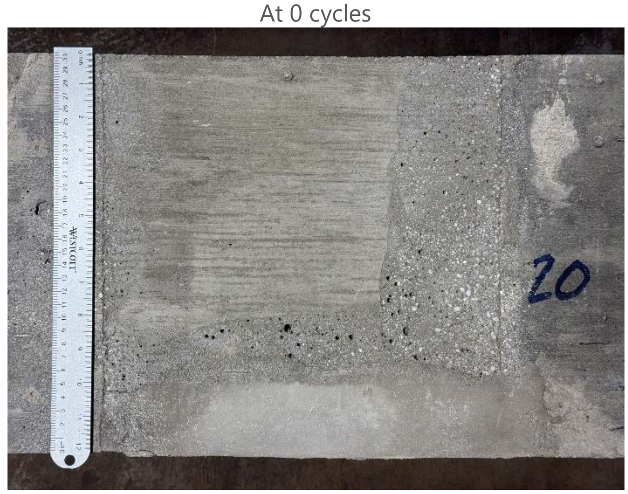
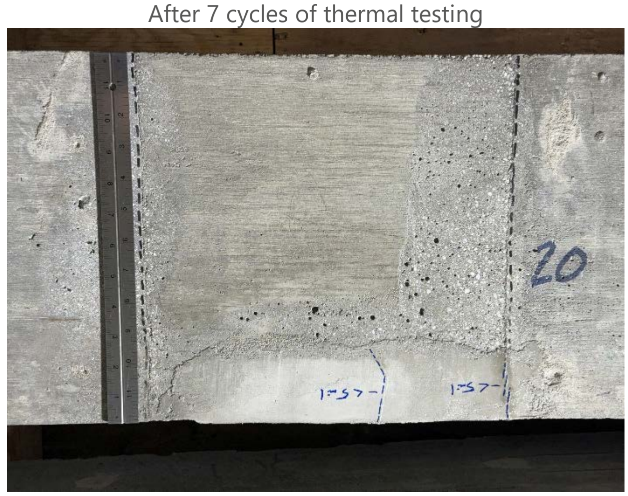


Figure C3.19. Specimen 19

At 0 cycles



After 7 cycles of thermal testing



After 28 cycles of thermal testing

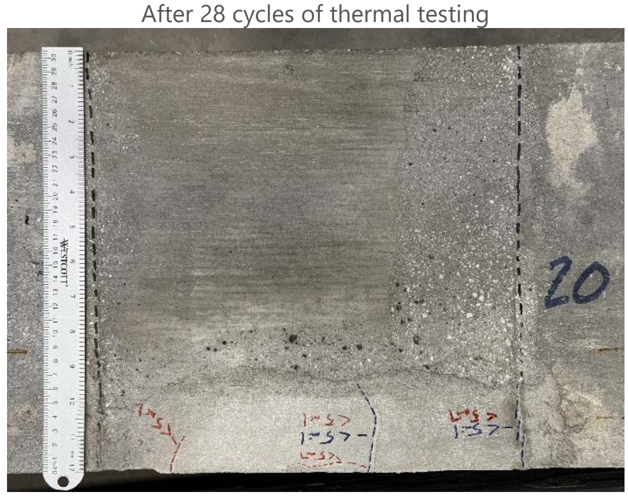
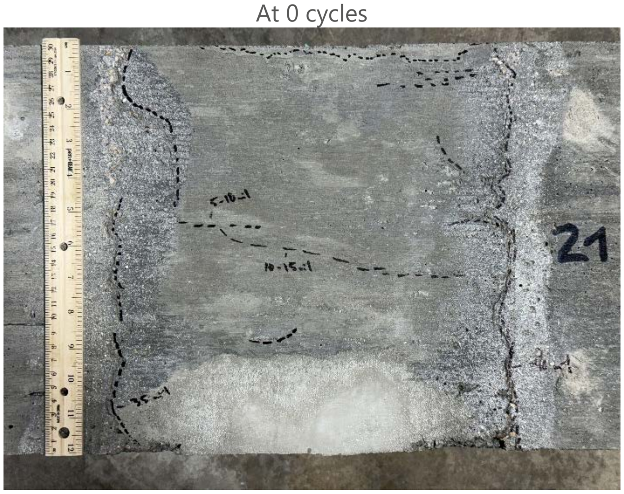


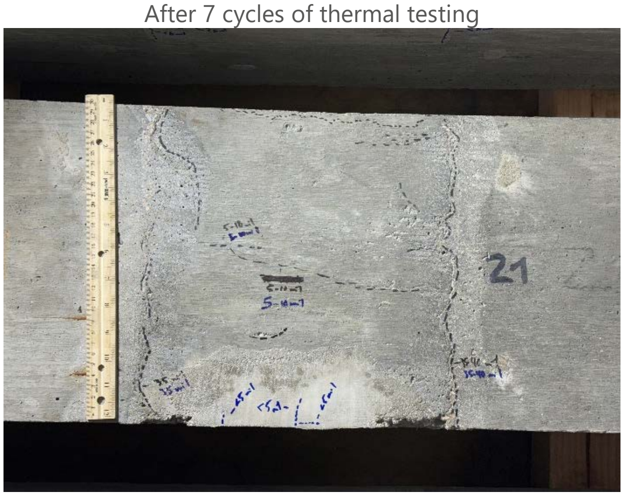
Figure C3.20. Specimen 20

(Marking indicates cracks and crack widths in mils (0.001 inch) within patch or at interface with substrate. Cracks in the repair to the patch and non-crack features were excluded in the analysis)

At 0 cycles



After 7 cycles of thermal testing



After 28 cycles of thermal testing

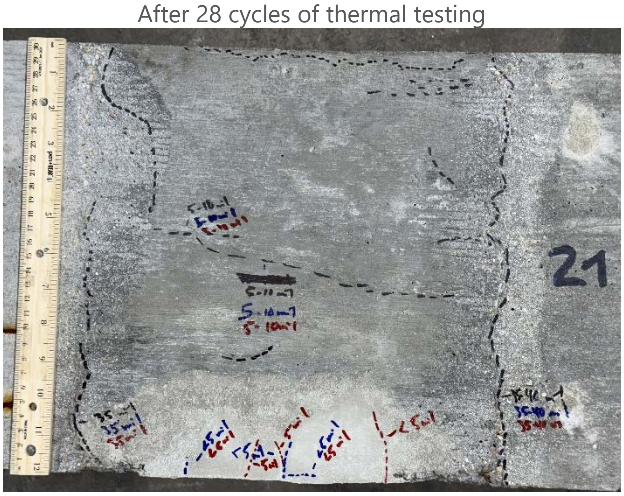
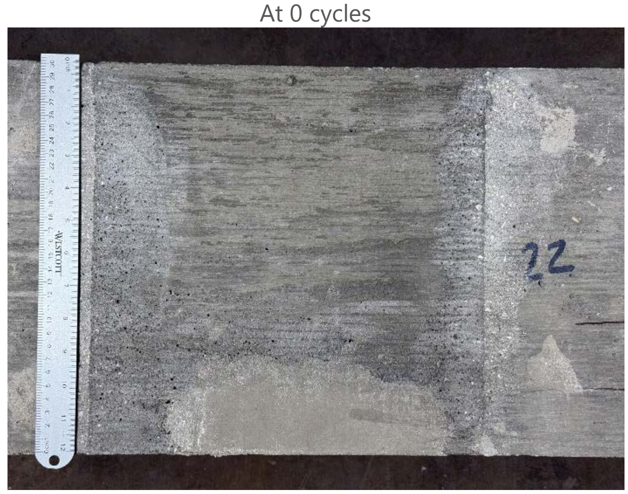
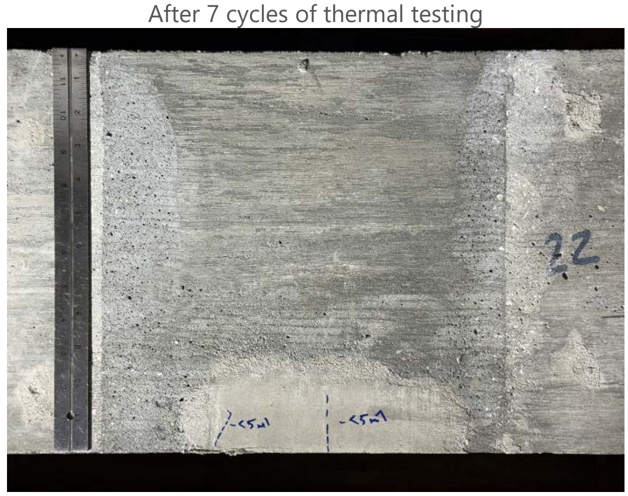


Figure C3.21. Specimen 11

At 0 cycles



After 7 cycles of thermal testing



After 28 cycles of thermal testing

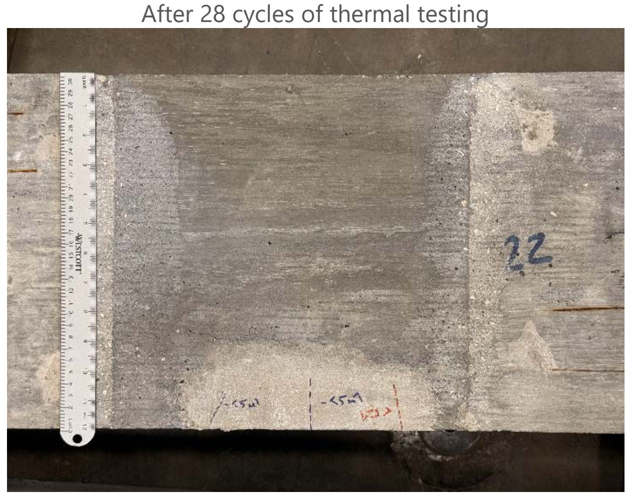
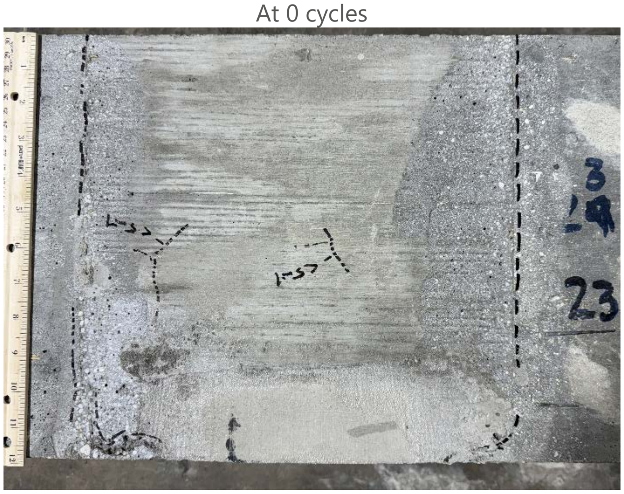


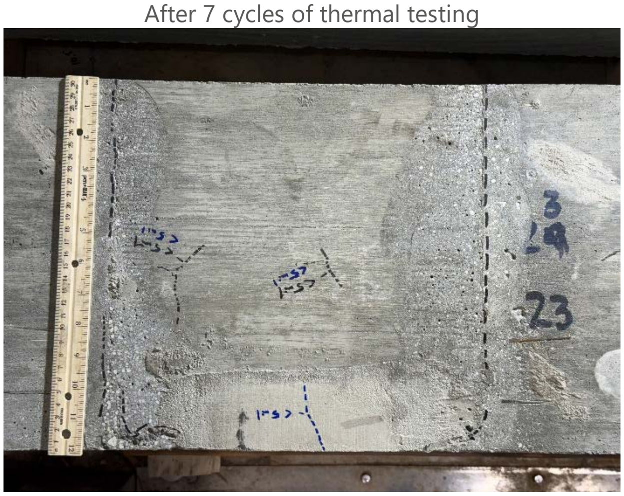
Figure C3.22. Specimen 22

(Marking indicates cracks and crack widths in mils (0.001 inch) within patch or at interface with substrate. Cracks in the repair to the patch and non-crack features were excluded in the analysis)

At 0 cycles



After 7 cycles of thermal testing



After 28 cycles of thermal testing

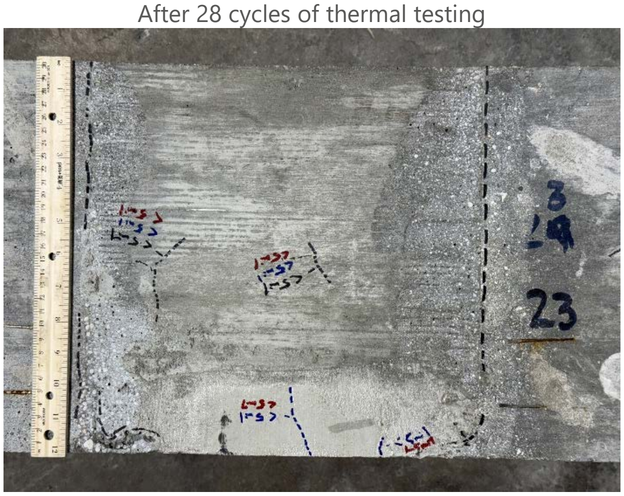
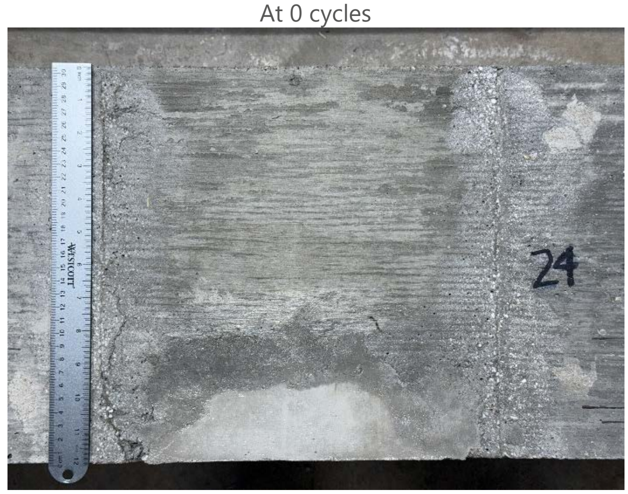
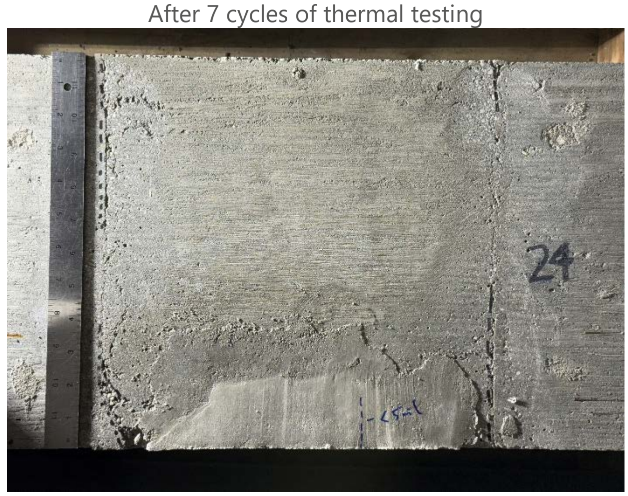


Figure C3.23. Specimen 23

At 0 cycles



After 7 cycles of thermal testing



After 28 cycles of thermal testing

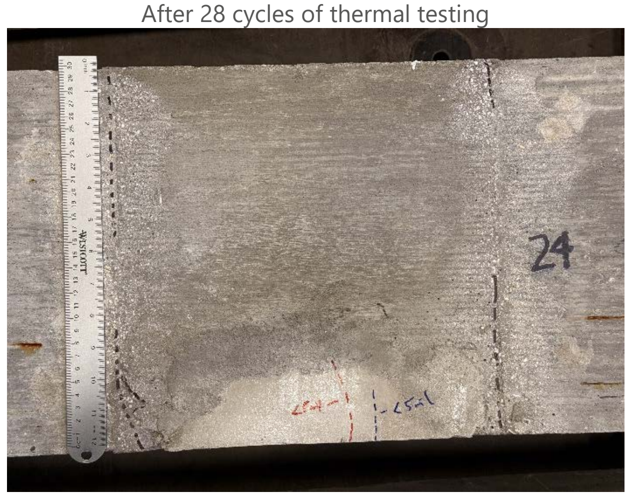
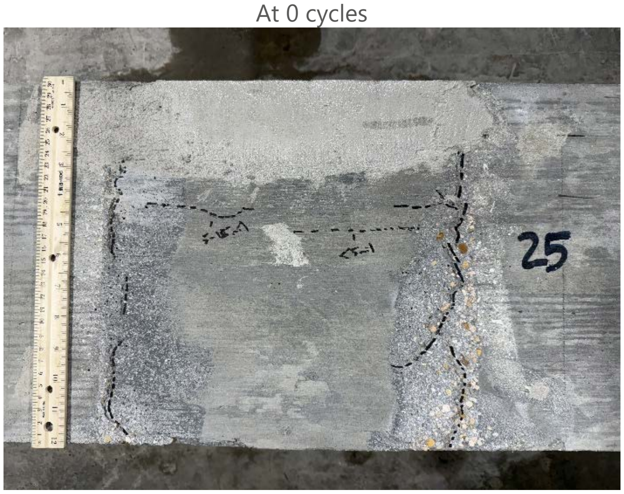


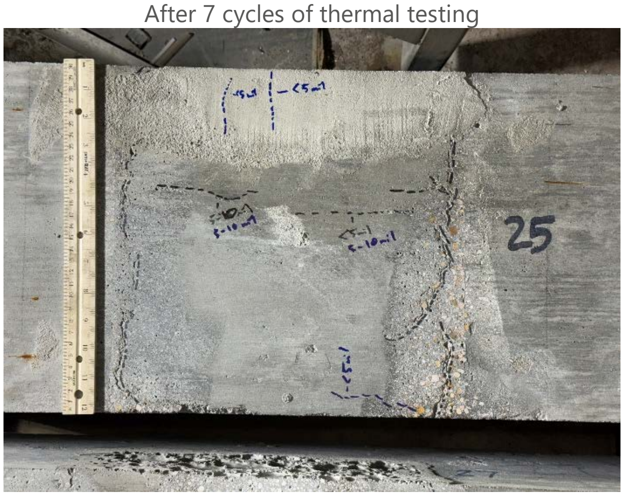
Figure C3.24. Specimen 24

(Marking indicates cracks and crack widths in mils (0.001 inch) within patch or at interface with substrate. Cracks in the repair to the patch and non-crack features were excluded in the analysis)

At 0 cycles



After 7 cycles of thermal testing



After 28 cycles of thermal testing

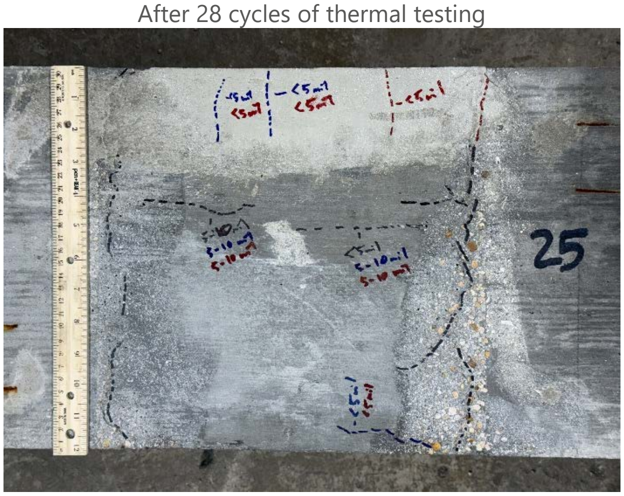
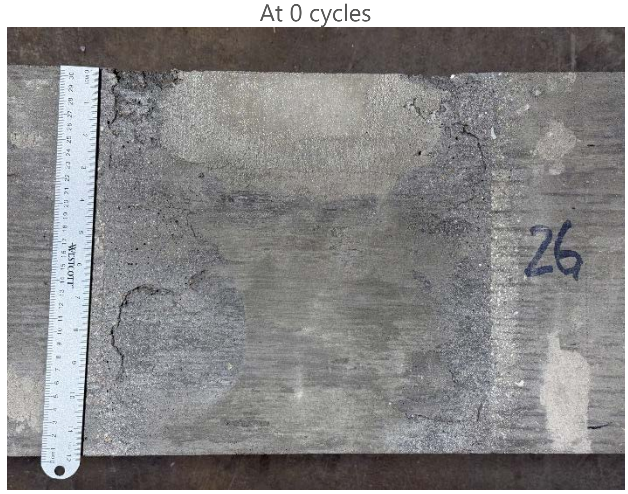
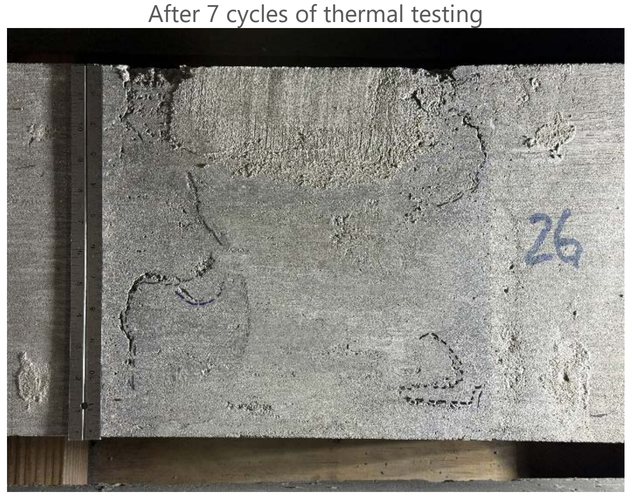


Figure C3.25. Specimen 25

At 0 cycles



After 7 cycles of thermal testing



After 28 cycles of thermal testing

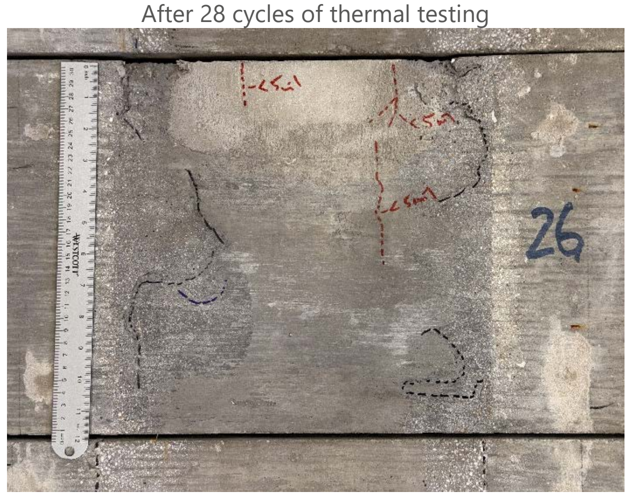


Figure C3.26. Specimen 26

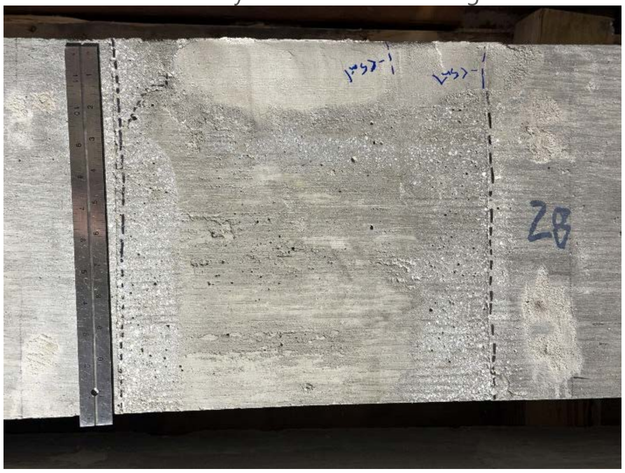
(Marking indicates cracks and crack widths in mils (0.001 inch) within patch or at interface with substrate. Cracks in the repair to the patch and non-crack features were excluded in the analysis)

At 0 cycles

At 0 cycles

After 7 cycles of thermal testing

After 7 cycles of thermal testing



After 28 cycles of thermal testing

After 28 cycles of thermal testing

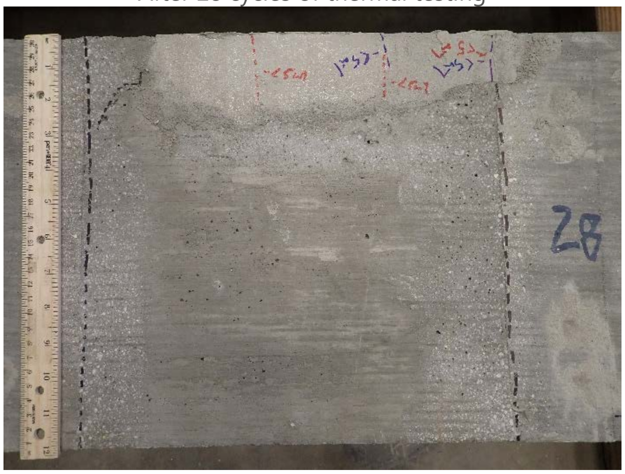


Figure C3.27. Specimen 27

Figure C3.28. Specimen 28

(Marking indicates cracks and crack widths in mils (0.001 inch) within patch or at interface with substrate. Cracks in the repair to the patch and non-crack features were excluded in the analysis)

At 0 cycles

At 0 cycles

After 7 cycles of thermal testing

After 7 cycles of thermal testing

After 28 cycles of thermal testing

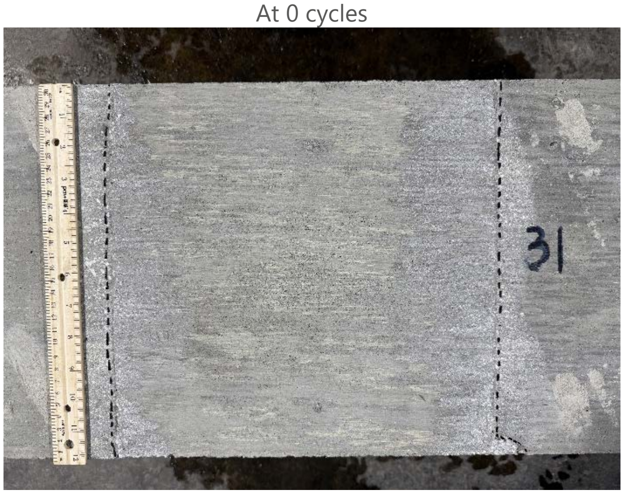
After 28 cycles of thermal testing

Figure C3.29. Specimen 29

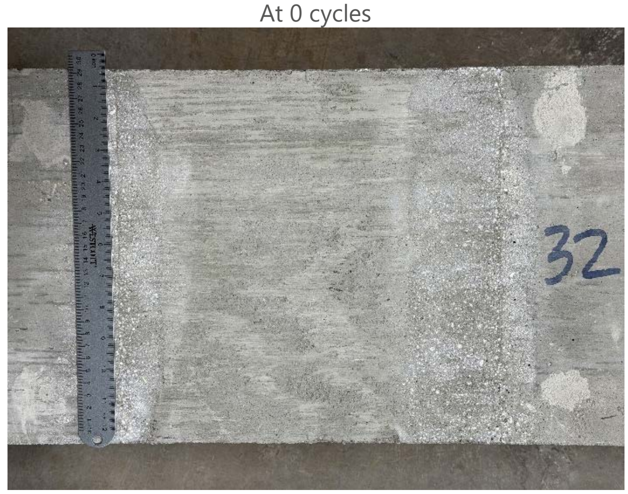
Figure C3.30. Specimen 30

(Marking indicates cracks and crack widths in mils (0.001 inch) within patch or at interface with substrate. Cracks in the repair to the patch and non-crack features were excluded in the analysis)

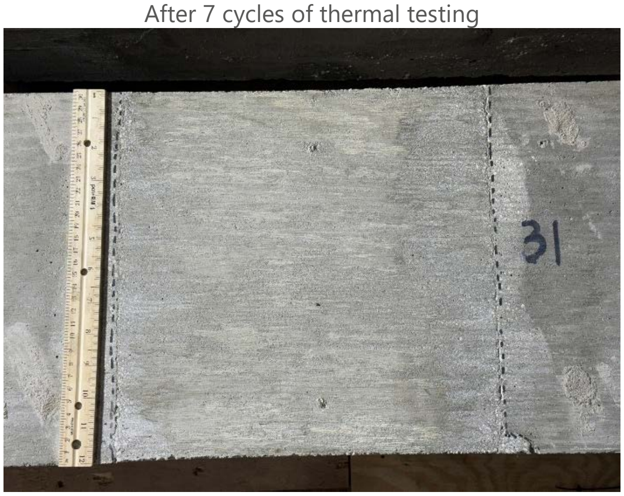
At 0 cycles



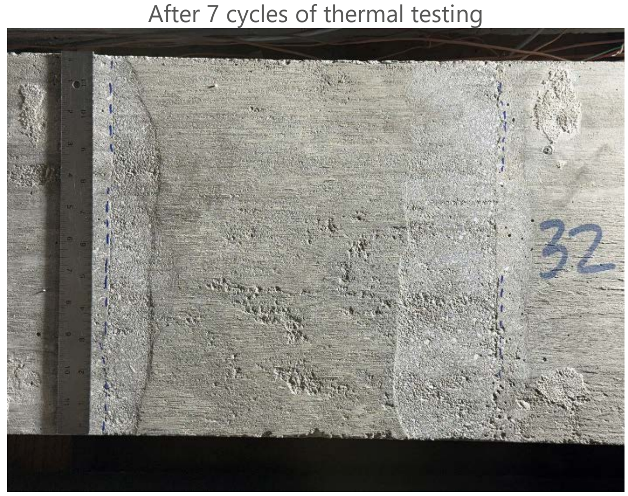
At 0 cycles



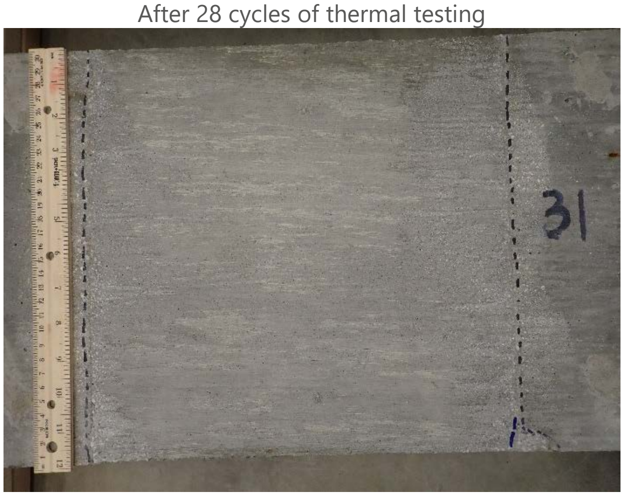
After 7 cycles of thermal testing



After 7 cycles of thermal testing



After 28 cycles of thermal testing



After 28 cycles of thermal testing

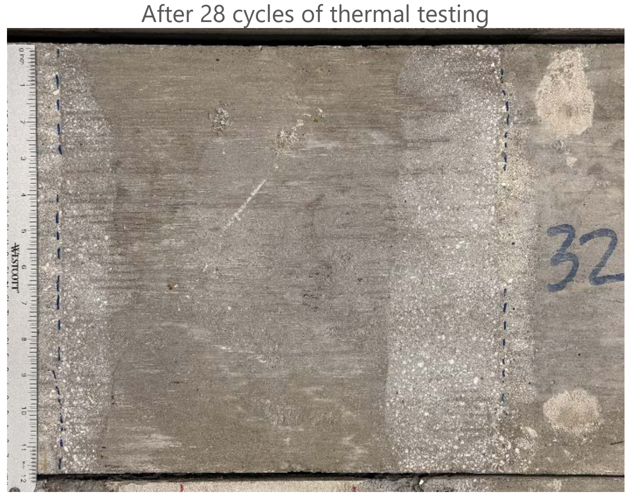


Figure C3.31. Specimen 31

Figure C3.32. Specimen 32

(Marking indicates cracks and crack widths in mils (0.001 inch) within patch or at interface with substrate. Cracks in the repair to the patch and non-crack features were excluded in the analysis)

APPENDIX C4. LOAD TESTING RESULTS

APPENDIX C4. LOAD TESTING RESULTS

Table C4.1. Vertical crack length, normalized to patch thickness (average of two sides)

	Normalized Crack Length (in./in.)				
Specimen	**Initial loading**	**Final loading**	**Anchorage**	**Method**	**Orientation**
4	3.50	3.50	No Anchor	Hand-applied	Overhead
8	4.17	4.17	Threaded rod U	Hand-applied	Overhead
10	2.00	2.00	Screw w/mesh	Hand-applied	Overhead
12	3.00	3.00	Screw w/mesh	Hand-applied	Overhead
14	3.00	3.00	No Anchor	Hand-applied	Overhead
18	2.00	2.50	Threaded rod U	Form & pour	Vertical
22	2.25	3.06	Screw w/mesh	Form & pour	Vertical
24	2.00	2.00	Screw w/mesh	Form & pour	Vertical
26	2.06	2.06	Existing rebar	Form & pour	Vertical
30	2.00	2.50	Existing rebar	Form & pour	Overhead

Table C4.2. Horizontal crack length, normalized to patch length (average of two sides)

	Normalized Crack Length (in./in.)				
Specimen	**Initial loading**	**Final loading**	**Anchorage**	**Method**	**Orientation**
4	0.38	0.55	No Anchor	Hand-applied	Overhead
8	0.53	0.83	Threaded rod U	Hand-applied	Overhead
10	0.17	0.69	Screw w/mesh	Hand-applied	Overhead
12	0.48	0.79	Screw w/mesh	Hand-applied	Overhead
14	0.32	0.69	No Anchor	Hand-applied	Overhead
18	0.21	0.58	Threaded rod U	Form & pour	Vertical
22	0.40	0.57	Screw w/mesh	Form & pour	Vertical
24	0.51	0.73	Screw w/mesh	Form & pour	Vertical
26	0.19	0.33	Existing rebar	Form & pour	Vertical
30	0.24	0.57	Existing rebar	Form & pour	Overhead

Table C4.3. Beam Stiffness During Cyclic Loading

Specimen ID	Beam Stiffness (kip/in) After Number of Loading Cycles						Change in Stiffness	Ultimate Load During Final Loading (kip)
	4,000	100,000	200,000	300,000	400,000	500,000[1]		
1	176	177	176	175	175	159	-10%	31.0
2	228	228	229	231	192	181	-21%	Not measured
3	182	186	187	187	188	192	5%	46.5
4	242	238	238	238	[2]	[2]	-1%	52.2
5	185	190	191	192	191	170	-8%	31.8
6	230	233	234	234	235	235	2%	50.7
7	188	183	182	181	180	180	-4%	44.9
8	227	228	230	230	231	231	2%	48.3
9	207	201	200	201	201	200	-3%	47.0
10	195	195	195	196	197	198	1%	49.9
11	191	189	189	188	188	187	-2%	47.0
12	242	239	232	233	234	234	-3%	50.1
13	187	184	184	184	184	184	-2%	48.0
14	251	250	250	250	[2]	[2]	0%	51.5
15	193	194	195	194	194	194	0%	45.7
16	242	244	245	245	[2]	[2]	1%	49.0
17	193	192	192	192	192	192	-1%	45.3
18	225	228	228	229	[2]	[2]	2%	48.1
19	197	197	197	197	178	76	-62%	16.2
20	242	242	243	244	[2]	[2]	1%	45.5
21	183	169	169	169	169	169	-8%	37.7
22	239	239	240	241	[2]	[2]	1%	44.4
23	198	196	195	194	166	70	-65%	14.4
24	236	237	238	201	[2]	[2]	-15%	23.2
25	207	204	202	201	201	201	-3%	46.1
26	243	245	246	247	[2]	[2]	2%	43.3
27	193	189	189	189	190	190	-2%	46.1
28	235	237	238	238	[2]	[2]	1%	44.1
29	186	189	190	189	160	158	-15%	28.9
30	229	225	226	226	[2]	[2]	-1%	40.8
31	174	173	173	173	173	173	-1%	46.5
32	242	242	242	202	[2]	[2]	-16%	33.6

Notes:

[1] Test terminated after approximately 408,000 to 416,000 cycles for Specimens 2, 19, and 23 due to occurrence of large cracks and significant loss in beam stiffness.

[2] Test terminated after 300,000 cycles to avoid fracture of longitudinal bars.

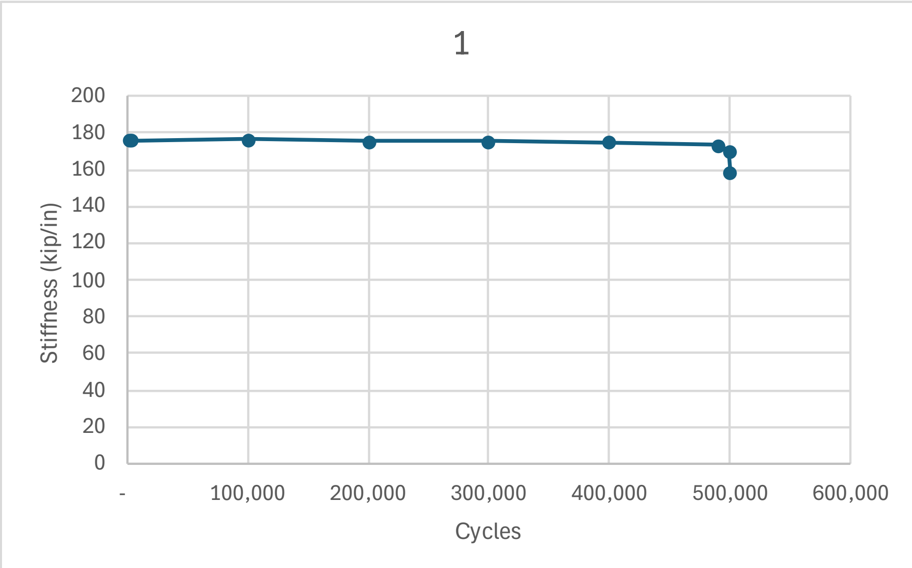


Figure C4.1. Specimen 1. Beam stiffness during cyclic loading

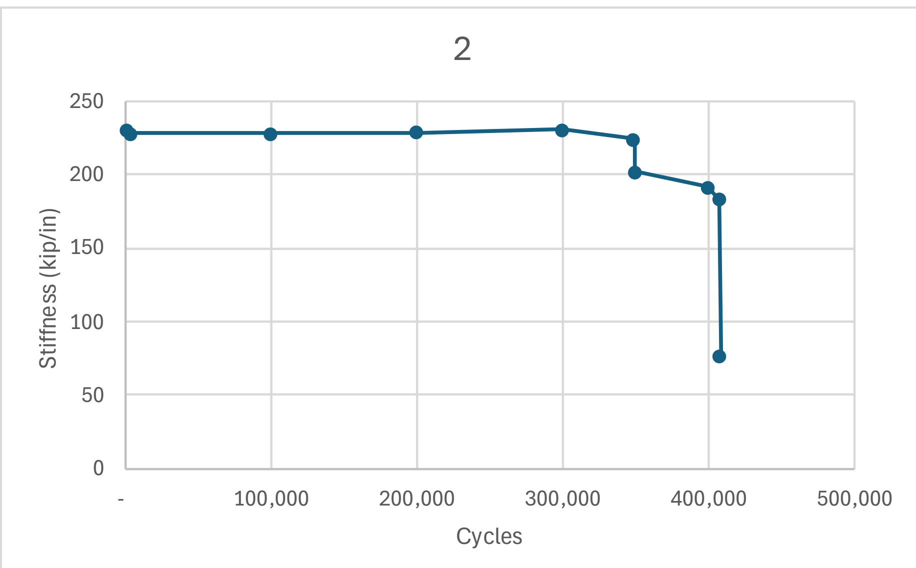


Figure C4.2. Specimen 2. Beam stiffness during cyclic loading

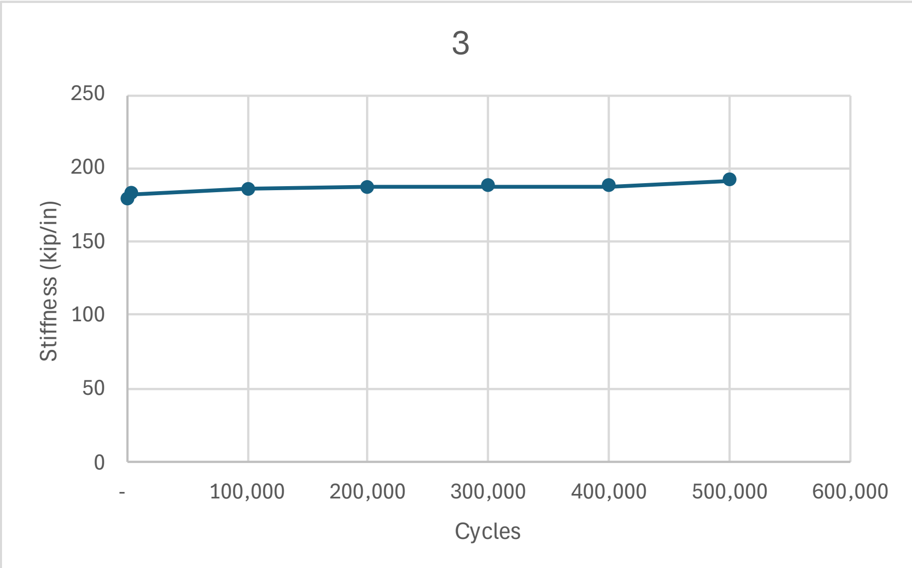


Figure C4.3. Specimen 3. Beam stiffness during cyclic loading

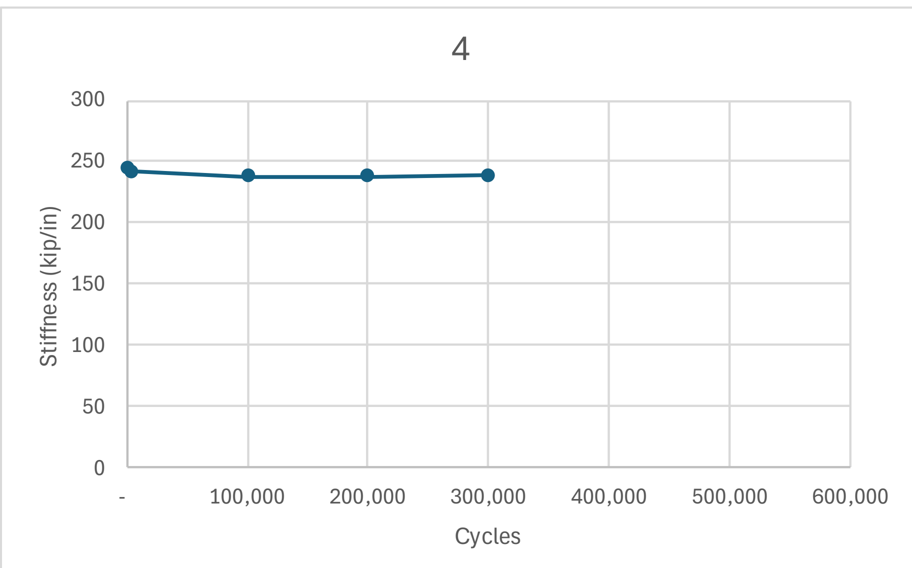


Figure C4.4. Specimen 4. Beam stiffness during cyclic loading

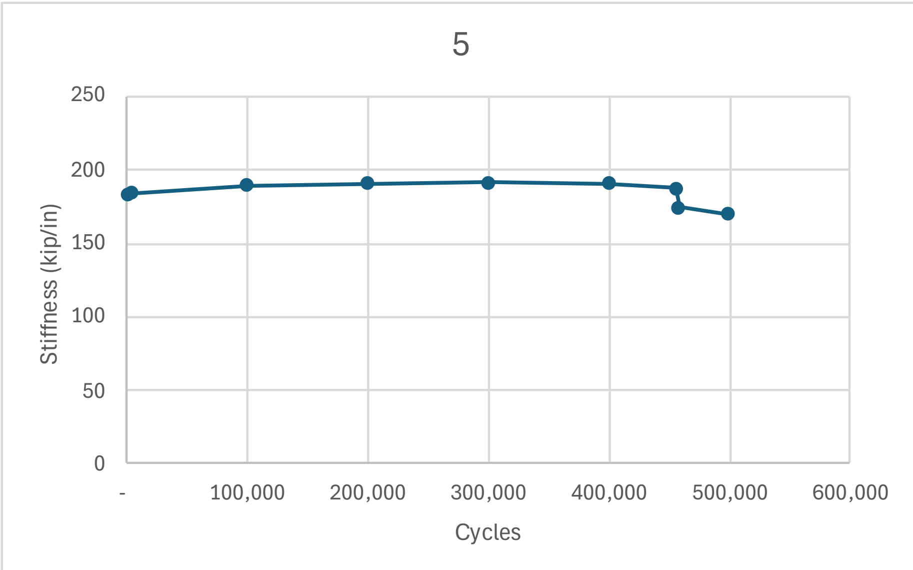


Figure C4.5. Specimen 5. Beam stiffness during cyclic loading

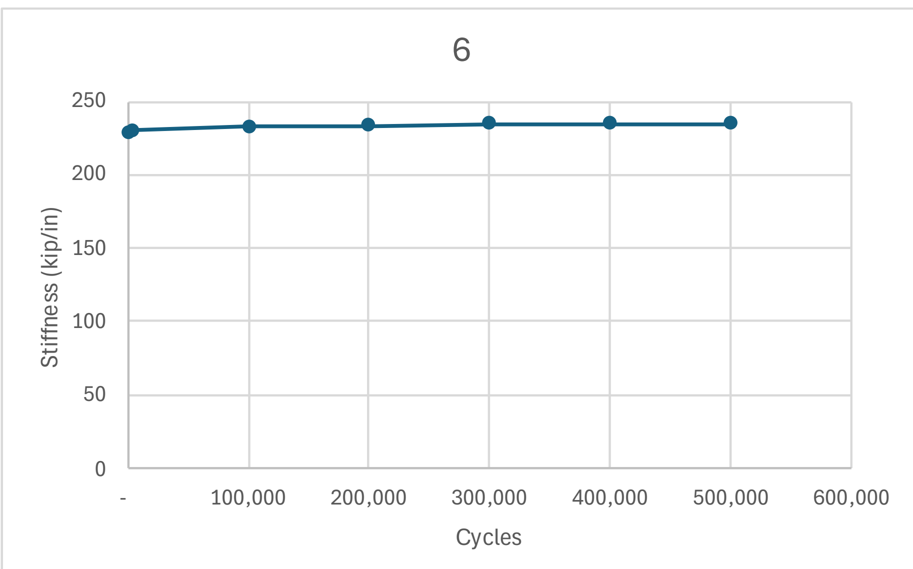


Figure C4.6. Specimen 6. Beam stiffness during cyclic loading

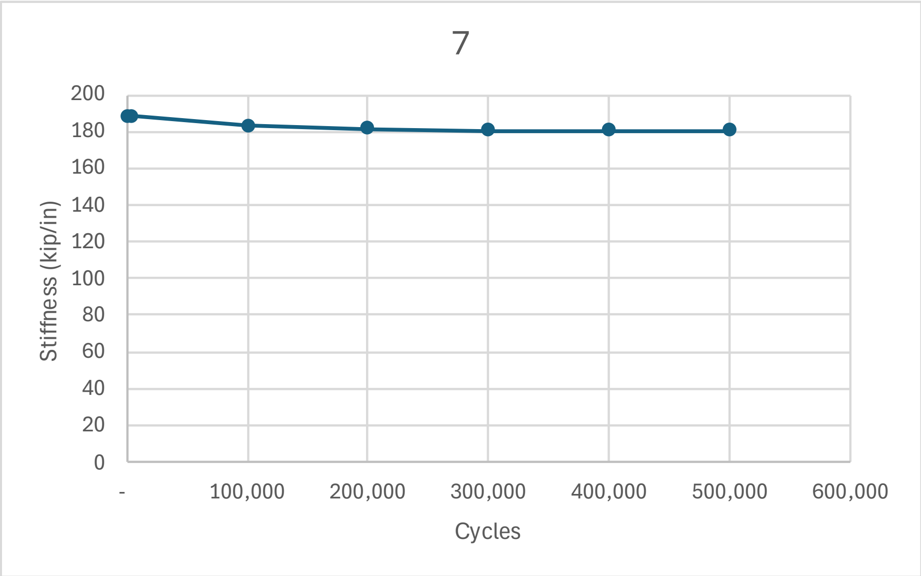


Figure C4.7. Specimen 7. Beam stiffness during cyclic loading

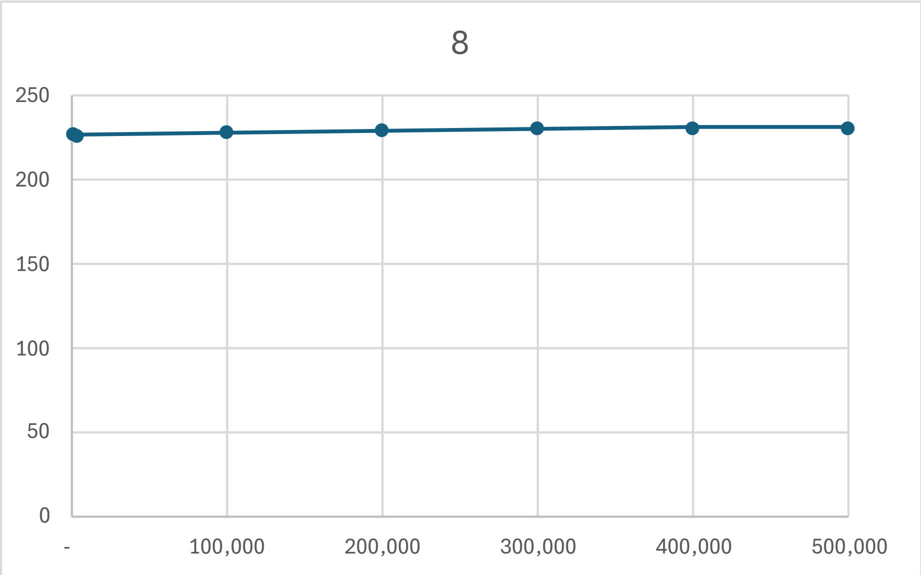


Figure C4.8. Specimen 8. Beam stiffness during cyclic loading

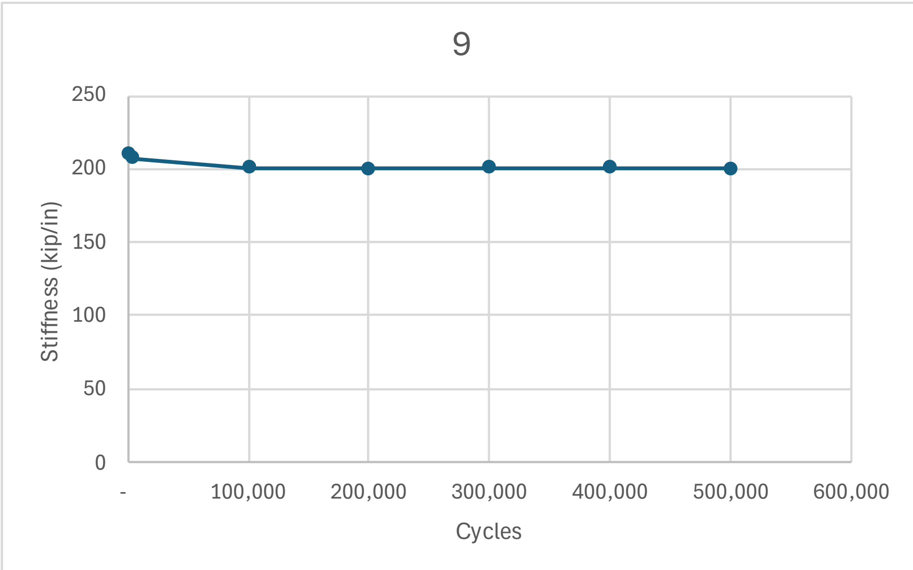


Figure C4.9. Specimen 9. Beam stiffness during cyclic loading

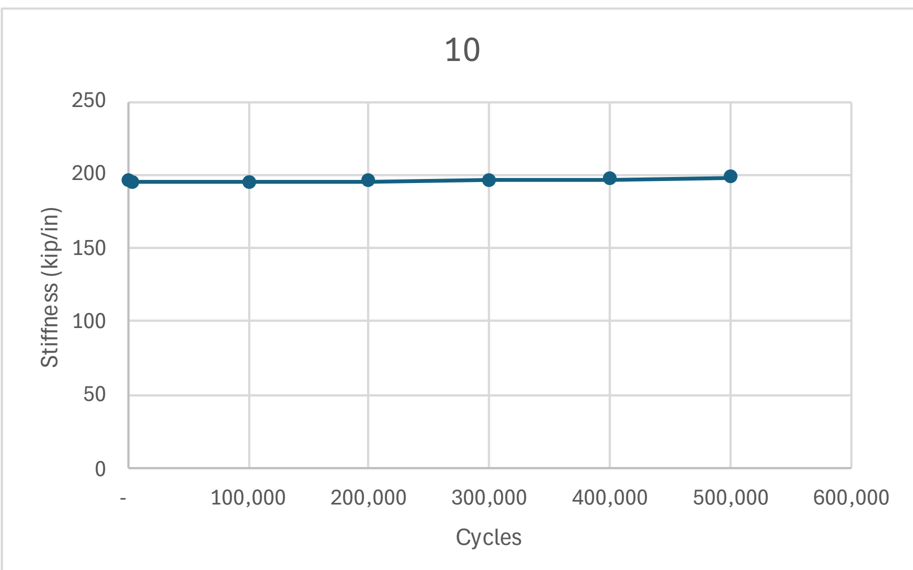


Figure C4.10. Specimen 10. Beam stiffness during cyclic loading

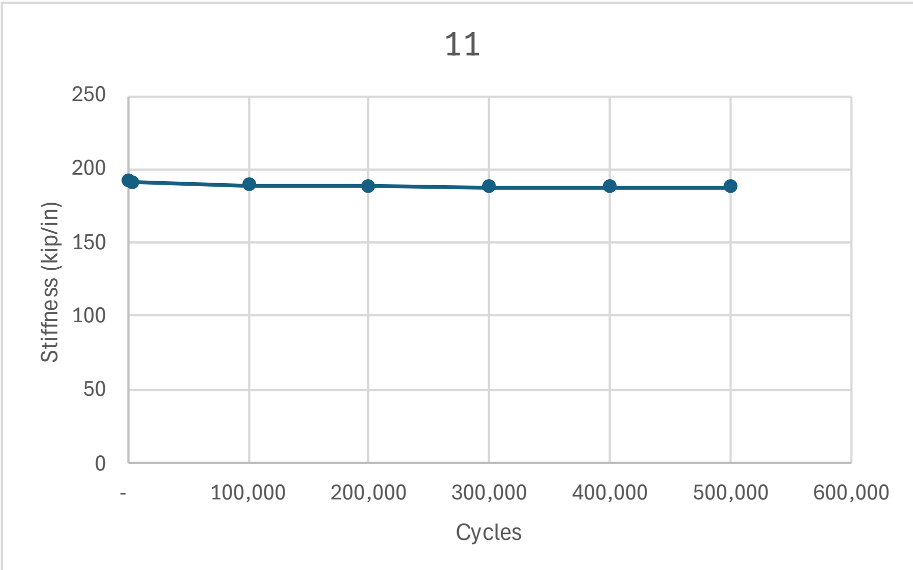


Figure C4.11. Specimen 11. Beam stiffness during cyclic loading

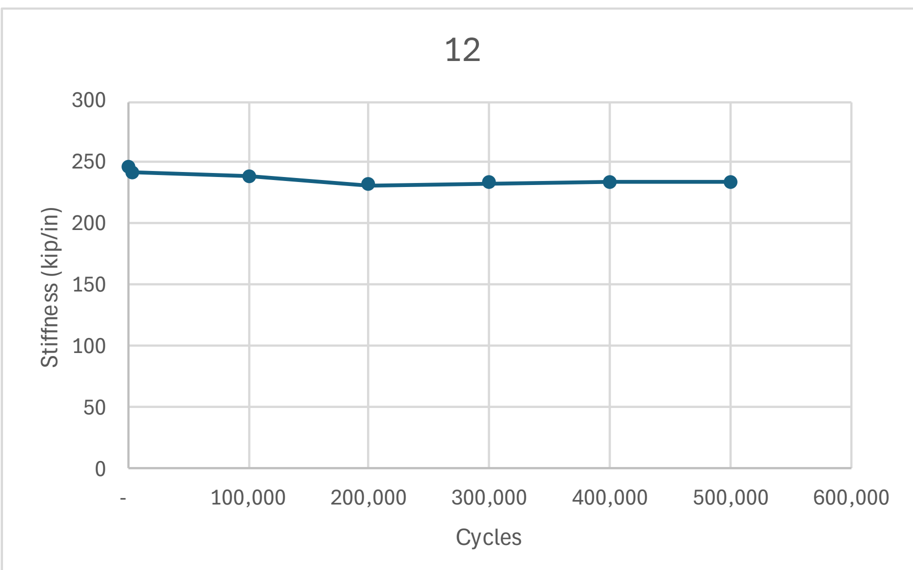


Figure C4.12. Specimen 12. Beam stiffness during cyclic loading

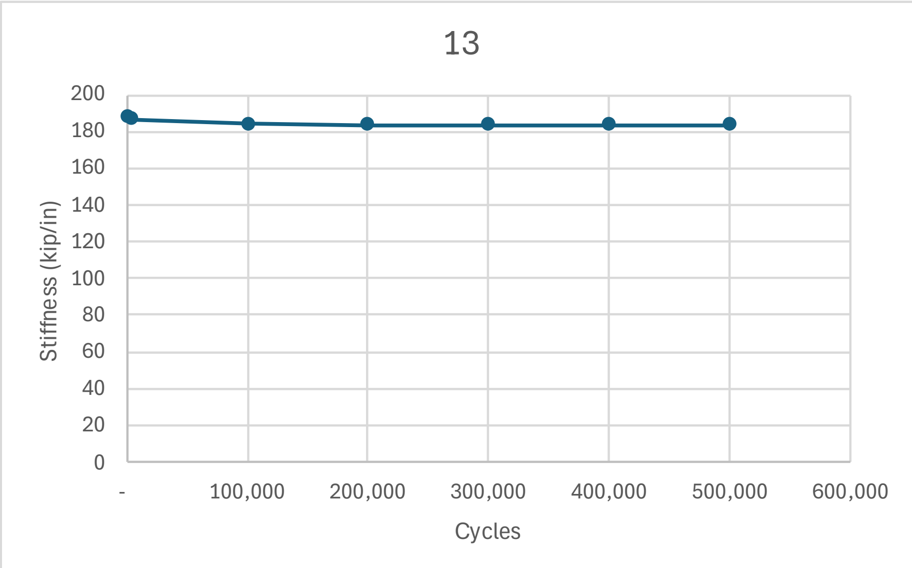


Figure C4.13. Specimen 13. Beam stiffness during cyclic loading

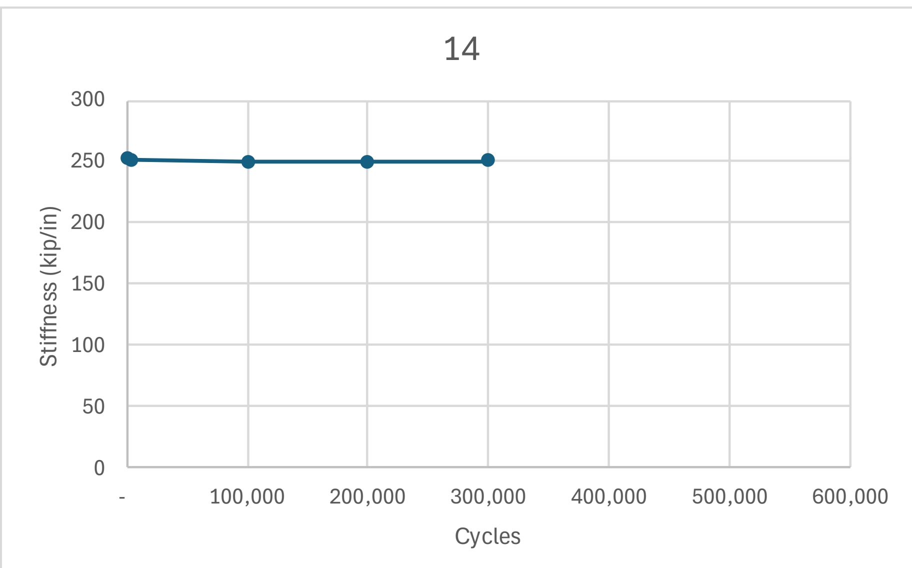


Figure C4.14. Specimen 14. Beam stiffness during cyclic loading

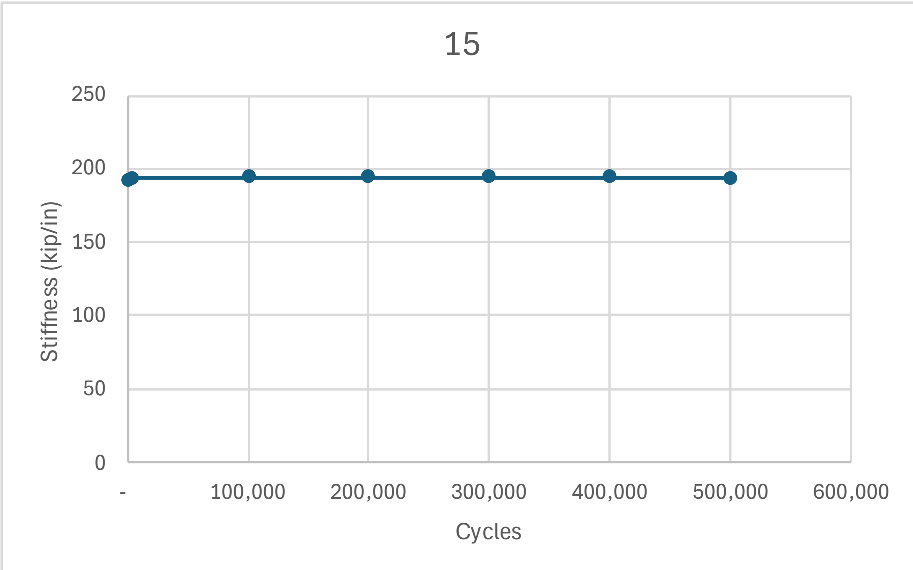


Figure C4.15. Specimen 15. Beam stiffness during cyclic loading

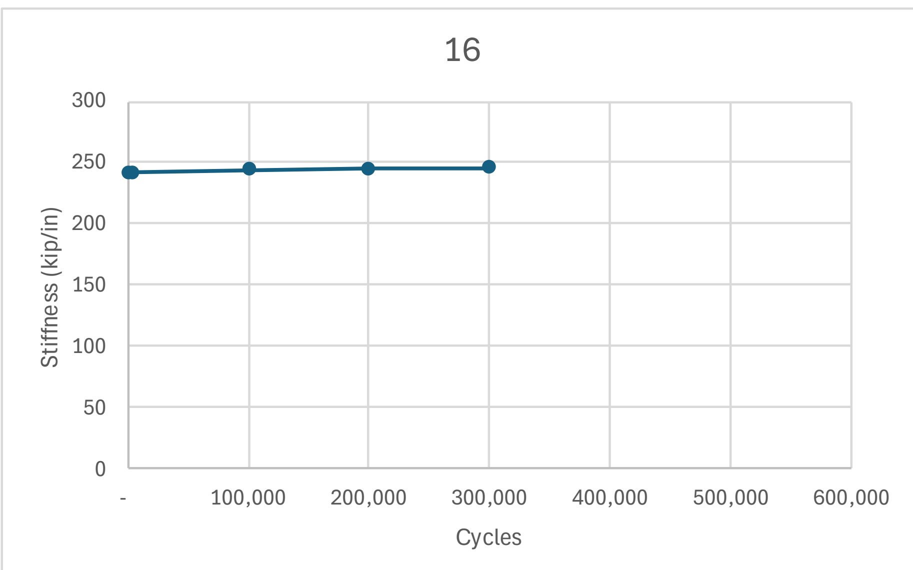


Figure C4.16. Specimen 16. Beam stiffness during cyclic loading

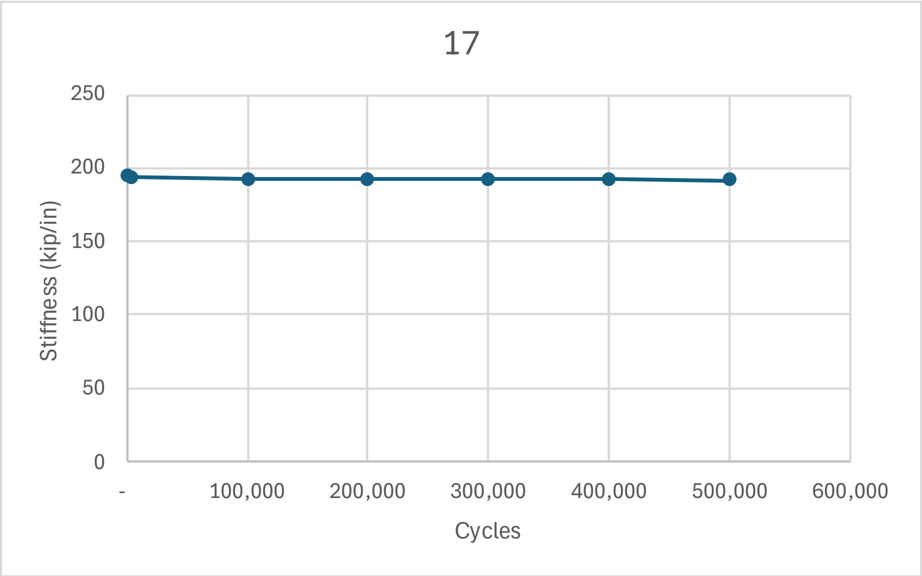


Figure C4.17. Specimen 17. Beam stiffness during cyclic loading

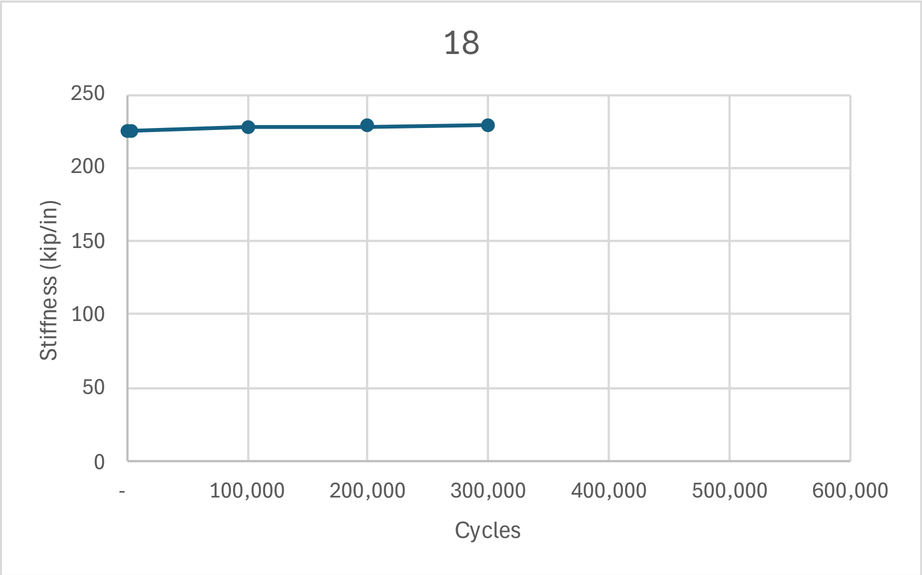


Figure C4.18. Specimen 18. Beam stiffness during cyclic loading

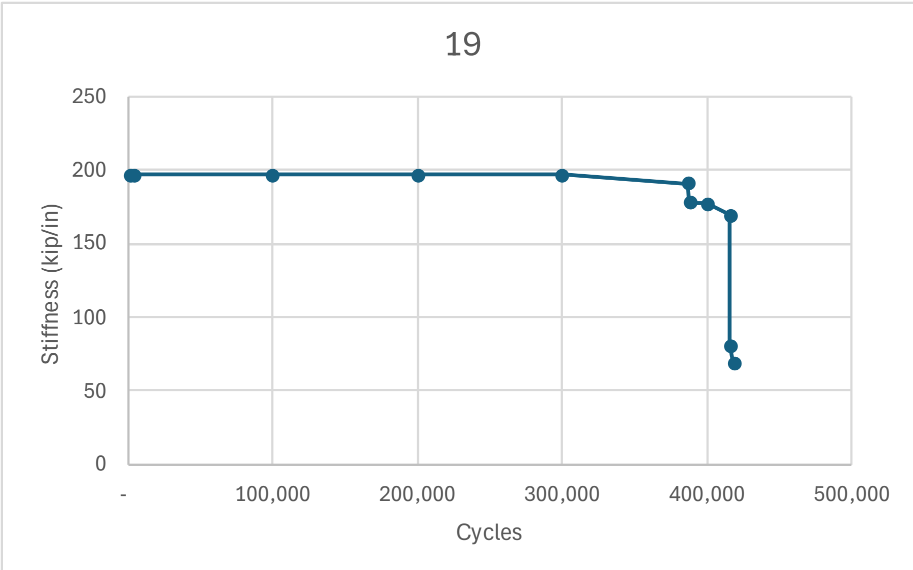


Figure C4.19. Specimen 19. Beam stiffness during cyclic loading

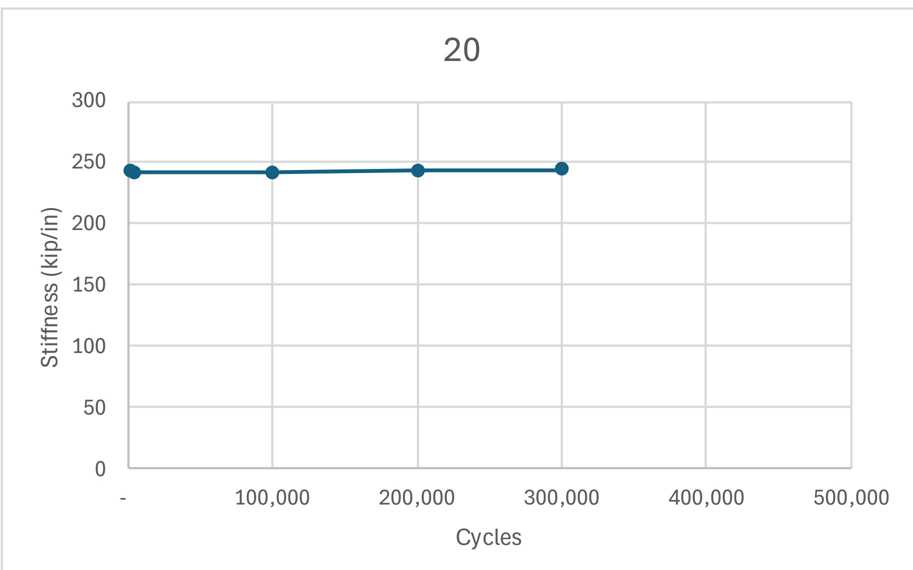


Figure C4.20. Specimen 20. Beam stiffness during cyclic loading

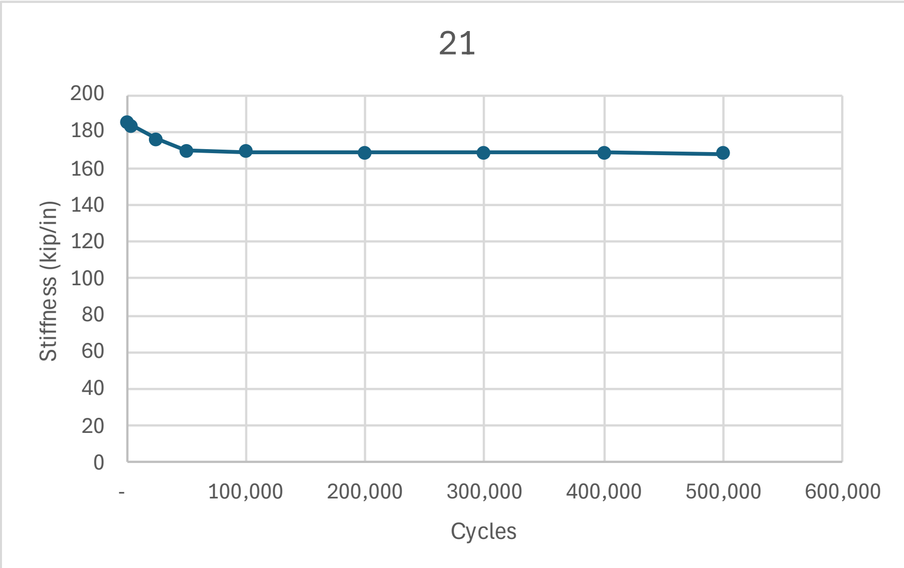


Figure C4.21. Specimen 21. Beam stiffness during cyclic loading

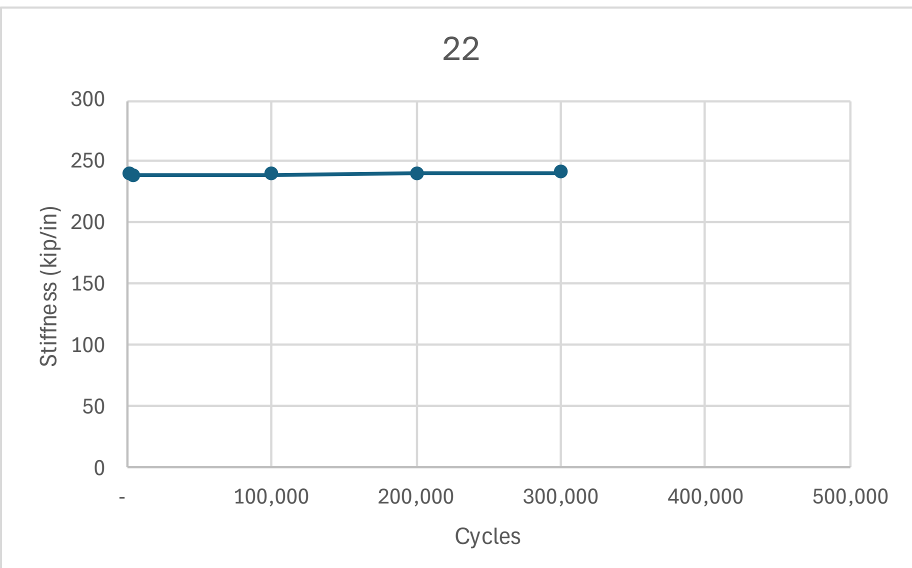


Figure C4.22. Specimen 22. Beam stiffness during cyclic loading

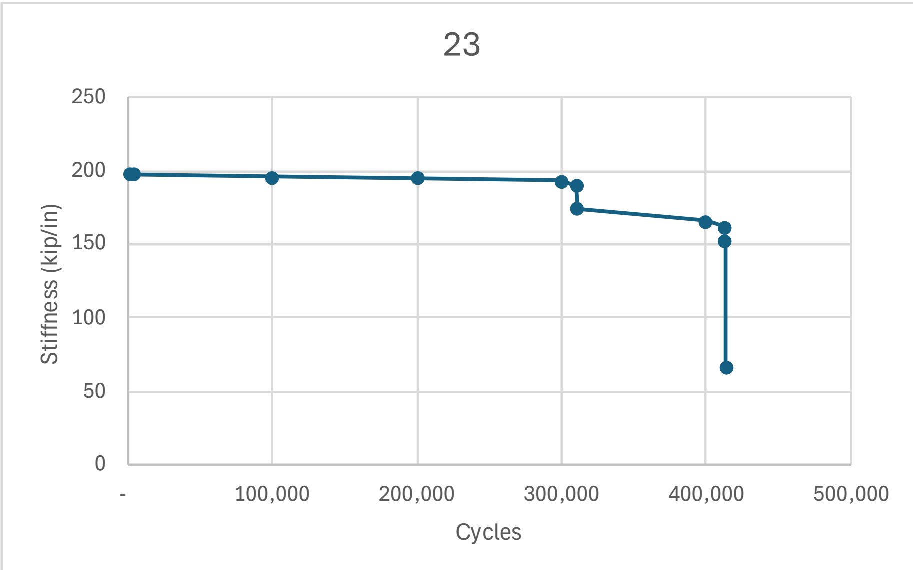


Figure C4.23. Specimen 23. Beam stiffness during cyclic loading

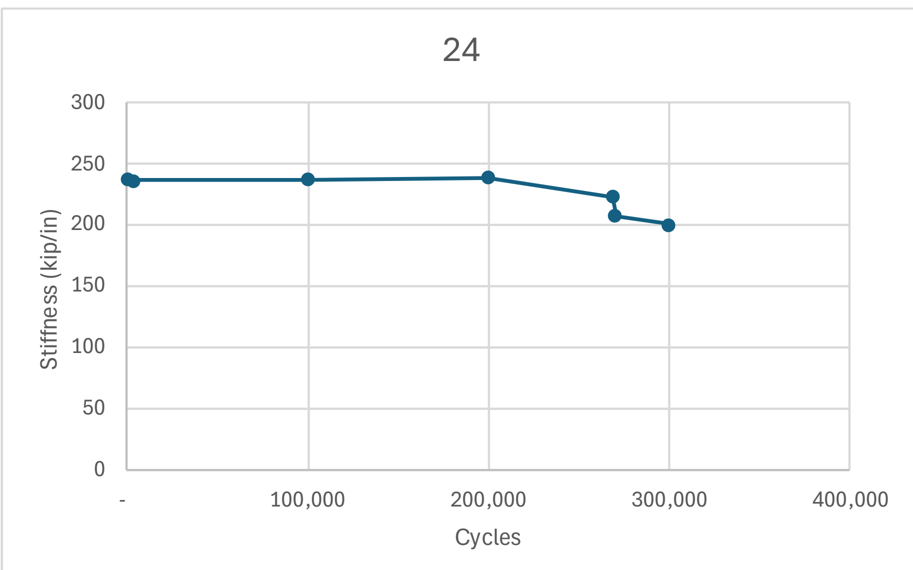


Figure C4.24. Specimen 24. Beam stiffness during cyclic loading

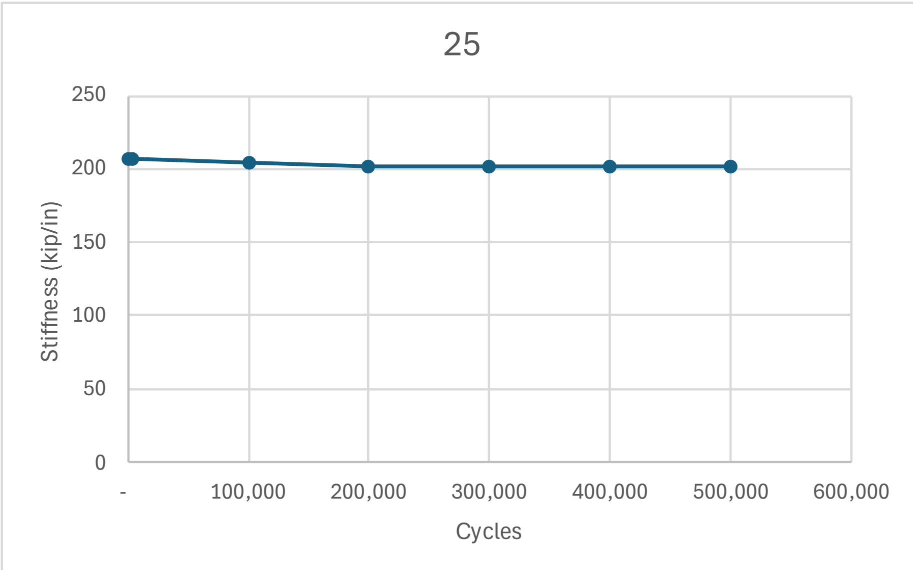


Figure C4.25. Specimen 25. Beam stiffness during cyclic loading

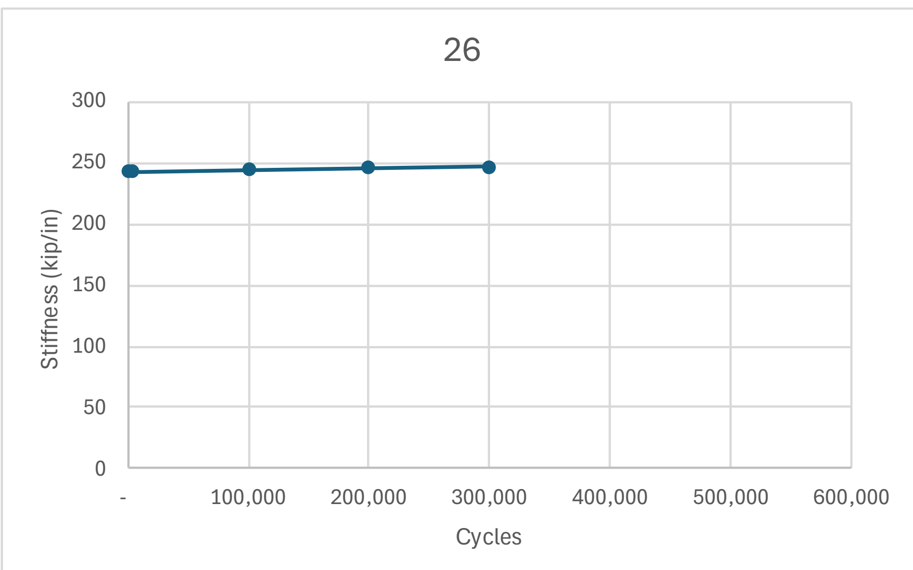


Figure C4.26. Specimen 26. Beam stiffness during cyclic loading

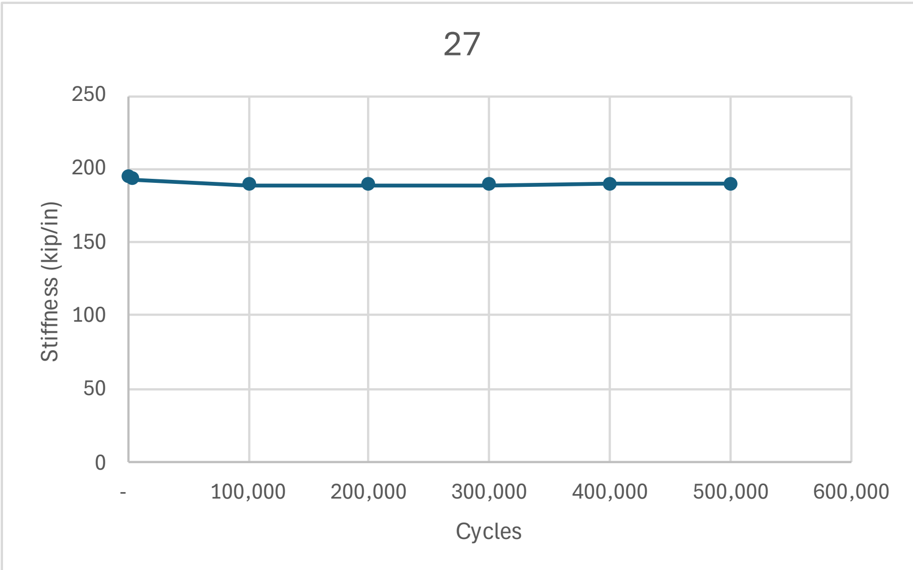


Figure C4.27. Specimen 27. Beam stiffness during cyclic loading

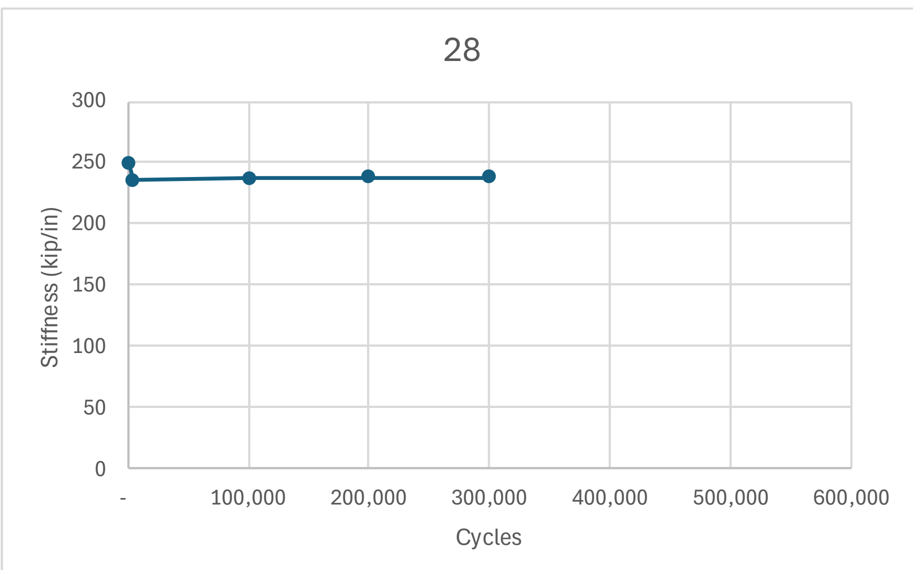


Figure C4.28. Specimen 28. Beam stiffness during cyclic loading

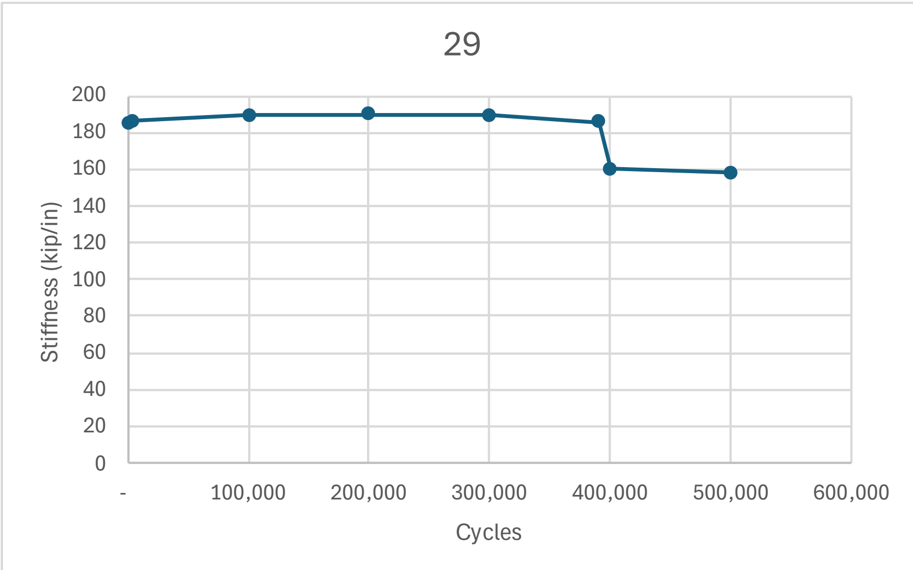


Figure C4.29. Specimen 29. Beam stiffness during cyclic loading

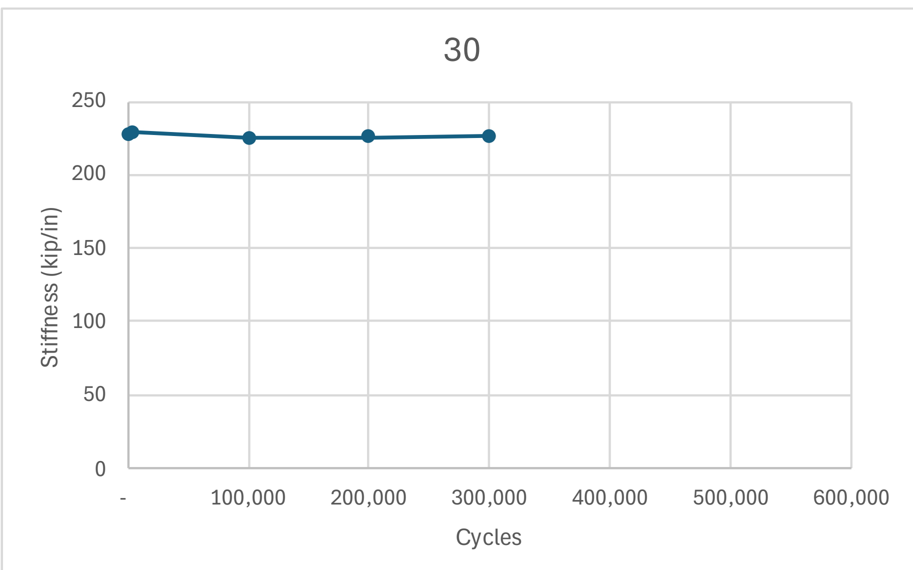


Figure C4.30. Specimen 30. Beam stiffness during cyclic loading

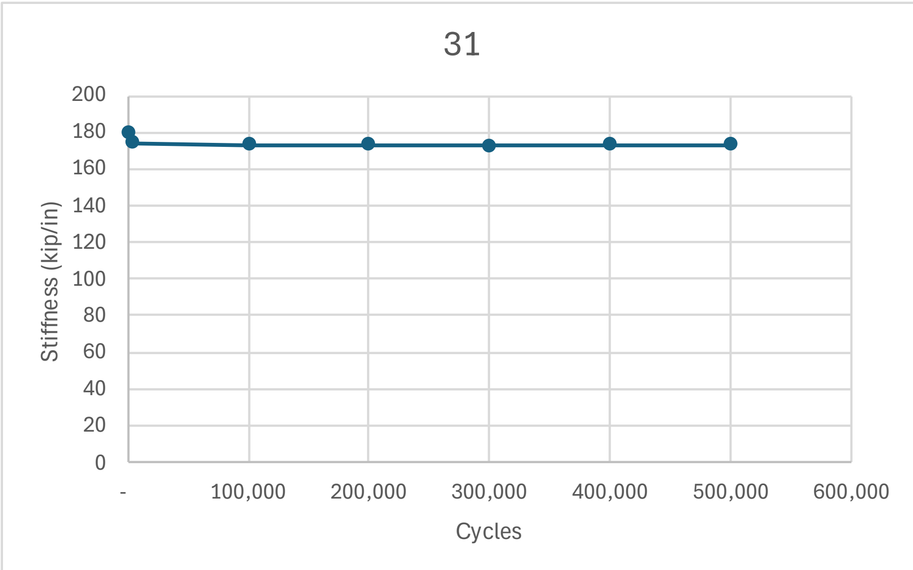


Figure C4.31. Specimen 31. Beam stiffness during cyclic loading

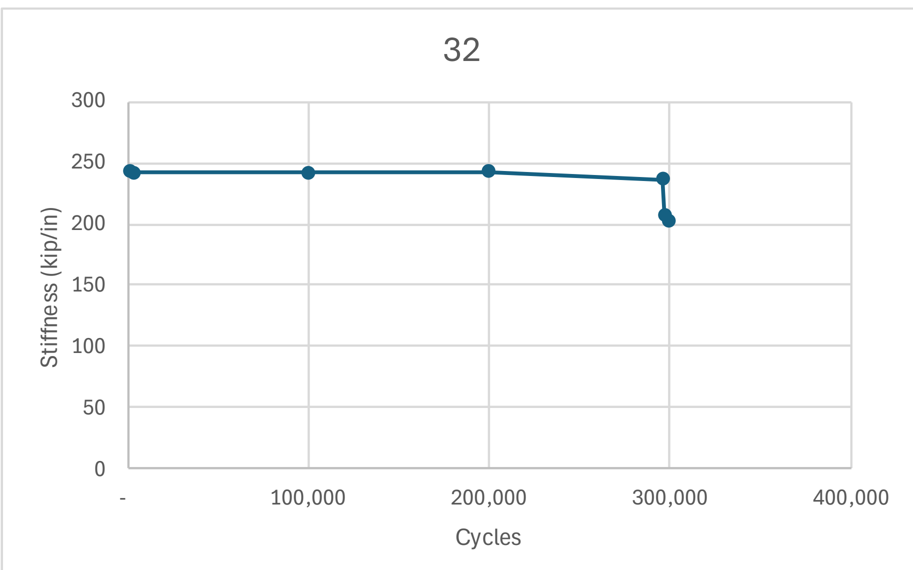


Figure C4.32. Specimen 32. Beam stiffness during cyclic loading

APPENDIX D. RECOMMENDED VOH REPAIR MATERIAL PROPERTY AND APPROVAL PROCESS

APPENDIX D. RECOMMENDED VOH REPAIR MATERIAL PROPERTY AND APPROVAL PROCESS

VOH Repair Material Property Requirements

Replace section **Material Property Requirements** in the WisDOT Approved Product List Application Process for Vertical and Overhead Repair Materials (dated April 14, 2025) with the following:

Material Property Requirements

- Vertical and overhead repair materials must be capable of resisting the effects of gravity and must be suitable for exterior applications, and produce repairs demonstrating resistance to corrosion, freeze-thaw, and deicing salts.
- The vertical and overhead repair material must meet the testing requirements as specified in Table D.1.

Table D.1. Vertical and Overhead Repair Material Test Requirements

Property/Performance Criterion	Test Method	Requirement[1]
Drying shrinkage and Expansion	ASTM C157, modified per ACI PRC-364.3-22.	Maximum shrinkage: 0.07% at 28 days Maximum expansion: 0.05% at 28 days
Compressive strength	Concrete or extended mortar: ASTM C39. Mortar: ASTM C109.	≥ 4,500 psi at 28 days
Splitting tensile strength	ASTM C496/C496M	≥ 400 psi at 28 days
Freeze-thaw durability	ASTM C666 Procedure A	Durability factor ≥ 90 at 300 cycles
Rapid chloride permeability	ASTM C1202	Charge passed ≤ 2,000 Coulombs
Bond strength	ASTM C882, modified per ASTM C928	≥1,000 psi at 1 day ≥ 1,500 psi at 7 days

[1] Based on average of a minimum of three specimens unless otherwise defined by the test standards

VOH Repair Material Approval Process

Add the following to section **Approval Process** in the WisDOT Approved Product List Application Process for Vertical and Overhead Repair Materials (dated April 14, 2025):

WisDOT Mockup Program

The manufacturer/supplier shall perform a mockup for each product seeking approval. Requirements for the mockup program include the following elements:

- Substrate: substrate should be cast using a concrete mixture meeting requirements of WisDOT Grade A, Class 1 concrete (Standard Specifications sections 501.3.2.2.2 and 715.2.2.2) with the following properties:
  - Compressive strength: 4,000 to 6,000 psi at 28 days
  - Cementitious materials: 565 lb/cy minimum

    - Supplementary cementitious materials (SCMs): 15 to 30 percent replacement by weight of total cementitious materials with SCMs complying with WisDOT requirements
    - Air content: 6±1.5%
    - Water–cementitious materials ratio (w/cm): 0.40 to 0.45

- Installation:
    - Prepare clean and sound substrate surface in accordance with the product data sheets.
    - Sandblast the concrete substate followed by air blasting. These methods provide the most consistent surface for achieving adequate bonding of repair material to the substrate based on our experience and the testing program.
    - Each repair material should be installed in the orientation(s) that the manufacturer indicates is appropriate for their material (i.e. in both vertical and overhead orientations or in just one orientation), using the intended repair method (i.e., hand-applied and/or form-and-pour methods, as applicable).
    - The repair area should be 1 ft x 1 ft minimum. For hand-applied materials, the repair depth should be the maximum lift thickness recommended by the manufacturer. For form-and-pour materials, the repair depth should be 2 inches.
    - The material should be mixed, installed, and cured in accordance with the manufacturer's recommendations.
    - The mockup installation should be thoroughly documented, including substrate surface preparation; batch weights, mixing, installation and curing procedures; and photos of substrate before installation and of repair after finishing and after curing.

- Inspection:
    - Inspect the mockup repairs for cracking, delamination, or debonding of the repair material using the sounding method in accordance with ASTM C4580. Any cracks wider than 0.010 inch shall be considered unacceptable. Any identified delamination area should be investigated through coring (see below).
    - Perform pull-off testing on each mockup repair in accordance with ASTM C1583. Acceptance criteria should meet the following requirements:
        - Minimum five tests per installation orientation.
        - Average bond strength ≥ 150 psi.
        - Individual test value ≥ 120 psi.
    - Published literature commonly reports pull-off bond strengths in the range of 200 to 300 psi; however, these values are generally based on horizontal repairs. Achieving similar values for vertical and overhead repairs can be more challenging due to installation constraints. Therefore, a minimum average bond strength of 150 psi is recommended for APL approval. For structural repairs, bond strength requirements should be evaluated by the Engineer of Record on a case-by-case basis.
    - Obtain two cores through the repair and substrate for visual inspection. Core locations will be selected by WisDOT. The presence of voids or irregularities at the repair–substrate interface or within the repair material that may adversely affect bond shall be considered grounds for rejection.

- Documentation:

  - Upon completion of the mockup program, provide WisDOT with a report documenting the mockup installation procedures and inspection results.
- WisDOT mockup witness:
  - WisDOT will witness the mockup installation, sounding inspection, and pull-off testing, and will select the locations for coring. The manufacturer shall provide advance notice to allow a WisDOT representative to observe these activities.

Performance Records.

The manufacturer/supplier shall submit documentation of field performance to demonstrate a minimum of five years of successful use on a minimum of five projects of the repair materials in vertical and overhead repair conditions on bridge projects.

Letter On Sulfate Content

The manufacturer shall provide a letter identifying the maximum total sulfate content of the cementitious portion of the product, expressed as a percentage of SO3 (sulfur trioxide), and stating that the product does not contain substances that are reactive in amounts sufficient to cause deleterious expansion of the concrete.

APPENDIX E. VERTICAL AND OVERHEAD CONCRETE REPAIR GUIDE

This document provides a guide on applications and repair procedures for three repair types used in vertical and overhead (VOH) applications, including the following:

- Coating Exposed Reinforcement Without Patching
- Hand-applied Concrete Repair
- Form-and-pour Concrete Repair

Repair Type Application

A summary of applications for the three repair types is provided in Table E.1.

Table E.1. VOH Repair Types

Repair Type	Applications	Example Picture/Sketch
Coating Exposed Reinforcement Without Patching	Temporary measure for limited spalled conditions with the intent to patch as soon as practical. Most appropriate where the concrete distress is primarily physical (e.g., impact damage) rather than spalling due to corrosion of reinforcing steel.	Figure E.1
Hand-applied Concrete Repair	For smaller repairs, particularly where access for formwork is challenging. Depth <= 2 in; area <= 2 ft^2; no more than one lift. Repair should be mechanically anchored to the substrate concrete with physical anchors. A curing compound should be applied to hand-applied patches to minimize cracking.	Figure E.2, Figure E.3
Form-and-pour Concrete Repair	Preferred over hand-applied patching when access allows installation of formwork. Repair materials should be pre-extended with coarse aggregate Measures to reduce entrapped air and improve consolidation of material at the bond interface, along with the use of anchorage crossing the interface, are recommended.	Figure E.4

Repair Procedures

Coating Exposed Reinforcement Without Patching

- Surface preparation: Remove loose concrete, debris, and corrosion products to the extent practical. At minimum, clean exposed reinforcement to remove loose rust and clean the adjacent concrete surface using wire brush.
- Materials: Use coating materials suitable for field application on bridges (e.g., epoxy or zinc-rich primers) and follow manufacturer requirements for surface condition and thickness.
- An example of coating exposed reinforcement in an overhead application is shown in Figure E.1.

Figure E.1. Example of coating exposed reinforcement

Concrete Repairs

Patch Geometry, Anchorage, and Reinforcement

- Use rectangular patch geometry where feasible and avoid reentrant corners.
- Whenever practical, repairs should encompass existing reinforcement.
- When repairs cannot encompass existing reinforcement, provide supplemental anchorage and reinforcement crossing the repair–substrate interface:
  - Repairs less than 3 inches deep: Provide screw anchors with welded wire reinforcement (WWR). The following details may be used (see Figure E.2 for an example):
    - ¼-inch diameter concrete screw anchors; stainless steel anchors are recommended for improved corrosion resistance; Maximum anchor spacing: 6 inches on center in both directions
    - WWR: 4 x 4 inches, D4.0 x D4.0 or W4.0 x W4.0
    - Minimum cover to anchor head: ¾ inch
    - Minimum clearance between WWR and substrate:
      - ¾ inch for form-and-pour repairs
      - ½ inch for hand-applied repairs
  - Repairs deeper than 3 inches: Provide larger anchorage using hooked dowel bars (No. 3 or No. 4) in conjunction with supplemental grid of reinforcement in plan (WWR or reinforcing bars). Final detailing should be based on the repair geometry and site conditions.

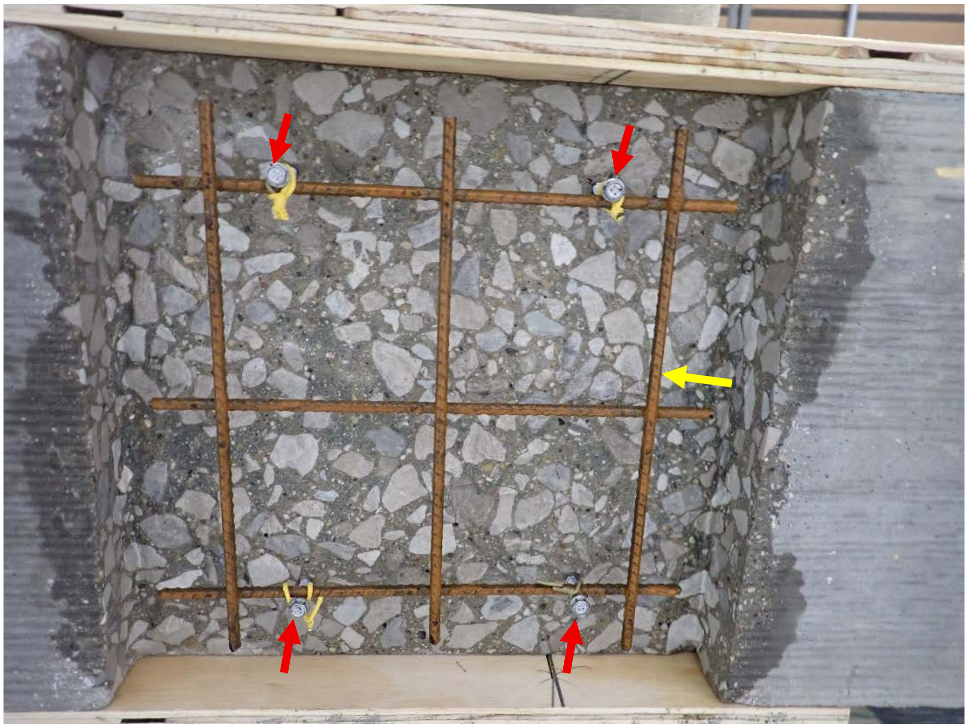


Figure E.2. Supplemental anchors (red arrows) and welded wire reinforcement (yellow arrow) for concrete repair

Concrete Removal and Surface Preparation

- Sawcut the perimeter of the repair area to a depth of 1/2 to 3/4 inch. The sawcut should be made at least 2 inches beyond the perimeter of the spalled areas. Do not cut existing reinforcing steel.
- Remove concrete to sound substrate using a hand-held chipping hammer of nominal 15-lbs or less.
- If existing reinforcing steel is exposed and corroded, remove concrete behind the reinforcing bars to a minimum clearance of 3/4 inch. This helps remove chloride-contaminated concrete and provides sufficient space for the repair material to fully encapsulate the reinforcement.
- When repairs cannot encompass existing reinforcement, provide supplemental anchorage and reinforcement crossing the repair–substrate interface.
- Clean the substrate surface by sandblasting to remove loose material and microcracking. Where sandblasting is not permitted, clean the substrate using water blasting (minimum pressure of 5,000 psi) and/or mechanical needle scaling.
- The prepared substrate shall have a concrete surface profile (CSP) consistent with the repair material manufacturer's recommendations.
- Clean the repair area using oil-free compressed air to remove dust and debris.
- Condition the substrate surface in accordance with the repair material manufacturer's recommendations. If no specific guidance is provided, the substrate surface should be moist with no standing water, consistent with a saturated-surface-dry (SSD) condition prior to placement of cementitious repair materials.

Placement of Repair Materials

Hand-applied repairs (see Figure E.3 for a schematic example)

- Use repair materials specifically intended for VOH, hand-applied (troweled-applied) applications.
- Hand-applied patching should be limited to small repairs with a maximum depth of 2 inches and an area not exceeding 2 square feet.
- Repairs should be placed in a single lift to minimize the risk of voids and poor bond between lifts. Do not exceed the maximum lift thickness recommended by the manufacturer.
- Follow the manufacturer's recommended mixing and batching. Measure components accurately and maintain batch records.
- Follow the manufacturer's installation procedures including applying a scrub coat of the material when recommended.
- Do not retemper repair materials once workability is lost. Discard batches that lose workability.

Form-and-pour repairs (see Figure E.4 for a schematic example)

- Use repair materials specifically intended for VOH, form-and-pour applications. Form-and-pour materials should be pre-extended with coarse aggregate.
- Minimum repair depth should generally be a minimum of 2 inches, and as recommended by repair material manufacturer to allow the repair material to flow around anchors and reinforcement.
- Formwork should be securely attached to the structure. Provide a bird's-mouth opening with sufficient placement head (recommended ≥4 inches, unless otherwise specified by the manufacturer).
- Overhead form-and-pour applications require special attention to venting and placement head to mitigate air entrapment.
    - Where feasible, taper the repair geometry toward the bird's mouth to promote flow of the repair material.
    - Consider using more than one bird's mouth opening during placement.
    - Provide air vents or vent paths to allow trapped air to escape during placement.
- Follow the manufacturer's recommended mixing and installation procedures.
- Mix full-bag batches to maintain proper material proportions.
- Measure water accurately and maintain batch records where applicable.
- For self-consolidating concrete (SCC) repair materials, tapping of formwork may be used to assist flow and reduce voids.
- For non-SCC materials, internal or external vibration will be required, consistent with manufacturer guidance and formwork constraints.

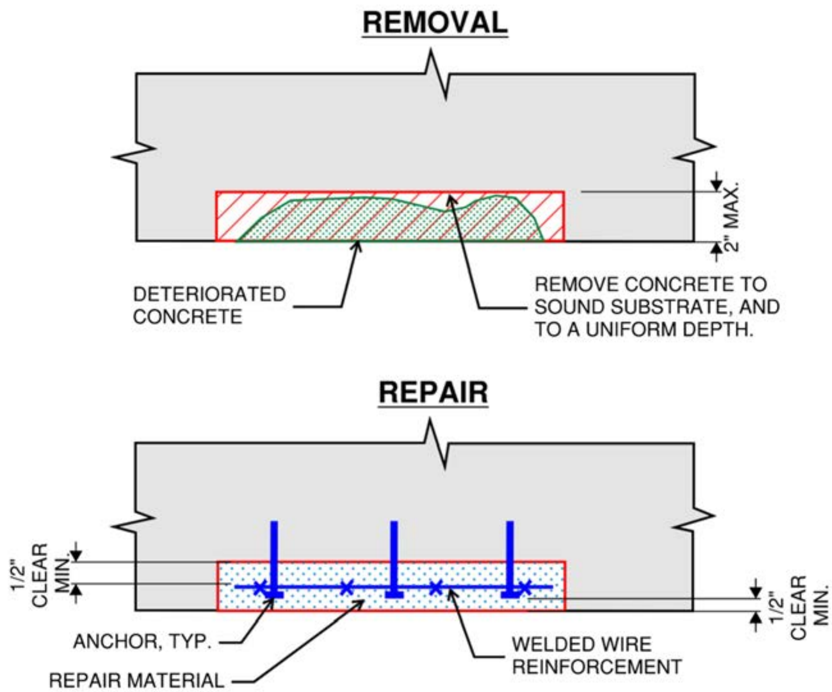


Figure E.3. Hand-applied Overhead Repair

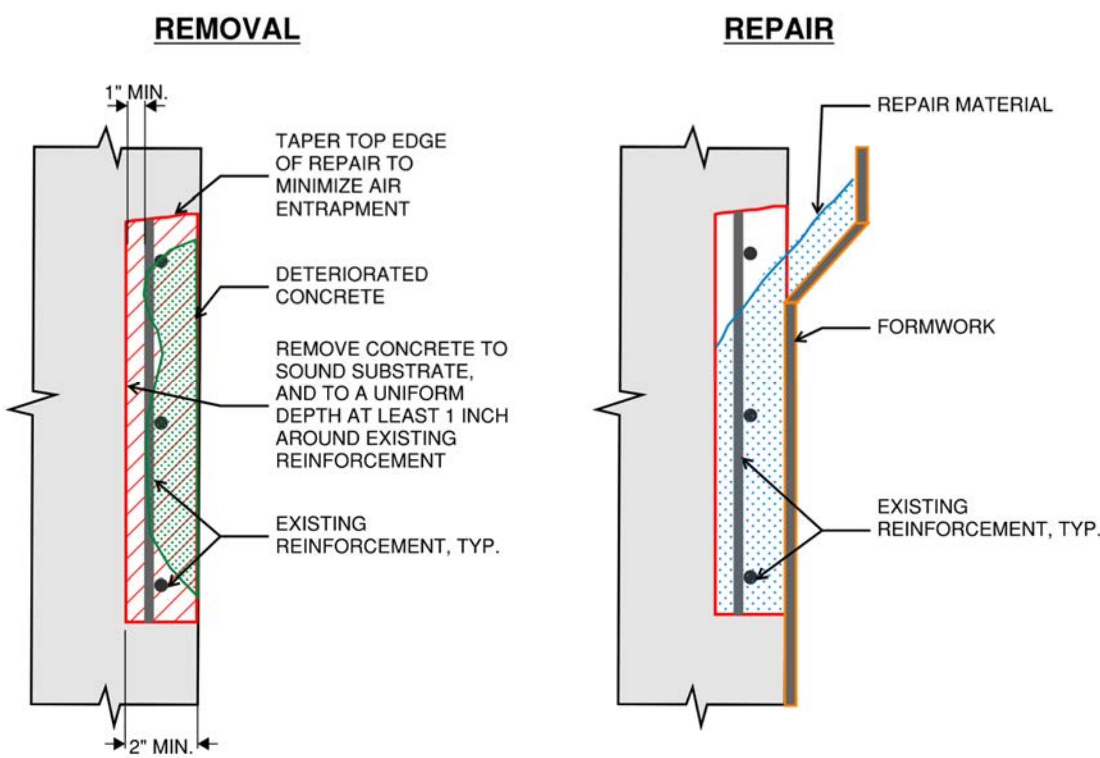


Figure E.4. Form-and-Pour Vertical Repair

Curing

Patches should be cured in accordance with the repair material manufacturer's recommendations. The following minimum curing requirements are recommended:

- Hand-applied repairs:
  - Apply a curing compound in accordance with the manufacturer's guidance, typically 15 to 30 minutes after finishing.
- Form-and-pour repairs:
  - Leave formwork in place for a minimum of 3 days, and until the repair material has achieved a compressive strength of at least 3,500 psi, or as recommended by the repair material manufacturer, whichever is longer.

Post-Installation Inspection

After curing the patch, the following inspections are recommended:

- Perform sounding (hammer tapping) to identify hollow areas or potential debonding of the repair material.
- For larger projects, or where bond performance is critical, perform pull-off testing in accordance with ASTM C1583. The recommended acceptance criteria are an average bond strength of at least 150 psi, with no individual test result less than 120 psi.

If debonding or insufficient bond strength is identified, the patch should be replaced.