2023

Final Report SPR-FY21(006)

WBS Report #
26-1122-0099-001

Performance of High Early-Strength Used in Concrete Bridge Repair

Marc Maguire, PhD
Assistant Professor
Durham School of Architectural Engineering and Construction
University of Nebraska-Lincoln

Zachary Benson
Graduate Student
Durham School of Architectural Engineering and Construction

Zina Ebrahim
Graduate Student
Durham School of Architectural Engineering and Construction

Mohammad Mastali, PhD
Postdoctoral Research Associate
Durham School of Architectural Engineering and Construction

Fray F. Pozo-Lora, PhD
Postdoctoral Research Associate
Durham School of Architectural Engineering and Construction

Jiong Hu, PhD
Professor
Department of Civil and Environmental Engineering

Nebraska Department of Transportation Research
Headquarters Address
1400 Nebraska Parkway
Lincoln, NE 68509
ndot.research@nebraska.gov
(402) 479-4697
https://dot.nebraska.gov/business-center/research/

Nebraska Transportation Center
262 Prem S. Paul Research Center at Whittier School
2200 Vine Street
Lincoln, NE 68583-0851
(402) 472-1932
http://ntc.unl.edu

This report was funded in part through grant from the U.S. Department of Transportation Federal Highway Administration. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the U.S. Department of Transportation.

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. SPR FY21(006)	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Performance of High Early-Strength Materials Used in Concrete Bridge Repair		**5. Report Date** May, 2023 **6. Performing Organization Code**
7. Author(s) Zina Ebrahim, Fray F Pozo-Lora, Zachary Benson, Mohammad Mastali, Marc Maguire, Jiong Hu		**8. Performing Organization Report No.** WBS 26-1122-0099-001
9. Performing Organization Name and Address University of Nebraska-Lincoln 1110 South 67th St. Omaha, Nebraska 68182-0178		**10. Work Unit No.** **11. Contract** SPR-P1 FY21(006)
12. Sponsoring Agency Name and Address Nebraska Department of Transportation Research Section 1400 Hwy 2 Lincoln, NE 68502		**13. Type of Report and Period Covered** Final Report Start date – May, 2024 **14. Sponsoring Agency Code**
15. Supplementary Notes		

16. Abstract

High early-strength materials are widely used for rapid concrete patching projects to limit road closure time and traffic obstruction. This research investigated the field performance of multiple high early-strength materials used in maintenance projects across Nebraska. Data from high early-strength products included in the state's approved product list were collected and compared to field performance. In addition, a survey was prepared and distributed to the surrounding states to understand standard practices related to appropriate specifications of these materials that can be later used to develop specifications for the utilization of high early strength materials in Nebraska based on experimental and filed evaluation data. Field inspections of multiple repair projects across Nebraska were performed. The field data were analyzed and plotted against the experimental data of each high early-strength material to investigate the potential of utilizing experimental data to predict the long-term performance of high early-strength materials. Based on the results, early strength and setting time showed a potential correlation with the field data represented by the normalized crack length.

17. Key Words High early strength concrete, bridge maintenance, field inspection	**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service. 5285 Port Royal Road Springfield, VA 22161

19. Security Classification (of this report) Unclassified	**20. Security Classification (of this page)** Unclassified	**21. No. of Pages** 164	**22. Price**
Form DOT F 1700.7 (8-72)	Reproduction of completed page authorized		

Table of Contents

List of Figures

List of Tables

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. The contents do not necessarily reflect the official views or policies of either the Nebraska Department of Transportations or the University of Nebraska-Lincoln. This report does not constitute a standard, specification, or regulation. Trade or manufacturers' names, which may appear in this report, are cited only because they are considered essential to the objectives of the report.

The United States (U.S.) government and the State of Nebraska do not endorse products or manufacturers. This material is based upon work supported by the Federal Highway Administration under contract SPR-P1 FY20(006). Any opinions, findings and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the Federal Highway Administration."

This report has been reviewed by the Nebraska Transportation Center for grammar and context, formatting, and 508 compliance.

Acknowledgements

The authors would like to thank all the Nebraska Department of Transportation staff that helped organize the field visits in districts one, two, and four as well as the Research Advisory Committee in particular Fouad Jaber, Wally Heyen and Lieska Halsey.

Abstract

High early-strength materials are widely used for rapid concrete patching projects to limit road closure time and traffic obstruction. This research investigated the field performance of multiple high early-strength materials used in maintenance projects across Nebraska. Data from high early-strength products included in the state's approved product list were collected and compared to field performance. In addition, a survey was prepared and distributed to the surrounding states to understand standard practices related to appropriate specifications of these materials that can be later used to develop specifications for the utilization of high early strength materials in Nebraska based on experimental and filed evaluation data. Field inspections of multiple repair projects across Nebraska were performed. The field data were analyzed and plotted against the experimental data of each high early-strength material to investigate the potential of utilizing experimental data to predict the long-term performance of high early-strength materials. Based on the results, early strength and setting time showed a potential correlation with the field data represented by the normalized crack length.

Chapter 1 Introduction

1.1 Project Overview

This report includes the findings of a research project funded by the Nebraska Department of Transportation (NDOT) to investigate the field performance of high early-strength (HES) materials currently used in Nebraska and the surrounding states. Site visits for multiple districts in Nebraska were scheduled to depict the field performance in addition to distributing a survey to the surrounding states related to the performance of the HES materials. Experimental data of the HES materials included on NDOT's approved product list (APL) were gathered from the product datasheet or the National Transportation Product Evaluation Program (NTPEP) database to create a reference that can be used in the HES material selection process. In addition, the collected field data were plotted against different material properties to determine the possibility of predicting the long-term performance of HES materials using experimental testing data.

1.2 Problem Statement

There is currently limited knowledge and experience in the NDOT regarding using HES materials in bridge repair. In addition, little information is available in the literature regarding the long-term performance of these materials and whether it is possible to use experimental data of different material properties to determine the long-term performance of HES materials.

1.3 Project Objective

The main goal of this research is to gather the available experimental testing results of different mechanical and durability properties of HES materials listed on the Nebraska APL to create a database that can help NDOT make decisions about the suitability of an HES material for specific projects. In addition, the project aims to estimate the field performance of HES materials used in the state of Nebraska and attempt to use experimental testing data to predict the future performance of these materials.

1.4 Report Outline

This report is divided into six chapters as follows:

- Chapter One presents an overview of what has been done in the project and lays out the main objectives and problem statement.
- Chapter Two presents a review of the literature related to bridge deck deterioration processes and an overview of infrastructure repair research.
- Chapter Three includes the details and results of a survey that was distributed to surrounding states related to the performance and use of HES materials. In addition to the results of an analysis that was performed to investigate the effect of repair materials on the flexural capacity of the structural element.
- Chapter Four presents the results of the field evaluation that has been performed in different districts in Nebraska, in addition to data analysis results and their relationship with different material properties.
- Chapter Five presents a summary, the main project findings, and recommendations.
- Chapter Six includes future recommendations related to the use of HES materials based on the findings of this research.
- Appendix A includes all the data collected from the field visits to different districts in Nebraska.
- Appendix B includes the moment-curvature and moment-strain curves obtained from analyzing a T-beam repaired using HES and polymer-based repair materials.

Chapter 2 Literature Review

2.1 Brief History

A large portion of modern transportation infrastructure is constructed using concrete (steel, GFRP or fiber-reinforced) or similar materials (McRory et al., 2022). Because of this, concrete repair and maintenance have become constant tasks to maintain the Nation's and Nebraska's infrastructure. Economic recessions have played a role in exacerbating repair issues. In the mid-1980s and from 2008–2012, these recessions delayed maintenance plans for highways and bridges nationally. In some cases, these plans were neglected outright (Ghafoori et al., 2017). This backlog of maintenance leads to a greater need for patching roadways and bridges, as decreased maintenance leads to increased challenges for state transportation agencies.

High early-strength repair concrete mixtures, while not used routinely in Nebraska for bridge decks, have gained national popularity due to decreased road and bridge closure times, perceived durability, and more forgiving weather dependence (Quezada et al., 2019). HES materials themselves suffer from high costs, but these costs are often perceived as minor compared to the total cost of repair action.

This chapter provides a brief overview of deterioration processes related to bridge deck repair for completeness and reviews infrastructure repair research. The goal is to inform the next steps of the current research project on a review and survey of HES mixtures in Nebraska.

2.2 High Early Strength Concrete Use and Repair

Partial depth repairs, the removal, and replacement of small areas of damaged pavement or slabs, are used to slow or eliminate the spread of spalling distress (Quezada et al., 2019). They also provide a well-defined, uniform joint prior to resealing, which helps keep harmful substances and water out of the joints. Partial depth repairs help restore structural integrity, enhance rideability, and extend the surface life of road surfaces.

Maintenence repairs offer quick installation, but temporary (lasting a few years maximum) materials are common and take up a large amount of time and money for maintenance crews. However, if proper materials and techniques are used in a timely manner, these repairs can last 10–15 years (Quezada et al., 2019). This makes it much more cost-effective.

Partial-depth patches can fail for a variety of material-related reasons (Frentress & Harrington, 2012), which include:

- Thermal incompatibility between the repair material and the pavement.
- Excess shrinkage or volume changes compared to the pavement.
- Incompatibility between the joint bond breaker and the joint sealant.
- Inadequate cure time prior to opening repairs to traffic.
- Incompatibilities between the climatic conditions during repair replacement and the materials or procedures used.
- Extreme climatic conditions during the life of the repairs are beyond the capabilities of the repair material.

HES materials are becoming popular for concrete repair as a way to reduce the costs and delays associated with lane closures (Dornak et al., 2015). However, when using HES materials, many factors can affect the outcome of the repair. Therefore, it is important to consider the compatibility of the repair material and the existing substrate when planning a repair. This helps ensure that the repair can withstand all the stresses the patch will face, including volume changes, chemical effects, and electrochemical effects (Morgan, 1996).

Considering this compatibility, all potentially influencing parameters should be considered when designing and implementing repairs. These parameters include mechanical compatibility, dimensional compatibility, bond compatibility, chemical and electrochemical compatibility, and durability. Additionally, external factors such as the temperature and moisture conditions of the substrate and ambient air, applied loads, freeze/thaw cycling, etc., should also be included when designing a repair (Morgan, 1996).

As the use of HES materials for patching grows, it is important that the properties of these materials are properly understood. Multiple studies on this topic have been conducted, ranging from modifying existing concretes to comparing proprietary blends. Despite these studies, many questions remain regarding HES materials when used for pavement and bridge repair.

To fill the need for HES materials, several different binders have become popular, especially in proprietary products. These binders include calcium aluminate cement (CAC), calcium sulfoaluminate cement (CSA), Belitic Calcium Sulfo Aluminate Cement (BCSA), magnesium phosphate cement (MPC), polymer concrete, alkali-activated binders (geopolymer), and prepackaged proprietary blends.

Calcium Aluminate Cement (CAC) gains strength quickly, making it a good choice for HES repair, potentially in combination with Portland cement. CAC is primarily composed of monocalcium aluminate at approximately 40–60%. Mayenite also plays a vital role in accelerating and changing the early hydration of cement since it is the most reactive calcium aluminate in CAC (Koehler et al., 2022) and is the second most available compound.

CSA and BCSA types of cement are primarily used in rapid strength gain applications, where the first setting time can be as short as ten minutes if retarding admixtures are not used

(Burris & Kurtis, 2018). This makes CSA cements ideally mixed and placed with the help of a volumetric mixer (Thomas et al., 2018). Moist curing and cure-seal curing of CSA and BCSA mixtures are often performed until the concrete has a minimum of 1 hour (e.g., see datasheets for CTS or other CSA cement-based products).

Properly proportioned BCSA concrete can reach compressive strengths exceeding 5,000 psi in as little as two hours, along with the development of other mechanical properties (Bescher & Kim, 2019; Glasser & Zhang, 2001; Hu et al., 2017; Janotka & Mojumdar, 2007; Péra & Ambroise, 2004). In addition, as much as 80% of the 28-day compressive strength can be reached within three days; whereas 28-day compressive strengths have been reported in the range of 5,000 psi to more than 10,000 psi (Burris & Kurtis, 2018; Murray et al., 2019). CSA-containing cement can also exhibit expansive or shrinkage-compensating characteristics, reducing the amount of shrinkage (Glasser & Zhang, 2001; Thomas et al., 2018). Autogenous shrinkage occurs and could be exacerbated by poor curing and water use (Pelletier et al., 2010), but internal curing, which is a technique used to improve cement hydration and reduce shrinkage by providing additional water in concrete, has been shown to reduce autogenous shrinkage in BCSA cement mixtures and other HES proprietary products.

Magnesium phosphate cement (MPC) is a hydraulic cement that exhibits high early strength and does not require water curing. It also has lower shrinkage than Portland cement-based mixtures (Ding & Li, 2005; Li et al., 2014). Water content sensitivity is a noted weakness, and low toughness and preclusion of calcium-based aggregates are limitations of MPC for patching use (Alice, 2014).

While successfully meeting short-term requirements, these proprietary mixtures containing alternative cements have not been thoroughly tested in the US for durability within the literature, and there are questions regarding long-term performance (Dornak et al., 2015, Quezada et al., 2019). Many of the aforementioned materials have third-party testing available on the American Association of State Highway Transportation Officials (AASHTO) National Transportation Product Evaluation Program (NTPEP) website. However, there is some skepticism about the long-term performance of HES patching materials and their relation to such laboratory tests by the NDOT (per previous technical advisory committee (TAC) meetings) and others (Gholami et al., 2019a; Quezada et al., 2019; Zuniga, 2013). For instance, research continues to attempt to develop new and customized tests (Cervo & Schokker, 2008; Morency et al., 2005) with the goal of filling the gap between field performance and lab testing, although there is limited information about the on-field performance, as mentioned below, and no established link. Most customized or nonstandard testing relies on modified versions of restrained shrinkage testing, such as the shrinkage ring (AASHTO T334), Baenziger Block (Gillespie, 1999), German Angle Test (Emmons et al., 1998) or large-scale simulated repairs (Cervo & Schokker, 2008; Morency et al., 2005). The only comprehensive survey of field repair performance was conducted by Burnham et al. (2016) and their report only includes information related to data collection. Still, it does not establish performance related to a laboratory test or lab testing of any kind. The NTPEP database does have some limited information on repair monitoring, but it is not currently widespread.

2.3 Repair Deterioration and Best Practices

Repair materials should be compatible, or they will not act together as intended; the properties of one material could cancel the properties of the other. Compatibility is the balance of physical, chemical, and electrochemical properties and dimensions between a repair material and the existing substrate. To make an appropriate choice and understand the uses and limitations of repair materials, publications such as (Heiman & Koerstz, 1991; Hewlett & S.A., 1985; Wilkinson, 1987) discuss issues such as the stiffness and thermal and electrochemical compatibility of repair systems. Compatibility between the repair and the concrete substrate guarantees the capability of the repair to endure all the stresses caused by changes in volume, in addition to chemical and electrochemical effects, without causing distress and deterioration over a specified period of time. Figure Chapter **2.1** presents the factors affecting the durability of a concrete repair which is taken from previous work by Emmons et al. (1993).

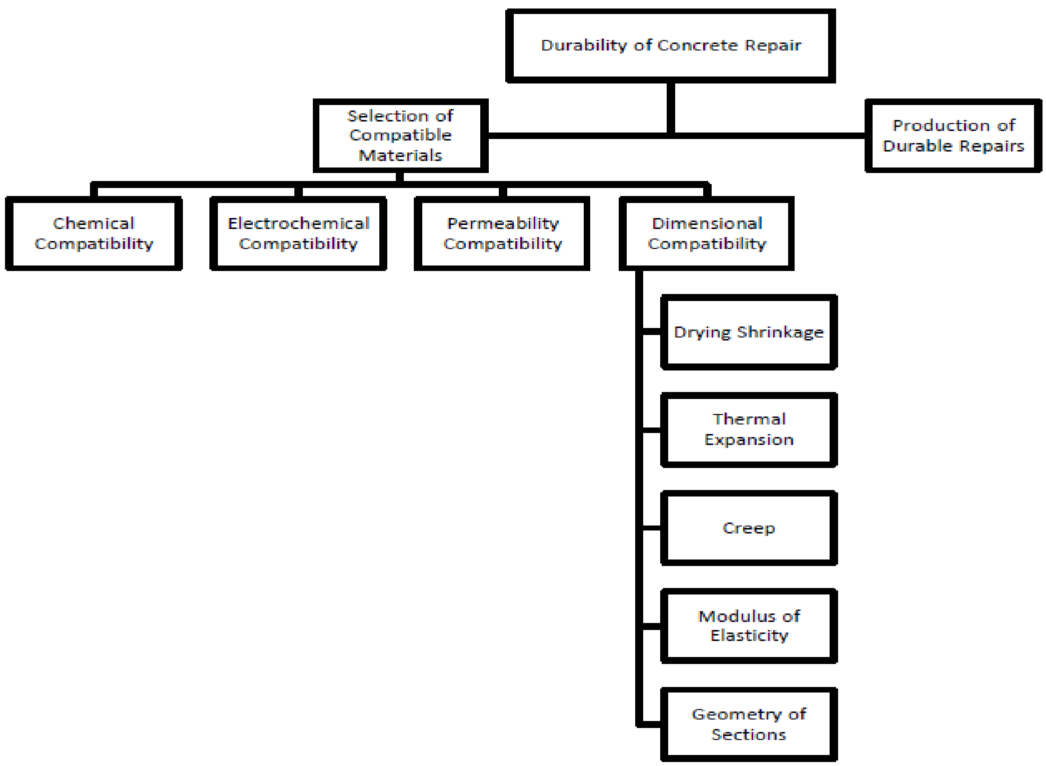


Figure Chapter 2.1 Factors affecting the durability of a concrete repair (Emmons et al., 1993)

Dimensional compatibility is considered the most significant factor affecting the durability of a concrete repair since it refers to the ability of a repair material to support applied loads without causing distress. In addition, it encompasses the capability of a repair material to tolerate volume changes without experiencing detachment and separation from the substrate. To ensure durable repair, the selected repair material must have chemical compatibility with the concrete substrate to avoid having significant effects on the repaired structure. Electrochemical compatibility must also be considered in selecting a repair material, especially if the repair structure is highly susceptible to deterioration caused by reinforcement corrosion (Emmons et al., 1993; Morgan, 1996).

Dimensional compatibility is influenced by several factors, such as the shrinkage of the repair material and substrate, thermal expansion, modulus of elasticity, and repair section geometry (Quezada et al., 2019). According to Emmons (1993), there are other factors that affect the dimensional compatibility of the concrete repair, which are the size, shape, and area of the repair area, the amount of reinforcing and anchorage, and strain capacity. According to Quezada et al. (Quezada et al., 2019), the repair becomes debonded due to the following reasons:

- Excessive shrinkage strains in Portland cement and some polymer-modified concrete and polymer concrete systems (Emmons et al., 1993; Plum, 1991).
- Excessive expansion in certain shrinkage-compensated repair materials (Morgan, 1996).
- Excessively high thermal expansions followed by cooling and shrinkage occur during early setting and hardening reactions (Plum, 1991).
- Very high thermal expansion occurs in repair materials during diurnal or seasonal temperature changes (Woodson, 2011).

A repair material is said to be ideal for a specific application if it has a high strain capacity that enables the resistance of the applied strains without substantial cracking, low shrinkage rate, and modulus of elasticity and coefficient of thermal expansion that are similar to those of the substrate (Yuan & Marosszeky, 1991). Repairs can be classified based on their function into non-structural and structural repairs (Plum, 1991). In non-structural repairs, the material is used for purposes other than supporting the induced stresses. On the contrary, the repair material used for structural repairs is required to carry the load supported by the removed deteriorated concrete.

Table **Chapter 2.1** presents the general requirements of a repair material to ensure structural compatibility depicted in previous research by Emberson and Mays (1990). According to Quezada et al. (Quezada et al., 2019), Saucier & Pigeon (1991), and Woodson (Woodson, 2011), the first requirement is typically met. However, a material with a significantly high modulus of elasticity should be avoided to prevent the repaired area from attracting more loads.

Table Chapter 2.1 General requirements of repair media for structural compatibility (Emberson & Mays, 1990)

Property	**Relationship of Repair (R) to Concrete Substrate (C)**
Strength in Compression, Tension, and Flexure	R≥C
Modulus in Compression, Tension, and Flexure	R˜C
Poisson's Ratio	Dependent on modulus and type of repair
Coefficient of Thermal Expansion	R˜C
Adhesion in Tension and Shear	R≥C
Curing and Long-Term Shrinkage	R≥C
Strain Capacity	R≥C
Creep	Dependent on whether creep causes desirable or undesirable effects
Fatigue Performance	R≥C

The second requirement is to have a similar modulus and coefficient of thermal expansion between the repair material and the substrate. This requirement can be met in most Portland cement-based and polymer-modified repair materials, but it can be a potential problem in different polymer concretes (Emberson & Mays, 1990). Having significant differences in the modulus of elasticity and coefficient of thermal expansion of the repair material and the concrete substrate will lead to deterioration, according to Marosszeky (1991).

The potential for success or failure of the repair will depend on factors such as chemical and electrochemical compatibility, which are related to concrete corrosion. An oxide film forms around the reinforcement at concretes with a pH of 12–13. The film remains until carbon dioxide diffuses through the concrete, which reduces the pH to approximately 9 (Luca et al., 2004). As long as this film remains, it is better than man-made protection such as galvanizing (Broomfield, 2003). The film can also be damaged when chloride ions, commonly found in deicing salts, penetrate the concrete (Poulsen & Mejlbro, 2010). This corrosion reaction has been studied and is thought to be well understood (Broomfield, 2003). Although the standard deicing salt is sodium chloride (NaCl), other salts, such as calcium chloride ($CaCl_2$) and potassium chloride (KCl), are also used along with urea (CH_4N_2O). Overall, chloride compounds contribute to the corrosion process (Kirchner, 2001). While urea is a non-chloride deicer, testing has shown it to cause greater deterioration in the concrete (Farha et al., 2002).

The "halo effect" is a corrosion phenomenon of special concern for deck patching and has been noted by NDOT personnel as a concern with HES bridge deck repair in the past (see HES polymer repair in Figure Chapter **2.2**). The beginnings of some haloing (efflorescence around the patching interface) were potentially observed on a recent site visit by the research team. When a damaged area of concrete is repaired and the existing substrate is contaminated with chloride ions, a chloride gradient exists between the two materials, creating a large corrosion potential. This leads to rapid corrosion in the area around the repair (Whitmore, 2005).

Figure Chapter 2.2 Early minor halo efflorescence on NDOT bridge polymer concrete repair

Early-age cracking has been noted as a cause for concern with HES mixtures due to autogenous and drying shrinkage. Research programs have developed guidelines and customized tests for the mitigation of cracking and strategies, including internal curing with presaturated lightweight aggregate, optimized gradation, and reduced cement content (Quezada et al., 2019). Dimensional stability has also been noted as important, as matching the substrate concrete and preventing excessive shrinkage is essential to bond preservation and cracking prevention and is thought to be related to long-term performance (Morency et al., 2005).

Other deterioration mechanisms include crumbling of the surface mortar or scaling, which is a common form of deterioration associated with freeze/thaw cycles (Cordon, 1966), and abrasion damage caused by vehicular loads. Vehicular loads cause deterioration through abrasion damage at contact points between the wheel and road. Studded tires, chains, and snowplow blades can cause significant damage to roads as they scrape the surface (Russell, 2004).

Vehicular loading can also exacerbate cracking and other damage, such as spalling, which is typically caused by other mechanisms.

2.4 Specific Findings

McDaniel et al. (2014) explored the current practices used with pavement and concrete patching, also addressing the use of technology and computerized systems to analyze patching and maintenance programs. From a survey, approximately 30% of states have researched concrete repair, primarily on material performance, and the cost-effectiveness of these materials (McDaniel et al., 2014). This same survey showed that there were still areas where further research is needed, including improvement of patching tools and material performance and especially new materials and material comparisons. The survey results showed that the greatest needs were similar for local and state agencies.

Quezada et al. (2019) also performed a survey of all state departments of transportation. It was determined that states' expectations were not being met with respect to HES pavement repairs, but HES repairs were generally regarded favorably. Specifically, states expected repair performance at an average of 20 years, but 40% observed repairs failing at less than 10 years and 90% saw failure under 17.5 years. However, from this survey, state agencies (STAs) were satisfied with the HES pavement repairs they were making.

2.4.1 State requirements

Highways often require repairs to be performed during limited closure times, often at night. Specifically, freeways and toll roads often permit only overnight closures (Delatte, 2008). Overnight construction is also typical for airport pavements (Elhindy et al., 1996; Kohn & Tayabji, 2003). Table Chapter **2.2** shows some details from some states' Departments of

Transportation (DOTs), which specify both an opening time and mechanical strength criteria to reopen the traffic.

Accordingly, there is a national demand for using fast and durable repair materials for bridges, where minimal operation disruption is needed. The minimum operation disruption requires that the used repair materials rapidly gain strength during an early age and remain durable throughout the repaired structure's service life (M. Li & Li, 2011).

Table Chapter 2.2 State requirements for opening to traffic obtained from different DOTs (California Department of Transportation, 2008, 2015; Colorado Department of Transportation, 2011; Delaware Department of Transportation, 2014; Georgia Department of Transportation, 2013; Illinois Department of Transportation, 2012; NCDOT, 2012; New York Department of Transportation, 2014; Van Dam et al., 2005; Virginia Department of Transportation, 2016; Washington Department of Transportation, 2016)

State	Minimum age at opening to traffic	Compressive strength requirement	Flexural strength requirement	Slump (in)	Air content (%)
Arkansas	6 hours	2000 psi	N/A	N/A	N/A
California	2-4 hours	2000 psi	400 psi	N/A	N/A
Colorado	Contractor specified	3000 psi	650 psi at 28 days	N/A	N/A
Delaware	Contractor specified	2,000 psi	N/A	N/A	N/A
Florida	6 hours	2200 psi	N/A	1.5-4	1-6
Georgia	4 hours	2000 psi	N/A	N/A	N/A
Illinois	4-8 hours	3200 psi	N/A	2-8	4-6
Iowa	10 hours	3500 psi	N/A	4	6
Kansas	4-6 hours	3500 psi	360 psi	N/A	N/A
Maryland	4-12 hours	2000-2500 psi	N/A	N/A	N/A
Michigan	8 hours	N/A	290 psi	N/A	N/A
Minnesota	12-hours	3000 psi	N/A	N/A	N/A
Missouri	4 hours	3500 psi	N/A	N/A	N/A
New Jersey	6.5 hours	N/A	350 psi	N/A	N/A
New York	Contractor specified	3000 psi	N/A	N/A	N/A
Nebraska	4-8 hours	3000 psi	N/A	N/A	6-8.5
North Carolina	4-6 hours	N/A	2,500 psi	N/A	6
Ohio	4 hours	N/A	400 psi	N/A	N/A
Pennsylvania	Less than 7 hours	1200-1450 psi	N/A	N/A	N/A
Texas	24 hours	N/A	420 psi	N/A	N/A
Virginia	N/A	2500 psi	600 psi at 28 days	N/A	N/A

Table 2.2 (continued) State requirements for opening to traffic obtained from different DOTs (California Department of Transportation, 2008, 2015; Colorado Department of Transportation, 2011; Delaware Department of Transportation, 2014; Georgia Department of Transportation, 2013; Illinois Department of Transportation, 2012; NCDOT, 2012; New York Department of Transportation, 2014; Van Dam et al., 2005; Virginia Department of Transportation, 2016; Washington Department of Transportation, 2016)

State	Minimum age at opening to traffic	Compressive strength requirement	Flexural strength requirement	Slump (in)	Air content (%)
Utah	48 hours	4000 psi	N/A	N/A	N/A
Washington	Contractor specified	2500 psi	N/A	N/A	N/A
Wisconsin	8 hours	3000 psi	N/A	N/A	5-7

Most HES concrete repair information and specifications at DOTs are related to pavement repair (partial and full depth) rather than bridge deck or other reinforced concrete repairs, which often require less quantity and is performed using proprietary prebagged HES materials. For larger quantities, the mixture is typically a ready-mix supplied concrete. NDOT recent research indicates several mixture compositions meet the minimum strength opening requirements (Gholami et al., 2019). These compositions comprise of different binders (such as Type I/II Portland cement, slag, fly ash) and water-to-binder ratios of 0.36–0.45. The minimum required opening strength is 3000 psi; however, these mixtures provide a strength higher than 3500 psi. These mixtures are not suitable small quantity repairs on bridge decks due to strength, composition, and batching requirements.

The California Department of Transportation (Caltrans) uses three different mixture designs for HES concrete, which have been designed to meet opening requirements. The first mixture can be opened within 2 to 4 hours, while the second mix contains Type III cement with a non-chloride accelerator that can meet opening strength requirements within 4 to 6 hours. The third mixture uses a Type III cement with a lower dosage of a non-chloride accelerator, and the opening time for this mix is 12 to 24 hours. According to Table Chapter **2.2**, Caltrans's opening to traffic strength requirement is 2000 psi compressive strength and 400 psi flexural strength.

The Florida Department of Transportation specified a cement amount in the range of 840 to 900 lb/yd^3 with accelerators, which can meet this state opening requirement (a 3000-psi compressive strength within 8 hours). The Kansas Department of Transportation uses an HES concrete mix design incorporating a minimum cement content of 650 lb/yd^3 with an accelerator (calcium chloride). This mixture can reach a compressive strength of 3000 psi within 4 to 6 hours.

Shin and Walker (2020) assessed the compressive strength (after 4 hours) of the proposed mix composition for HES concrete in USDOT (Shin & Walker, 2020). They found that using only type III cement as the binder did not meet the target goal of 4000 psi as the required strength for 4-hour compressive strength. Therefore, they replaced type III cement with 6%, 8%, and 10% (by mass) silica fume. The measured 4-hour compressive strength showed that increasing the silica fume content increased the strength at early ages and reached 3850 psi, which is very close to the target goal. The 8-hour compressive strength reached 4200 psi (higher than 4000 psi) and met the required strength.

In 2019, Sprinkel et al. (2019) worked on the failure of concrete patching in Virginia. According to the VDOT, the proposed goal for a 5- to 8-hour compressive strength is 2000 psi. Sprinkel et al. (Sprinkel et al., 2019) found that the typical mixtures of VDOT need a high cement content (800 lb/cy for a 5-hour mixture and 752 lb/cy for an 8-hour mixture). Moreover, the 5-hour mixture did not reach 2000 psi. Therefore, Type I/II cement was replaced by fly ash to reduce cement and hot waters with temperatures of 75°F and 85°F. The results showed that the compressive strength gained 2000 psi in the modified mixture using 85°F mixing water after 6 hours. A list of repair projects in different states that used HES concrete is listed in Table Chapter **2.3**.

Table Chapter 2.3 List of repair projects of transportation infrastructures using HES concrete in different states (f'_c = compressive strength, MOR = flexural strength)

Project Location	Project Date	Project Name	Binder type	W/C	Strength	Ref.
Iowa	1987	Creating cement for fast track construction	Class C fly ash 70lbs/yd^3 & Type III 640 lbs/yd^3	0.43 to 0.45	f'_c: 3467 psi MOR: 607 psi (after 24 hours)	(Knutson & Riley, 1987)
Osceola, IA	1987	Osceola Airport project	Class C fly ash 70lbs/yd^3 w/Type III 640 lbs/yd^3	0.43 to 0.45	MOR: 415 psi (after 12 hours) & 780 psi (after 26 hours)	(Pearson, 1988)
Michigan	1987	Michigan road project	Type III 710 lbs/yd^3	0.38	MOR: 425 psi (after 12 hours)	
Cedars Rapids, IA	1989	Fast track for urban road construction	Class C fly ash 73lbs/yd^3 w/Type III 641 lbs/yd^3	0.41	f'_c: 3550 psi & 4660 psi (after 12 and 24 hours) MOR: 420 psi & 530 psi (after 12 and 24 hours)	(Grove et al., 1990)
			Class C fly ash 80lbs/yd^3 w/Type III 742 lbs/yd^3	0.38	f'_c: 4990 psi & 5260 psi (after 12 and 24 hours) MOR: 570 psi & 690 psi (after 12 and 24 hours)	
Vermilion, OH	1994	Early Strength gain of rapid highway repair concrete	Type III 900 lb/yd^3	0.4	MOR: 400 psi (after 4 hours)	(Whiting et al., 1994)
Vermilion, OH			900 lb/yd^3 of a blended cement	0.27	f'_c: 2000 psi (after 4 hours)	
Vermilion, OH			750 lb/yd^3 of a rapid set cement	0.4	f'_c: 2000 psi (after 4 hours)	

Table 2.3 (continued) List of repair projects of transportation infrastructures using HES concrete in different states (f'_c = compressive strength, Flex = flexural strength)

Project Location	Project Date	Project Name	Binder type	W/C	Strength	Ref.
Vermilion, OH	1994	Early Strength gain of rapid highway repair concrete	Type III 870 lb/yd^3	0.38	f'_c: 2000 psi (after 4 hours)	(Whiting et al., 1994)
Augusta, GA			850 lb/yd^3 blended cement	0.29	f'_c: 2000 psi (after 6 hours)	
Vermilion, OH			650 lb/yd^3 rapid set cement	0.5	f'_c: 2000 psi (after 6 hours)	
Augusta, GA			Type I 750 lb/yd^3	0.38	f'_c: 1000 psi (after 4 hours)	
New Jersey	1997	Fast track concrete for pavement repair	Type I 799 lb/yd^3	0.41	f'_c: 3865 psi MOR: 380 psi (after 24 hours)	(Ansari et al., 1997)
			Type I 799 lb/yd^3		f'_c: 3607 psi (after 24 hours)	
Storm Lake, IA	1980	Fast track concrete pavement	Type III	0.45	MOR: 350 psi (after 7.5 hours)	(American Concrete Pavement Association, 2004)
Barksdale, AFB (IA)	1992		Special blended cements	0.27	MOR: 450 psi (after 4 hours)	
Cedars Rapids, IA	1988		Type III	0.38	MOR: 400 psi (after 12 hours)	
Manhattan, KS	1990			0.44	MOR: 450 psi (after 24 hours)	
Lansing, MI	1989			0.45	MOR: 550 psi (after 19 hours)	
Denver, CO	1992			0.32	MOR: 2500 psi (after 12 hours)	
Dallas county, IA	1987			0.425	MOR: 350 psi (after 9 hours)	
Rawlins, WY	1992			0.47	f'c: 3000 psi (after 24 hours)	
Erie County, PA	1991			0.37	f'c: 3000 psi (after 24 hours)	
Dane County, MO	1991			0.4	f'c: 3500 psi (after 18 hours)	

Table 2.3 (continued) List of repair projects of transportation infrastructures using HES concrete in different states (Com = compressive strength, Flex = flexural strength)

Project Location	Project Date	Project Name	Binder type	W/C	Strength	Ref.
Cooper County, WI	1992	Fast track concrete pavement	Type III	0.455	f'c: 3500 psi (after 12 hours)	(American Concrete Pavement Association, 2004)
North Hampton, VA	1990			0.42	f'c: 3000 psi (after 24 hours)	
Menominee, NE	1992		Type II	0.423	f'c: 3500 psi (after 24 hours)	
Smithfield, NC	1990		Type III	0.35	MOR: 450 psi (after 48 hours)	
US Highway 30,IN. From Illinois border past Dyer	2014	INDOT Project No. R35341	Type I/II	0.343	MOR: 300, 330, 360, 450 psi (after 4, 5, 6, 8 hours)	(Todd, 2015)
					MOR: 240, 320, 390, 400, 490 psi (after 4, 5, 6, 8, 24 hours)	
					MOR: 240, 320, 380, 400 psi (after 6, 8, 11, 24 hours)	
Florida	2018	FDOT Contract Number: BDV25-977-23	ACO4 Cement 900 lb/yd^3 & limestone (CA) 1680 lb/yd^3	0.384	f'c: 950 psi (after 6 hours), 2400 psi (after 12 hours), 4100 psi (after 24 hours)	(Zayed et al., 2018)
			ACO4 Cement 700 lb/yd^3 & limestone (CA)1150 lb/yd^3 &	0.384	f'c: 620 psi (after 6 hours), 1850 psi (after 12 hours), 3550 psi (after 24 hours)	

Table 2.3 (continued) List of repair projects of transportation infrastructures using HES concrete in different states (Com = compressive strength, Flex = flexural strength)

Project Location	Project Date	Project Name	Binder type	W/C	Strength	Ref.
Florida	2018	FDOT Contract Number: BDV25-977-23	limestone (IA) 690 lb/yd^3	0.384	f'$_c$: 620 psi (after 6 hours), 1850 psi (after 12 hours), 3550 psi (after 24 hours)	(Zayed et al., 2018)
			ACO4 Cement 700 lb/yd^3 & limestone (CA)1180 lb/yd^3 & limestone (IA) 710 lb/yd^3	0.34	f'$_c$: 1200 psi (after 6 hours), 3100 psi (after 12 hours), 5400 psi (after 24 hours)	
Wisconsin	2017	Better Concrete Mixes for Rapid Repair in Wisconsin, WisDOT: Project 0092-15-08	Type I cement 846 lb/yd^3, Crushed limestone, accelerator $CaCl_2$ solution	0.32	f'$_c$: 2433 psi (4 hours), 3760 psi (6 hours), 4760 psi (8 hours)	(Cramer et al., 2017)
			Type I cement 846 lb/yd^3, Crushed limestone, accelerator $CaCl_2$ dry		f'$_c$: 1930 psi (4 hours), 3407 psi (6 hours), 4277 psi (8 hours)	
			Type I cement 846 lb/yd^3, Igneous gravel, accelerator $CaCl_2$ solution		f'$_c$: 2140 psi (4 hours), 3340 psi (6 hours), 4090 psi (8 hours)	
			Type I cement 846 lb/yd^3, Igneous gravel, accelerator $CaCl_2$ dry		f'$_c$: 1813 psi (4 hours), 2897 psi (6 hours), 3503 psi (8 hours)	

2.4.2 HES Challenges

Although HES possesses the desired high-early strength properties, these materials are more prone to early-age cracking in the hardening stage due to their higher thermal and autogenous shrinkage caused by faster early-age hydration and heat release (Bentz & Peltz, 2008; Mehta & Burrows, 2001; Mihashi et al., 2002). Figure Chapter **2.3** illustrates a flowchart that evaluates the process and effective parameters of the cracking tendency of HES concrete.

Typically, the minimum compressive and flexural strength of HES concrete can be varied from 2000 to 3500 psi and 300 to 500 psi, respectively. For pavements, specifically, full-depth repairs, it is common for flexural strength to be specified, whereas the compression strength is a more appropriate value to specify for bridge decks or other flexural type members. The Federal Highway Administration (FHWA) accepts a minimum modulus of rupture of 300 psi and 250 psi obtained from HES concrete testing under the three-point bending test and four-point bending test, respectively. The American Concrete Pavement Association's (ACPA) "Guidelines for Full Depth Repair" recommends strength for opening to traffic that ranges from 2000 to 3000 psi for the compressive strength and 250 to 490 psi for the flexural strength depending on repair length and slab thickness (American Concrete Pavement Association, 2004).

In general, the performance of HES concrete for bridge deck repair has four major categories: mix design parameters, structure design parameters, construction parameters, and environmental parameters. Often, the structural design parameters are the most straightforward, as the mechanics and specified loading will dictate material strengths, and the remaining parameters are less straightforward. Mixed design parameters have been discussed above and vary from state to state based on experience, but there is also a limited understanding of what parameters should be controlled. Construction parameters can vary with local quality control, quality assurance protocols, and from contractor to contractor. Environmental parameters can be controlled through specifications, but there are limits to how restrictive a specification can be with respect to the local environment. Table Chapter **2.4** lists the details of the effective parameters of HES concrete's performance in the repair process of transportation infrastructures. This flowchart helps conceptually determine the mixture parameters that may interact with the structure or environmental parameters, ultimately resulting in cracking distress.

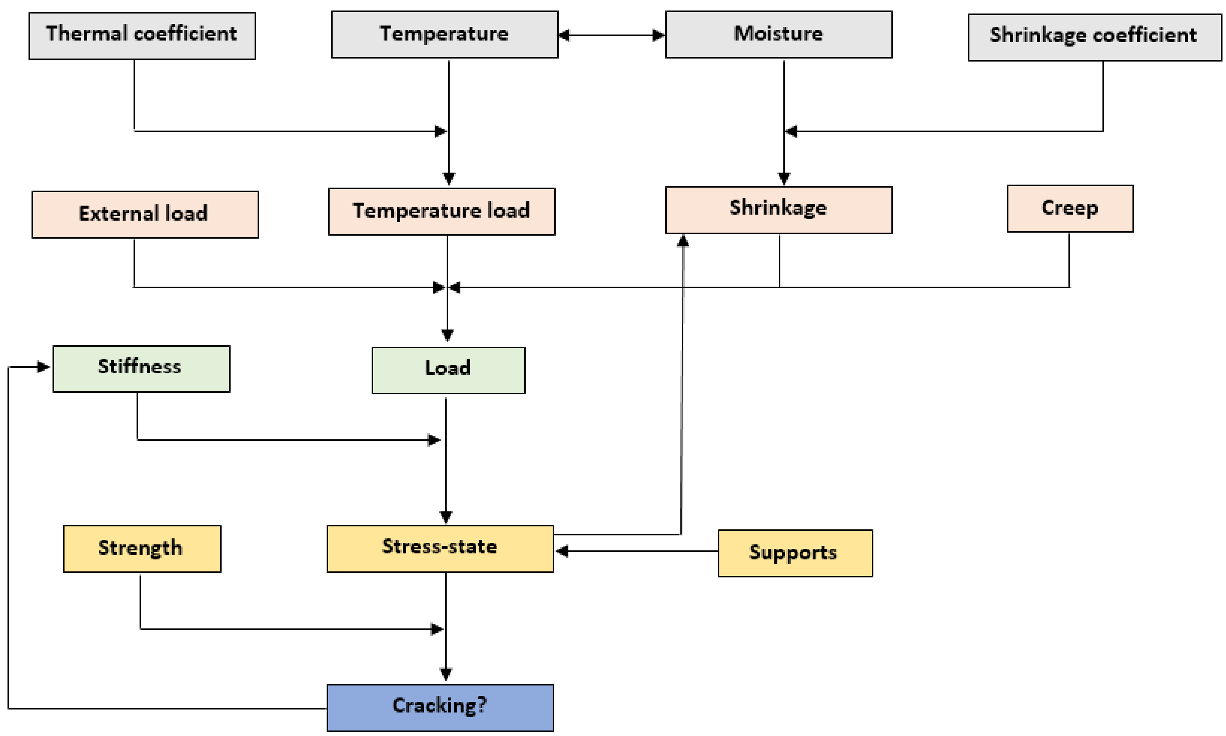


Figure Chapter 2.3 Flowchart for the analysis of early-age concrete behavior (redrawn and adapted from (Hauggaard et al., 1997)

Table Chapter 2.4 Effective parameters on the repair process of transportation infrastructures using HES concrete (adapted from Lee et al. (2003))

Mix design parameters	Design parameters	Construction parameters	Environmental parameters
- Binder type and content (ordinary Portland cement (admixed), calcium sulfo-aluminate cement, magnesium - phosphate cement, and polymer) - Fine/coarse aggregate type and content - Water to binder ratio - Use of water reducer - Use of retarder - Use of accelerator	- Structural component requirements - Mechanical strength and elastic modulus of concrete substrate - Structural system requirements	- Curing method - Duration of construction - Initial temperatures of concrete and substrate - Age of concrete at time of reopening to traffic	- Air temperature - Temperature and relative humidity distribution - Solar radiation - Average wind speed

Using HES concrete as the repair material for partial depth bridge deck repairs requires removing and replacing some small, damaged pavement areas. This replacement can introduce some extra challenges besides the previously proposed ones that can be reasons for the failures of the repairing efforts (Mauricio Ruiz et al., 2005). The challenges include:

- Structural incompatibility, thermal incompatibility, dimensional incompatibility, bond incompatibility, and electrochemical incompatibility between HES and the substrate;
- Corrosion potential of HES and the halo effect;
- Creep/relaxation phenomena;
- Construction procedures;
- Inadequate cure time before opening repairs to traffic;

- Incompatibilities between the climatic conditions during repair replacement and the materials or techniques used; and
- Extreme climatic conditions during the life of the repairs are beyond the capabilities of the repair material.

2.4.3 Laboratory Research

(Gholami et al., 2019) studied the impact of reducing cement content with optimized aggregate gradation and partial replacement of Type I/II or III Portland cement with IP cement for traditional ready-mixed style repair mixtures. Based on the evaluation of mechanical performance, durability, and constructability, the cement content could be decreased by up to 100 lb/yd^3. This was found to reduce the shrinkage and alkali-silica reaction (ASR) resistivity, but the mixtures did not have high early strength. Additionally, the authors looked at the effects of non-chloride accelerators. This allowed the authors to make guidelines to improve traditionally ready-mixed patching materials. However, this research did not extend beyond typical Portland cement. Additional research needs to be performed on other non-Portland cement mixes to determine viability (Gholami et al., 2019b).

Dornak et al. (Dornak et al., 2015) evaluated several rapid repair mixes consisting of CAC, CSA, Portland cement, and proprietary blends. The authors evaluated the materials on a number of factors. These included mechanical properties, volume change, freeze/thaw resistance, and alkali-silica reaction. These results were used to make conclusions about the performance of the various mixes but were not tied to field performance. The conclusions made only concerned individual tests or properties, And were not used to make broader suggestions on how to use the different mixtures most effectively. Additionally, polymer-based concrete and MPC were not part of this study.

Cervo and Schokker (Cervo & Schokker, 2008) chose six repair materials for a series of ASTM tests to evaluate material properties and suitability for patching. They selected the materials based on correspondence with the Pennsylvania Department of Transportation (PennDOT) and other nearby DOTs. They found that Pavemend 15.0 (unknown material composition) and latex-modified Rapid Set Concrete Mix (BCSA based) outperformed the others and conducted additional testing on the two. They made conclusions on the best patching material to use in the study area from the results. They also created a recommended testing protocol for PennDOT to use when examining patch materials.

Ram et al. (2019) performed a study on non-cementitious repair materials. It consisted of a field survey of five different partial depth repair materials and limited laboratory testing. Laboratory testing was used to assess the bond and dimensional stability of the materials. From this research, the authors provided several suggestions for future research opportunities:

- A Controlled Field Study: The field investigations of this study were performed on existing repairs. As such, the ages, contractors, preexisting conditions, and installation techniques were not controlled.
- Bond Durability Study: For the purposes of this study, the pull-off test method was mostly unsuccessful. For that reason, a direct shear bond test should be used to evaluate the bond durability during freeze–thaw cycling.
- Cost-benefit Analysis: This analysis can be performed by quantifying the cost of each non-cementitious material per unit volume. The benefit would be the approximate service life of the repair performed using each material. Local agencies would need to quantify the benefits of extended service life and the reduced closure time.

Ghafoori et al. (Ghafoori et al., 2017) sent out a survey in the fall of 2015 and the spring of 2016. The survey was sent to the DOT of each state as well as the FHWA's regional offices. It was focused on how each state used HES material in road repairs. The authors used this information to determine the materials they tested. Some of the results they found are listed below.

- All states used/allowed high early-age strength concrete for pavement repairs, and almost all used/allowed high early-age strength concrete for bridge deck repairs.
- Opening times varied with geographic location and cement type used. Times as low as 4-6 hrs have been documented using Type III Portland cement (PC) and 8-10 hrs using Type I PC during summer placement. Opening times as low as 2.5 hours have been seen using HES repair materials.
- Some states based opening time on compressive or flexural strength, while some imposed a 4-6 hr minimum (at least one cold-weather state has a 12 hr minimum). Typical maximum opening times are 24, 48, and in some cases 72 hrs (at least one hot weather state has a 12 hr maximum)
- Many states required strength testing at intervals of 24, 48, and/or 72 hrs, regardless of opening time.
- The required compressive strength at the opening to traffic ranged between 1500–3500 psi (4000 psi for deep repairs), with the majority being 3000 psi.
- Many states did not have flexural strength requirements. When needed, the range was 380–600 psi.
- Few states had a specification for drying shrinkage. When specified, the range was 0.03–0.05% at 28 days after placement.

- Type(s) I, II, III Portland Cement, and in some cases, proprietary bag mixes such as Rapid Set, were the most prevalently used for high early-age strength concrete in bridge and road repair.
- The cement factors used for HES repairs ranged between 600–900 lb/yd^3, with lower values of 600–750 lb/yd^3 being more favorable due to economics.
- Most states did not specify minimum water-to-cement ratios. Most did, however, specify a maximum value of 0.40–0.45.
- Nearly all states allowed the use or acceleration of admixtures for pavement and bridge deck repairs. Some allowed the use of pavement only.
- Nearly all states required non-chloride accelerators when used.

Ghafoori et al. (Ghafoori et al., 2017) concluded that it was not possible to label one type as the best concrete for HES road repair. This was due to different mixes performing best depending on the criteria. Although the authors showed how the mixes performed in each category (opening time, mechanical properties, volume stability, permeability, and durability), they did not recommend specifications or use cases/situations.

Markey et al. (2006) studied spall repair material performance using a suite of laboratory tests with the following generalized conclusions. When considering spall repairs, material compatibility should be considered. Materials with high shrinkage or the coefficient of thermal expansion (CTE) should have a low modulus. On the other hand, high modulus materials should have a low level of shrinkage and CTE to prevent large internal and bond stresses. From the study, high modulus materials reflected cracking in the existing pavement, but both provided adequate performance.

Falls (2019) tested the performance of 14 prebagged concrete repair materials for Portland cement concrete (PCC) airfield pavement. Partial depth repairs were constructed and subjected to simulated loading. Long-term performance over the repeated loadings was monitored and results included conclusions for each material, with CTS Rapid Set Mortar Mix, SikaQuick 2500, ProSpec Premium Patch 200, and Pavemend SLQ performing the best. Ulti-Pave 3, Fast Set DOT Mix, and MasterEmaco S 6000 performed the worst and were difficult to work with.

Kuo et al. (1999) performed laboratory tests on repair materials and selected six different materials for further field testing. This testing was performed at an accelerated circular test track on constructed joint repairs and spalls. Immediate cracking and debonding from shrinkage were observed on site. Two pot feather edge potholes, simulating real pothole conditions, performed well during testing (Kuo et al., 1999)(Kuo et al., 1999)(Kuo et al., 1999).

2.5 Field Research

Burnham et al. (Burnham et al., 2016) documented 93 patches of 22 different materials over a three-year span. Over this period, visual observations were used to make subjective condition ratings for each patch. Bond information was collected for each patch at a single time using a ball-peen hammer. The supplier installed some of the patches. In these cases, some suppliers did not follow the standard installation procedure by the Minnesota Department of Transportation (MnROAD) installers. This may have had negative effects on the patches investigated.

The Burnham et al. (2016) study was mostly qualitative due to data availability; as such, there are few quantitative data related to the investigated mixture properties. Of the materials observed in this study, several had a slow gain in strength. This slow gain may make them impractical for repairs on busy roads due to the extended closures needed. However, many of the slow-setting materials performed very well throughout the study. The database created in this study is highly valuable and deserves additional study if possible. Limited conclusions were made, but more could be done after the fact.

Zayed et al. (Zayed et al., 2018) performed both laboratory and field slab tests, with laboratory tests being used to determine which mixtures to use in the field tests. The field slabs studied several crack mitigation strategies, including the reduction of cementitious paste volume through aggregate grading optimization, internal curing using saturated lightweight aggregates, fiber reinforcement to inhibit plastic cracking, and the use of shrinkage-reducing admixtures. The authors found that most field-placed slabs were affected by moisture migration to the base and that cracking could be reduced by increasing aggregate packing density and lowering paste content (Zayed et al., 2018)(Zayed et al., 2018)(Zayed et al., 2018).

Ram et al. (2013) performed experimental and field testing for several HES materials to determine whether material properties and field performance are related. The investigated material properties included setting time, temperature development, workability, compressive strength, bond strength, free and restrained shrinkage, freeze-thaw resistance, resistance to chloride ion penetration, and scaling resistance. The compressive strength and freeze-thaw resistance experimental results were compared with the field performance of six commercially available HES materials installed on a deteriorated bridge deck in Indiana state. The field results obtained for the freeze-thaw resistance were very close to those obtained from the laboratory. However, the compressive strength data for some of the investigated materials obtained from the field significantly differed from the compressive strength lab data calculated using the regression model presented in the study, which predicts the compressive strength of the specimen given its age. The authors proposed recommendations for required experimental testing and target values for HES materials for the Indiana Department of Transportation (INDOT).

2.6 Synthesis of Material Selection and Repair Design

During repair material selection and design, the engineer must specify the criteria for the materials used in bridge deck repair. This depends on the allowable lane closure time, repair strength, shrinkage characteristics of the material, coefficient of thermal expansion, ambient temperature, size of the repair, and cost. Partial depth repair for reinforced concrete is governed by compressive strength rather than flexural strength, as in full-depth pavement repair. Partial depth repairs of reinforced concrete are considered unique in the way they carry load such that they are thought to primarily carry compressive stresses along with interfacial bond stresses. Furthermore, a partial depth repair is believed to be partially confined, perhaps allowing a lower opening strength.

The Federal Highway Administration/Strategic Highway Research Program (FHWA/SHRP) Manual of Practice, Materials and Procedures for Rapid Repair of Partial-Depth Spalls in Concrete Pavements (Wilson et al., 1999), which should be similar to partial depth repairs in reinforced concrete components, states that several causes can be attributed to the materials used in partial-depth patch failures:

- Thermal incompatibility between the repair material and the pavement.
- Incompatibility between the joint bond breaker and the joint sealant.
- Inadequate cure time prior to opening repairs to traffic.
- Incompatibilities between the climatic conditions during repair replacement and the materials or procedures used.
- Extreme climatic conditions during the life of repairs that are beyond the

capabilities of the repair material.

The goal of HES repairs—early opening to traffic—is opposed to the goal of dimensional stability. Because of the high strength requirements, concrete must gain strength quickly, often at the expense of dimensional compatibility due to high autogenous and drying shrinkage and a final concrete strength much in excess of the substrate, resulting in a modulus of elasticity mismatch.

While strength at the opening is often of primary concern to allow the early opening to traffic, the short- and long-term performance of the repair is often dictated by dimensional and thermal compatibility. Every effort should be made to ensure a similar coefficient of thermal expansion to guard against diurnal and seasonal differential expansion and contraction between the substrate and repair. Generally, this can be accomplished with conventional HES cement-based materials (Portland or similar cement such as CSA) while using a similar aggregate source and volume fraction to the substrate. Aggregates often comprise the bulk of the concrete volume, and the wide range of values is shown in

Table **Chapter 2.5** (see a range of 3.84 to 6.01 microstrain/°F). Aggregates contained in prebagged materials may not have this information and may not be at sufficient volume to obtain similar CTE for the two mating materials. Some prebagged, preextended materials in the NTPEP database have CTE information provided.

Table Chapter 2.5 LTPP aggregate CTE values provided for example (Hall & Tayabji, 2011)

Primary Aggregate Class	**Average CTE (/°F x 10^{-6})**	**Standard Deviation (s) (/°F x 10^{-6})**	**Average CTE (/°C x 10^{-6})**	**Standard Deviation (s) (/°C x 10^{-6})**	**Sample Count[1]**
Andesite	4.32	0.42	7.78	0.75	52
Basalt	4.33	0.43	7.80	0.77	141
Chert	6.01	0.42	10.83	0.75	106
Diabase	4.64	0.52	8.35	0.94	91
Dolomite	4.95	0.40	8.92	0.73	433
Gabbro	4.44	0.42	8.00	0.75	8
Gneiss	4.87	0.08	8.77	0.15	3
Granite	4.72	0.40	8.50	0.71	331
Limestone	4.34	0.52	7.80	0.94	813
Quartzite	5.19	0.50	9.34	0.90	131
Rhyolite	3.84	0.82	6.91	1.47	7
Sandstone	5.32	0.52	9.58	0.94	84
Schist	4.43	0.39	7.98	0.70	30
Siltstone	5.02	0.31	9.03	0.56	21
				Total Sample Count	2,251
1. A total of 2,991 CTE values are available in LTPP Standard Data Release 25.0 (January 2011); 628 CTE values were not used due to aggregate class not defined or only one sample available for the primary aggregate type; and 112 CTE outlier values were also not included in the table.					

Dimensional stability is a challenge for all HES materials. In a previous study by the authors on prebagged repair materials, there was no correlation between the observed early cracking in the field inspections (Figure Chapter **2.4**) and standard tests such as the ring test, autogenous shrinkage, or drying shrinkage, all of which are commonly specified tests for HES repair material. It is likely that factors such as curing, workmanship, and environmental effects play a larger role in the behavior of HES materials than other materials. The factor that best predicted cracking performance over a 12-month period was compression strength. Note that all materials were extended with local aggregate per supplier recommendation, and all were cementitious, although not all Portland cement.

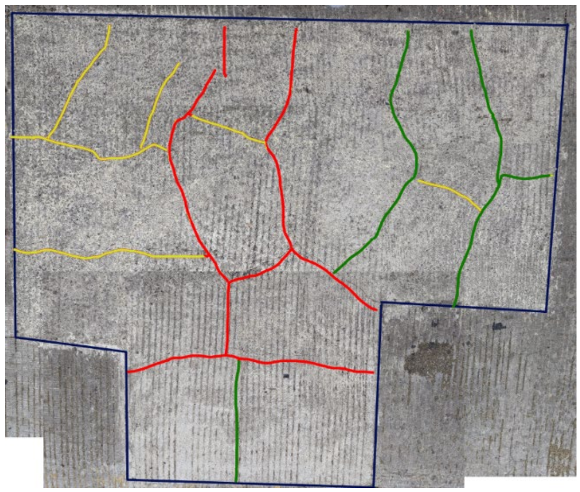


Figure Chapter 2.4 Example of field inspection of prebagged material in an ongoing study

The discussion above makes it impossible to specify a single mixture or test value, partly because there is not enough information about which factors an owner can specify that result in the greatest control over long-term performance. However, there are still best practices that can be followed, and there is an opportunity to gain new information in the future.

2.6.1 Summary of Best Practices

Generally, the best practices for HES repair material selection are the same as those for normal repair; however, the constraint of high early strength will, by necessity, create a stiffness and shrinkage mismatch. The specification of the materials selection process, as shown in Figure Chapter **2.5** for each DOT environment specifying materials, is not always straightforward, as specifications tend to be written in a broad manner that leaves the final selection up to the contractor. The anecdotal evidence above from ongoing research suggests that higher strength may mitigate these issues in practice, but this is based on short-term inspections. Strategies from the literature to limit these effects are the inclusion of presaturated lightweight aggregate or other internal curing mechanisms and shrinkage-reducing admixture, both of which are difficult to endorse as additions to prebagged products because their contents are unknown. Thus, the best practices for HES repair are discussed in the following sections.

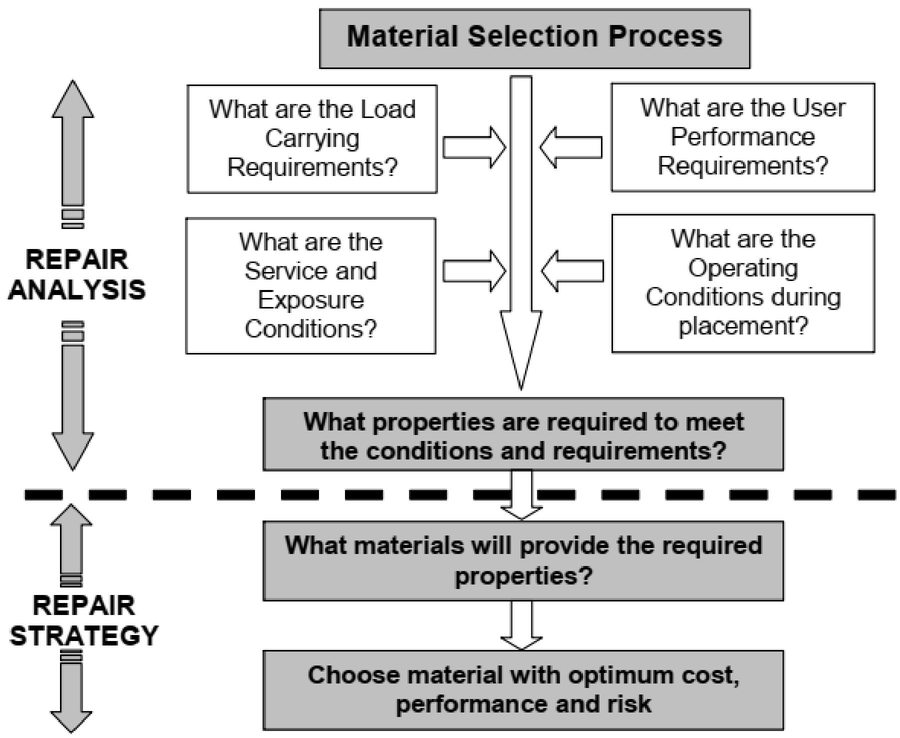


Figure Chapter 2.5 Material Selection Process (Barde et al., 2006)

2.6.1.1 Material Specification

- Recommendations for using prebagged materials provided by the manufacturer should be followed, including mixing times and strategies.

- The early and final strength of the material should be as close to that of the substrate as possible to enable a similar elastic modulus.
- Prebagged cementitious material should be extended with local aggregates, if possible, at a similar level to the substrate concrete; or the as-tested CTE of the material should match that of the substrate as closely as practicable.
- Cementitious materials (Portland, CSA, or other) are recommended for structural repairs.

2.6.1.2 Repair Specification

- If a chloride gradient is expected and a history of the haloing phenomenon exists, consider employing a galvanic protection strategy (often a sacrificial zinc anode) in the repair to prevent haloing.
- Properly clean surrounding concrete and steel to remove chlorides and damaged concrete or corrosion products.
- Ensure proper consolidation.
- If at all possible, repairs should be rectangular shaped.
- Follow best practices if the bonding agent (chemical or sand-cement) is specified. Anecdotal evidence with HES repairs has indicated that bonding agents do not provide value.
- Proper curing, per manufacturer and owner specifications, should be followed. Chemical or wet curing is recommended by different manufacturers. To reduce early shrinkage, curing for HES repairs is often specified such that more water or compound is supplied than normal concrete.

The following section attempts to synthesize the research on this topic related to the long-term performance of HES patch repairs. While the research has informed some of the above, the results are often mixed or focused on either laboratory or field studies with little crossover.

2.7 Research Synthesis

The collected information from other states' specifications regarding HES pavement indicates a wide range of definitions for HES concrete, including strength and opening requirements. With regard to the bridge deck and structural patching, prebagged mixtures are often more contractor friendly, have higher early strengths, and are likely repeatable. The NTPEP database has considerable third-party testing on such mixtures. However, there are significant challenges with the use of prebagged materials. The lab studies related to HES concrete patching all share commonalities that seem to be retesting prebagged materials that are partially or fully tested in the NTPEP database. The major shortcoming seems to be that they fail to link the lab results to fieldwork performed within their study or other studies. Generally, conclusions are that a certain test (e.g., ring or bond tests) that results in the best values should be selected for in-service repairs, although it is not known if this produces the best field performance. Several studies (Cervo & Schokker, 2008; Dornak et al., 2015; Morency et al., 2005; Ram et al., 2019) have developed custom tests to evaluate certain characteristics, such as cracking, but have not linked behavior to field performance and have resulted in only a relative comparison between mixtures. Few lab-centric studies have specific guidelines or broader conclusions about concrete repair based on the test results. Several studies have reported anecdotal evidence that a certain type of behavior results in repair failure. Most often this is bond (freeze-thaw related) or cracking, which is then used as the focus of the study.

Field research on this topic lacks breadth in some studies and depth in others, in both cases making it difficult to make specification-driven decisions on repair practice. Projects designed to test the effectiveness of patching materials are limited to less than a statistically relevant sample size, making it difficult to draw solid conclusions on the effectiveness of the materials. Burnham et al. (Burnham et al., 2016) collected data from a large sample; however, these data were qualitative, subjectively graded, and intentionally intended to transmit data without analysis or conclusions. The current study could put effort into the evaluation of this database. A similar style study has been discussed by the committee as part of the current study.

2.8 Summary

To achieve the most cost-effective patching methods, it is important to know not only what materials are most effective but also why. Understanding how the interaction between the patch material and the road surface works is critical in making guidelines for consistent patching. General guidelines for concrete repair are well-known and widely available but are limited in HES applications because of material constraints. To achieve longer-lasting repairs, correlations between lab results and field results need to be made between various patching and surface materials. Once these correlations are made, specifications can be decided that will ensure the best materials and practices are used regardless of the surface materials or ambient conditions. It is recommended that the current study investigate putting together a plan to provide similar field information as presented by Burnham et al. (Burnham et al., 2016) but provide a wider array of materials, quantitative information, and ultimately try to link NTPEP testing (or other testing) results to field deterioration.

Chapter 3 Data Collection and Analysis of HES Materials

3.1 High Early Strength Performance Survey

To understand common practices related to appropriate specifications of HES materials, a survey was prepared and sent out to the surrounding states in 2021. The states that participated in the survey were Delaware, Connecticut, Oklahoma, Iowa, Kansas, North Carolina, New Hampshire, Texas, and Alabama. Most states have experience with HES materials. Approximately 90% of the participating states reported using HES repairs in their bridge maintenance for years, and approximately 65% have been using them for more than ten years.

3.1.1 HES Approval Process

Before using a new HES product in a project, it may or may not go through certain testing and quality control procedures, which may differ across the United States. Based on the survey results, only three state DOTs have reported using NTPEPs to approve HES materials. Other state DOTs rely on internal testing, product datasheets, and the manufacturer testing data in the HES approval process. Although most participating states have reported using HES materials for many years, only 50% have an APL for HES materials. Various tests are required for the prequalification of HES materials. The commonly used tests are listed in Table Chapter **3.1**. In addition, tests related to durability properties, such as chloride ion penetration tests, surface resistivity, scaling resistance, and air content testing, are required by some states but are less common.

Table Chapter 3.1 Commonly required tests for prequalification of HES materials according to the survey

Required Experimental Testing	Reported Use (%)
Compressive Strength	70
Length Change	50
Tensile Strength	40
Bond Strength by Slant Shear	40
Bond Strength by Direct Tension	40
Bond Strength by Slant Shear	40
Freeze-Thaw	30
Permeability	30

3.1.2 Utilization of HES Repair Mechanisms for Bridge Maintenance

Based on the survey results, HES materials are typically used in bridge deck maintenance, as shown in Figure Chapter **3.1**. Different types of HES materials are typically used in bridge maintenance projects. Portland cement-based HES repair materials are the most commonly used materials, followed by polymer concrete, magnesium phosphate, and sulfoaluminate repair materials. Challenges commonly encountered when using HES materials include short setting time, improper mixing and/or curing, testing, and opening traffic time. Most of the surveyed states have quality control specifications for HES materials, including specific material and experimental testing requirements. The HES quality control process is currently limited to the preselection and early post-installation phases.

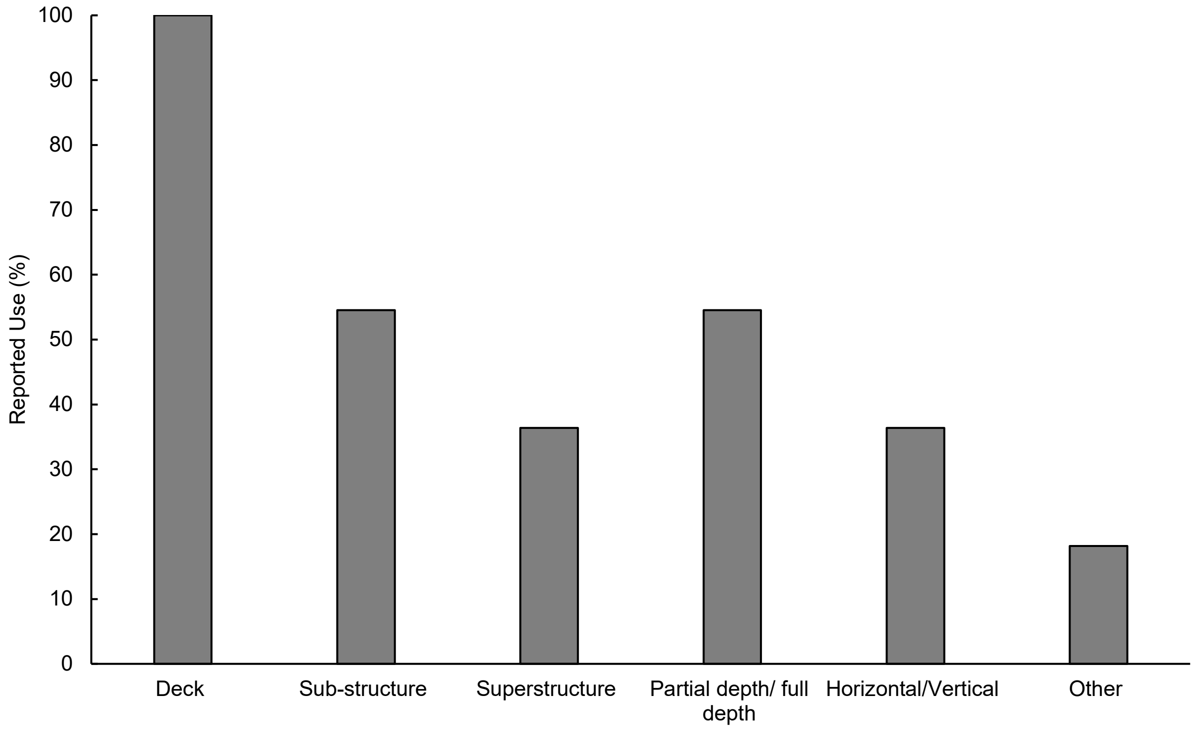


Figure Chapter 3.1 Utilization of HES materials for maintenance of different parts of the structures and different repair types

3.1.3 HES Standards and Specifications in the Neighboring States of Nebraska

To benefit from the experience of the surrounding states of Nebraska with the use of HES materials in their maintenance projects, a review of each state's current standards and specifications has been made, and each state's requirements are presented in Table Chapter **3.2**. The states considered are Iowa, Missouri, Kansas, Colorado, and Wyoming. No standards and specifications were found on the South Dakota Department of Transportation website for high-early-strength materials used in repair projects.

As shown in Table Chapter **3.2**, each state requires a set of experimental testing to qualify the material for use in the state construction projects. In addition, many states require testing by NTPEP before adding the manufactured HES materials to each state APL. Some states, like

Iowa, perform quality assurance testing to ensure the HES material performs as expected. The specifications of all the considered states focus on the prequalification and testing stage of the HES materials without having any specifications for the long-term field performance of these materials. The state of Nebraska should benefit from the experience of the surrounding states by creating HES materials specifications that focus on the prequalification stage of the materials, experimental testing performed by the AASHTO's NTPEP, retesting of the HES material performance after a specified number of years, and long-term field performance of the qualified material. This will help decision-makers select what HES materials are best for use in Nebraska based on field performance rather than only experimental testing.

Table Chapter 3.2 Standards and Specifications of HES Materials in the neighboring states of Nebraska

State	**Requirements**
Nebraska (Nebraska Department of Transportation, 2017)	- Curing must follow guidelines outlined in section 603.03 of the standard specifications for highway construction manual. - Compressive strength shall be greater than 3,500 psi (25 MPa) at 48 hours after placement. - Non-calcium chloride accelerator shall be used if the ambient temperature at the time of placing concrete is 70˚F or less. - Durability factor not less than 70 shall be achieved for all classes of concrete except PR1 and PR3. - Mass loss shall not be greater than 5% after 300 freeze/thaw cycles when tested in accordance with ASTM C 666 for all classes of concrete except PR1 and PR3. - The freeze/thaw testing shall be conducted according to Procedure A.
Iowa (Iowa Department of Transportation, 2023)	**General Requirements** - Identifiable brand names on the packages. - Materials packaging is a multi-wall moisture resistance paper bag. - Shelf life must be indicated on the materials bag. - Mixing sequence as recommended by the manufacturer. - If the coarse aggregate is used, the following must be specified: o Type and quantity as per the manufacturer's recommendations o Has a minimum of Class 2 durability rating - Approved materials listed in the Materials Approved Product Listing Enterprise (MAPLE) must be used. **Approval** - Product identification, including brand name. - Manufacturer's recommendation for usage. - Test report of the product by NTPEP. - Materials safety data sheet. - evaluation of the following material properties: o Compressive Strength o Bonding: Slant Shear or Direct Tension o Durability factor o Allowable length change o Resistivity or rapid chloride permeability

Table 3.2 (continued) Standards and Specifications of HES Materials in the neighboring states of Nebraska

State	**Requirements**
Iowa (Iowa Department of Transportation, 2023)	**Quality Assurance** - The manufacturer is required to file a certificate at the beginning of each year stating that the material is identical to the one tested and approved previously. - Sampling of HES materials to verify if it is meeting the approval requirements.

Missouri (Missouri Department of Transportation, 2023)	**Horizontal Repair Specifications**
	- Curing until a minimum compressive strength is 3200 psi is obtained
	- Materials must be tested through NTPEP
	- Product information
	  o Brand name of the product
	  o Material compliance certificate and curing instructions, And
	  o Application type.
	- Material must be included in the approved product list.
	- Minimum requirements for approval includes evaluation of the following material properties:
	  o Bond Strength by Slant Shear
	  o Linear Coefficient of Thermal Expansion (for bagged mortar only without extension aggregate)
	  o Resistance to rapid freezing and thawing
	  o Compressive Strength
	  o Rapid chloride permeability
	  o Length change
	  o Color

Kansas (Kansas Department of Transportation, 2015)	- Compliance with ASTM C 928 – Standard Specification for Packaged, Dry, Rapid-Hardening Cementitious Materials for Concrete Repairs. - Freeze-thaw durability as per ASTM C 666, Procedure B. - Prequalification under the AASHTO NTPEP.

Colorado (Colorado Department of Transportation, 2022)	- Product must be included in the approved product list.
	- Product must be tested as per ASTM C 928 every 4 years.
	- Prequalification under the AASHTO NTPEP.
	- Certified test reports including the following material properties:
	  o Compressive Strength as per ASTM C 39
	  o Setting Time as per ASTM C 26

Table 3.2 (continued) Standards and Specifications of HES Materials in the neighboring states of Nebraska

State	Requirements
Colorado (Colorado Department of Transportation, 2022)	o Resistance of Concrete to Rapid Freezing and Thawing as per ASTM C 666 o Bond Strength as per ASTM C 882 o Linear Shrinkage and Coefficient of Thermal Expansion as per ASTM C 531
Wyoming (Wyoming Department of Transportation, 2021)	**Horizontal Repair Specifications** - The product used must be preapproved by the Materials Program. - Equivalent product can be used if it is a non-chloride, non-vapor barrier, high-alumina cementitious mortar in accordance with ASTM C-928-99a and minimum requirements that can be found in the standard specifications for Road and Bridge construction documents. - The material properties that must be tested are: o Compressive Strength o Final setting time o Freeze/Thaw resistance o Drying Shrinkage - If the material is used with maximum aggregate extension: o Compressive Strength o Bond Strength - Extension Aggregate Gradation Requirements: o 100% passing sieve having a size of 3/8 in o 0% passing No.8 sieve **Vertical Repair Specifications** - The product used must be preapproved by the Materials Program. - Equivalent product can be used if it is a non-chloride, non-vapor barrier, high-alumina cementitious mortar in accordance with ASTM C-928-99a and minimum requirements that can be found in the standard specifications for Road and Bridge construction. The material properties that must be tested are: o Compressive Strength o Final setting time o Freeze/Thaw Resistance o Drying Shrinkage o Bond Strength

3.2HES Materials Listed on the NTPEP Approved Product List

The mechanical and durability properties of all the HES repair materials listed on the NDOT-approved product list were collected and organized in a spreadsheet. The current APL includes 60 HES repair materials; approximately 40% are tested and available on the NTPEP online database. The NTPEP database usually includes data for the following properties: compressive strength, bond strength, tensile strength, chloride ion penetration, chloride ion content, surface resistivity, shrinkage, freeze-thaw, and setting time. The properties of the HES materials that are not listed on the NTPEP were collected from the technical datasheet of each material published on the manufacturing company website. The HES materials spreadsheet will be available for use by the NDOT staff.

The values of several properties of HES materials included on the APL and tested on the NTPEP were compared with those reported on each material's datasheet. These properties are compressive strength, shrinkage, and initial and final setting time. The results are shown in Figure Chapter **3.2** through Figure Chapter **3.6**. In these graphs, the x-axis represents data obtained from the technical datasheet (TDS), the y-axis represents data obtained from the NTPEP, and the 45-degree line represents the ideal case where the NTPEP data match the data obtained from the TDS. As shown in the figures below, there is a significant difference between the data reported on the NTPEP and the data provided by the manufacturer.

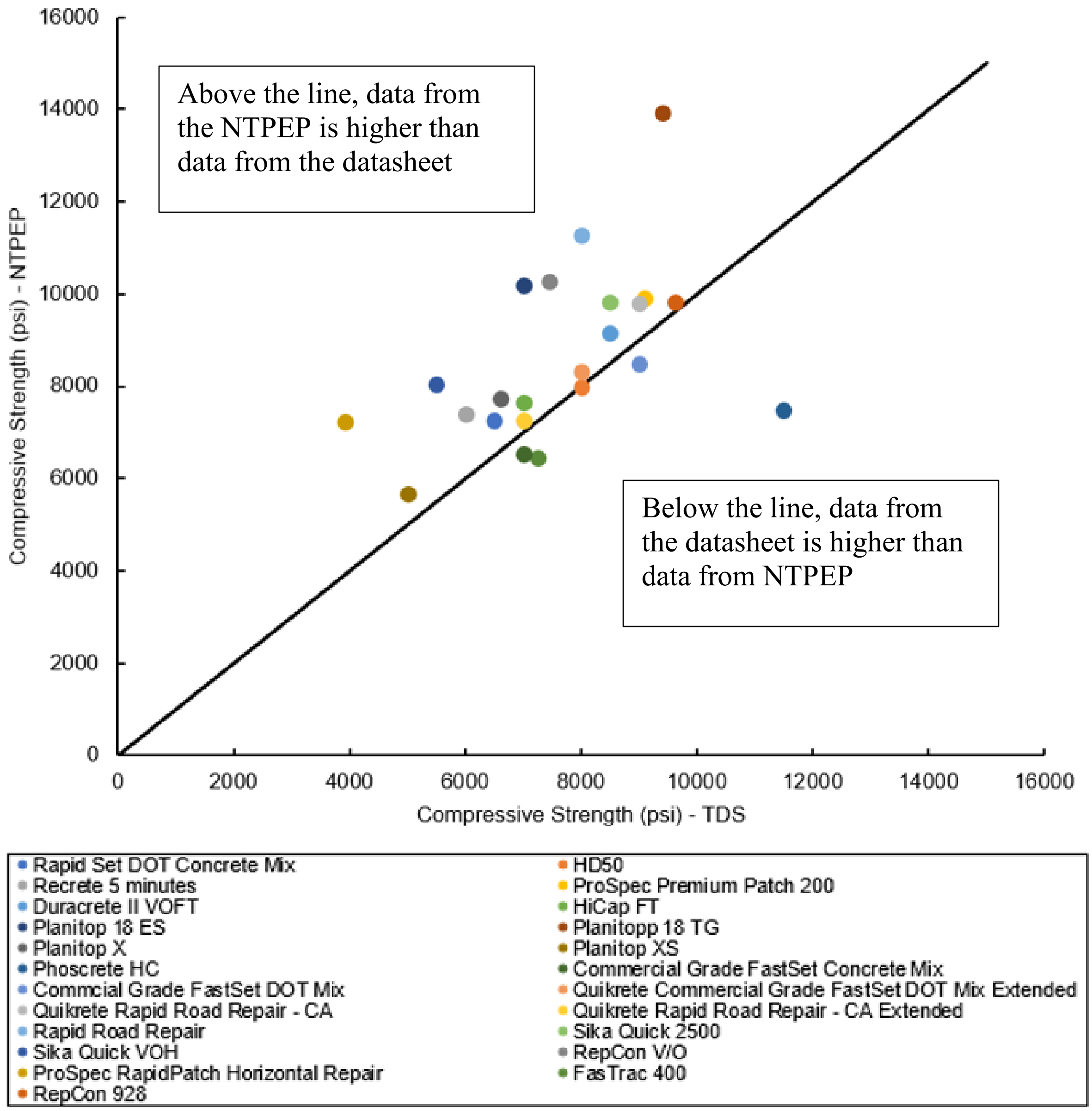


Figure Chapter 3.2 Comparison of the compressive strength data on the NTPEP and the material datasheet

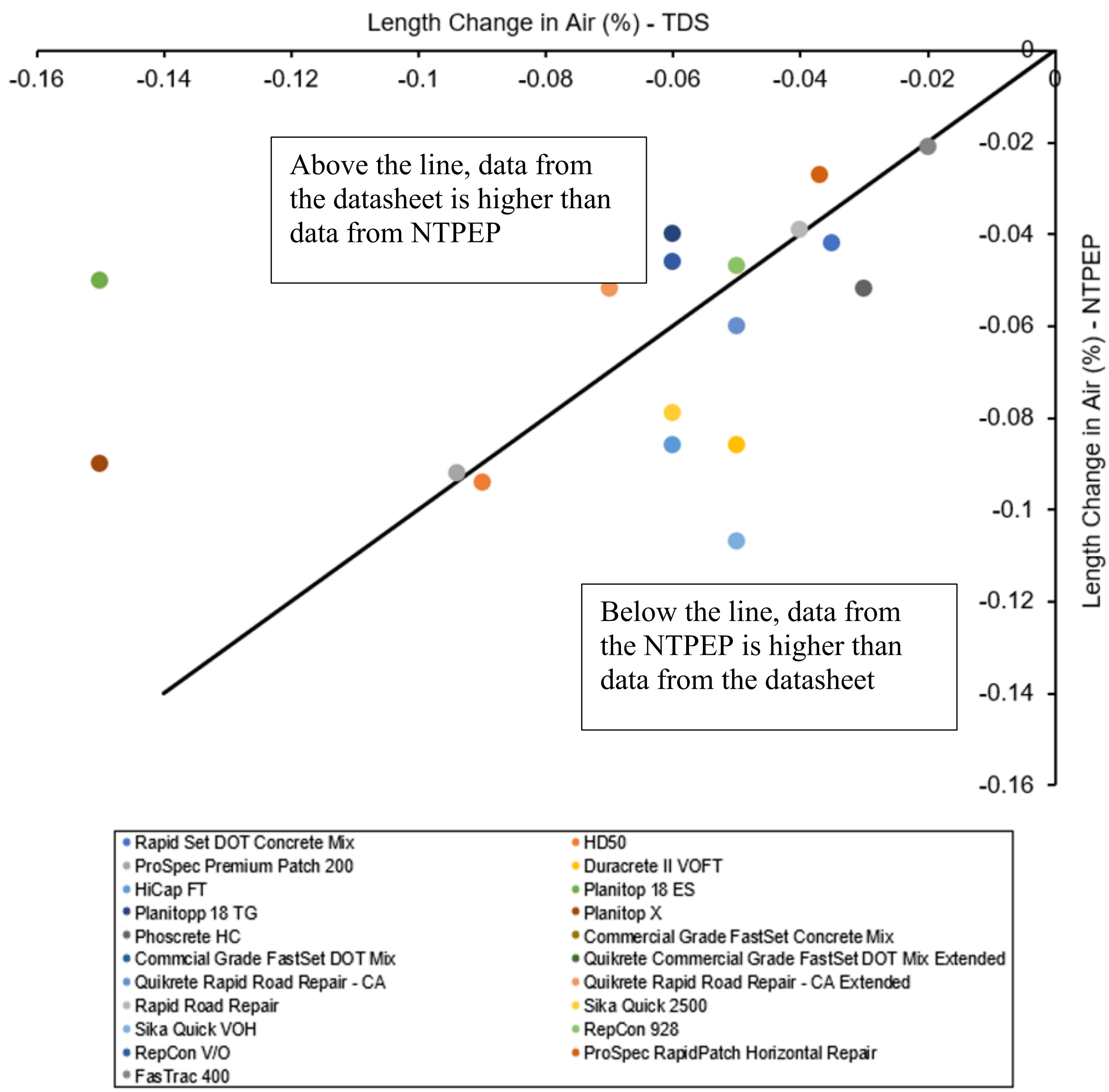


Figure Chapter 3.3 Comparison of the length change in air data on the NTPEP and the material datasheet

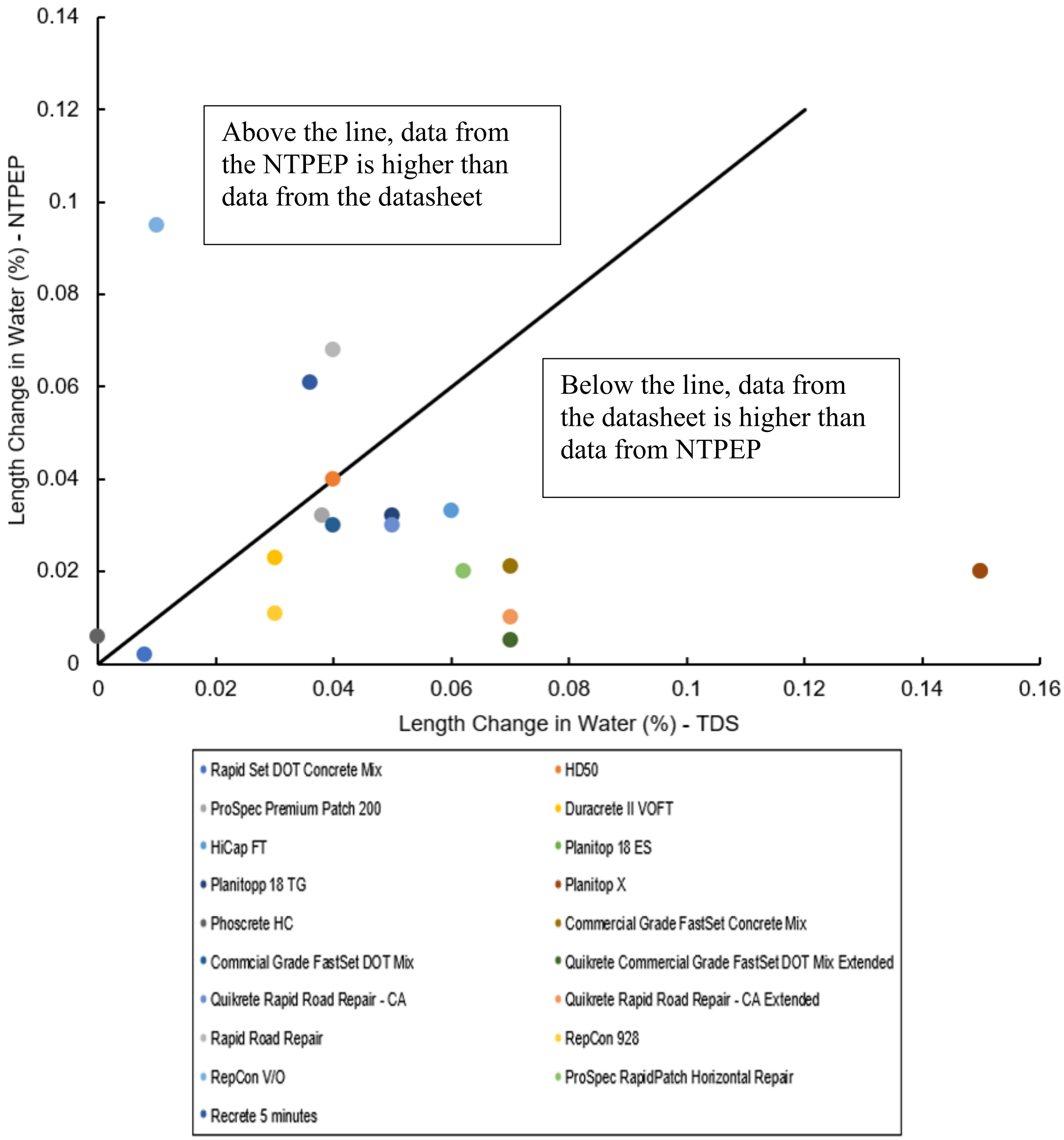


Figure Chapter 3.4 Comparison of the length change in water data on the NTPEP and the material datasheet

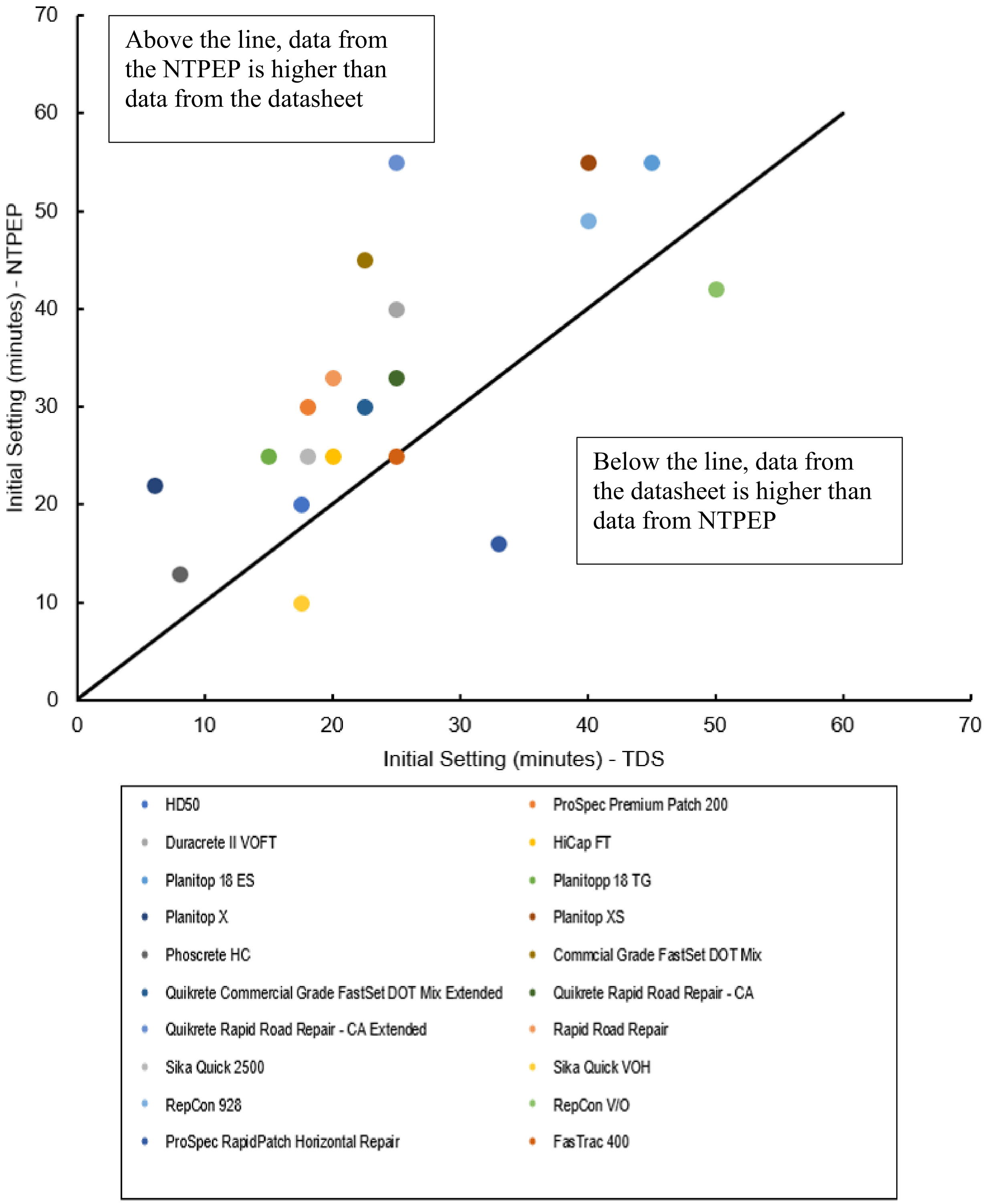


Figure Chapter 3.5 Comparison of the initial setting data on the NTPEP and the material datasheet

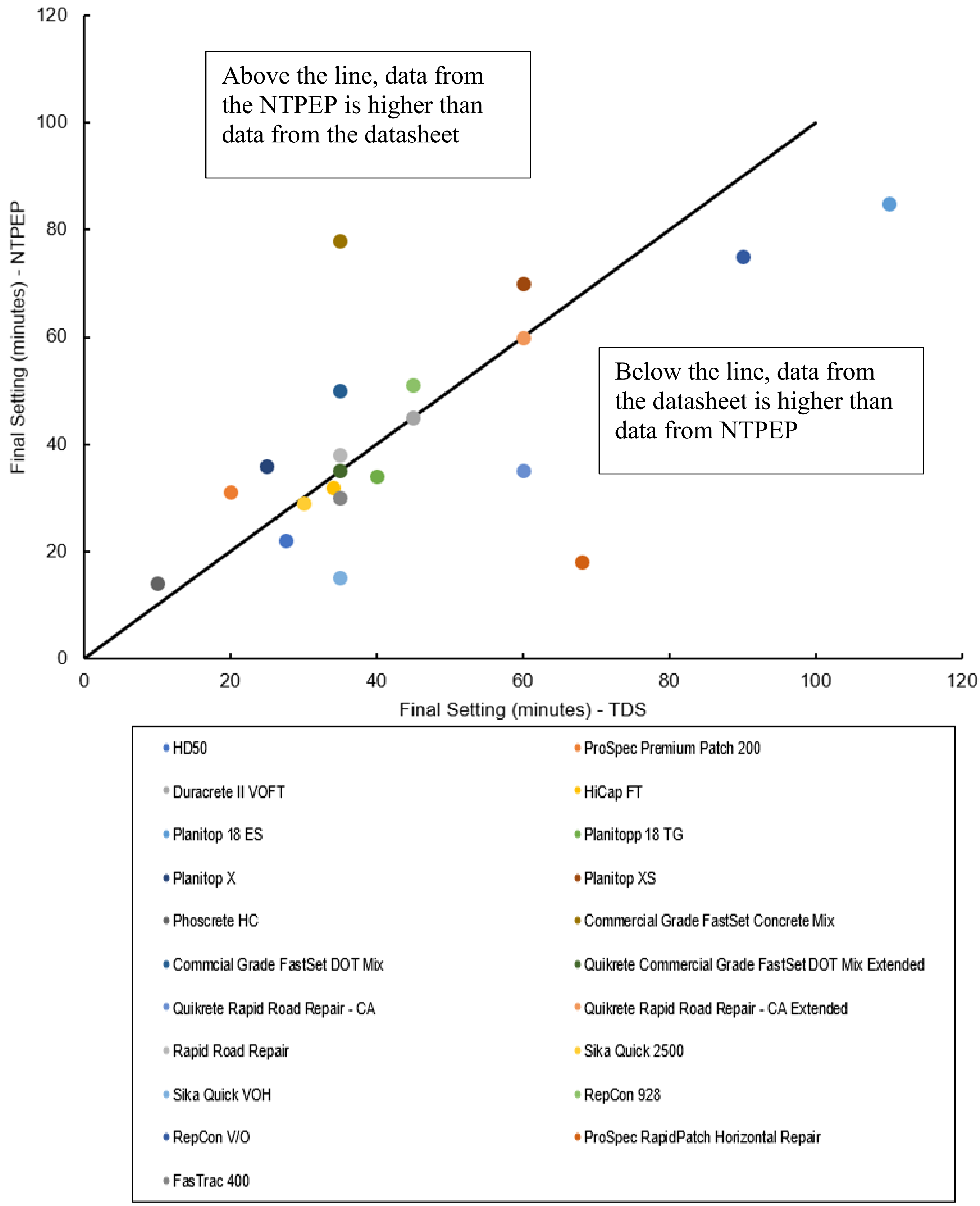


Figure Chapter 3.6 Comparison of the final setting data on the NTPEP and the material datasheet

3.3 Analysis of the Flexural Behavior of Repaired Structures Utilizing HES Materials

To better understand the influence of the depth and width of repair when using HES materials on the flexural behavior of structural members, a moment-curvature analysis was performed on a T-beam that has been repaired using a cement-based or polymer-based HES repair material. Figure Chapter **3.7** shows the cross-section of the investigated beam, and Table Chapter **3.3** presents all the investigated cases where b_f and t_f stand for the width and depth of the flange of the analyzed t-beam, respectively. The analysis only accounted for the tension reinforcement shown in Figure Chapter **3.7**. The compressive strength of the concrete, cement-based, and polymer-based HES repair materials used in the analysis were 4000 psi and 10,000 psi, and 6000 psi, respectively. The HES cement-based material strength represented a high-end strength from the available data sheets. The polymer-based material represented a typical strength from the available datasheet. These values were selected for discussion purposes.

For the layer analysis, the beam was divided into 0.25 inches layers across its depth, as shown in Figure Chapter **3.8**. First, equilibrium was enforced through an iterative procedure where the neutral axis depth (c) was estimated from an assumption of top fiber strain and the corresponding curvature. From this, the corresponding strain, stress, force, and moment of each layer were calculated after equilibrium was satisfied.

The moment-curvature and moment-top-fiber-strain curves for the repaired T-beam using cement-based HES material are shown in Figure Chapter **3.9**-a through Figure Chapter **3.9**. Figure Chapter **3.9**-e through Figure Chapter **3.9**-g illustrate the same moment (139 kip.ft) and the stress distribution in the post-cracking elastic range. This load was arbitrarily selected as it represents a service, load, and the relative stress changes in this preliminary investigation would hold at lower loads. Therefore, only the cases where the repair material is installed on 75% of the flange width and having a depth equal to 25%, 50%, and 75% of the flange thickness are shown in Figure Chapter **3.9** and compared with the case where no repair is installed. The rest of the investigated cases can be found in Appendix B.

The results show that installing a cement-based HES that will typically have a higher strength than the substrate concrete will result in a slight percent increase in the beam's flexural capacity, which is proportional to the depth of the installed repair. As the repair depth increases, a higher strength gain is expected. However, similar strength gain is obtained when the depth of the installed repair is 50% and 75% of the flange depth. The stress distribution curves shown in Figure Chapter **3.9**-e through Figure Chapter **3.9**-g show that at the same amount of load, the stresses developed in the installed HES material are much higher than those developed in the substrate concrete. The stresses developed in the repaired beam were compared with those in the original, fully intact beam. The results show how the installation of HES repair material attracts more stress which may explain the early deterioration of many HES materials. In general, these results are as expected and are shown for context.

The behavior of polymer-based HES materials was also investigated through a sectional analysis, and the results are presented in Figure Chapter **3.10**. The installation of polymer-based repair materials reduced the flexural capacity of the repaired T-beam by 14% for a repair having a depth of 75% of the flange thickness. This reduction is due to polymer-based repair materials' low modulus of elasticity compared to cementitious repair materials. The stress distribution curves of the repaired beam with polymer-based material in Figure Chapter **3.10**-e through Figure Chapter **3.10**-g show that the stresses in the polymer-based repair material and the substrate concrete do not match for the same amount of load. The stresses developed in the repair material are much lower than the remaining concrete. Comparing the stresses developed in the repaired beam with that case on an unrepaired beam show that the stresses in the substrate concrete with a polymer-based repair are higher than the stresses in concrete in its undamaged state. This increase indicates that when the concrete is repaired with polymer-based material, it will shift more stresses to the substrate concrete, which may already be at some level of stress, leading to more deterioration of the substrate concrete and higher interfacial shear stresses between the repair and substrate.

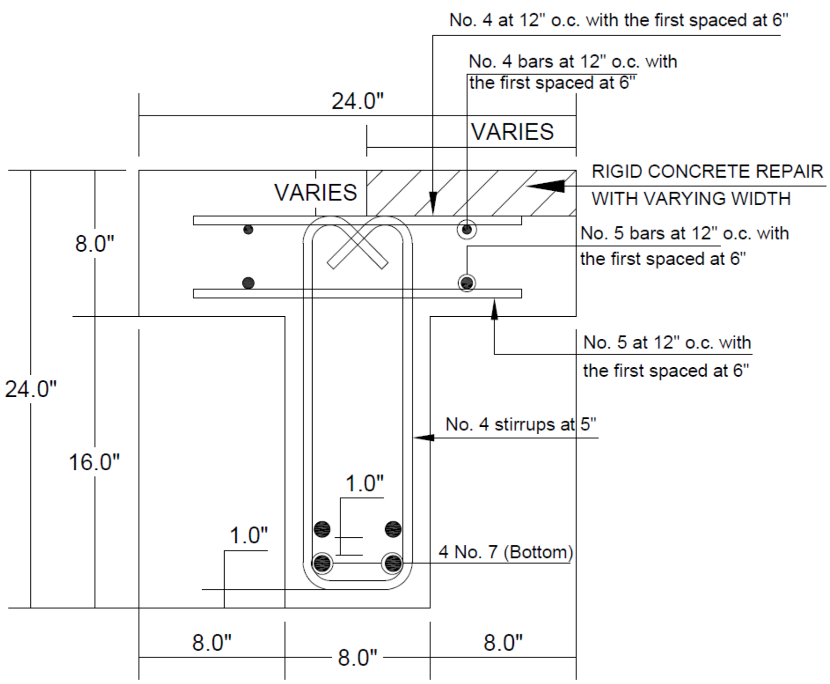


Figure Chapter 3.7 Cross-section of the T-beam used in the moment-curvature analysis

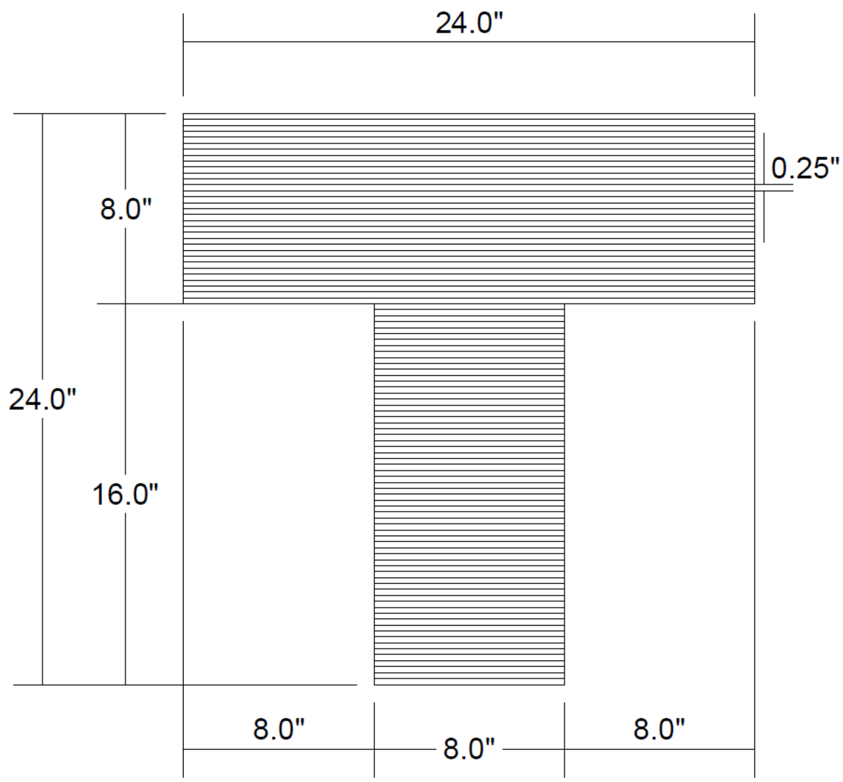


Figure Chapter 3.8 Layers of the analyzed T-beam

Table Chapter 3.3 A summary of the cases investigated in the moment-curvature analysis

Case Number	**Width of Repair (%b_f)**	**Depth of Repair (%t_f)**
1	0	0
2	25	25
3	25	50
4	25	75
5	50	25
6	50	50
7	50	75
8	75	25
9	75	50
10	75	75

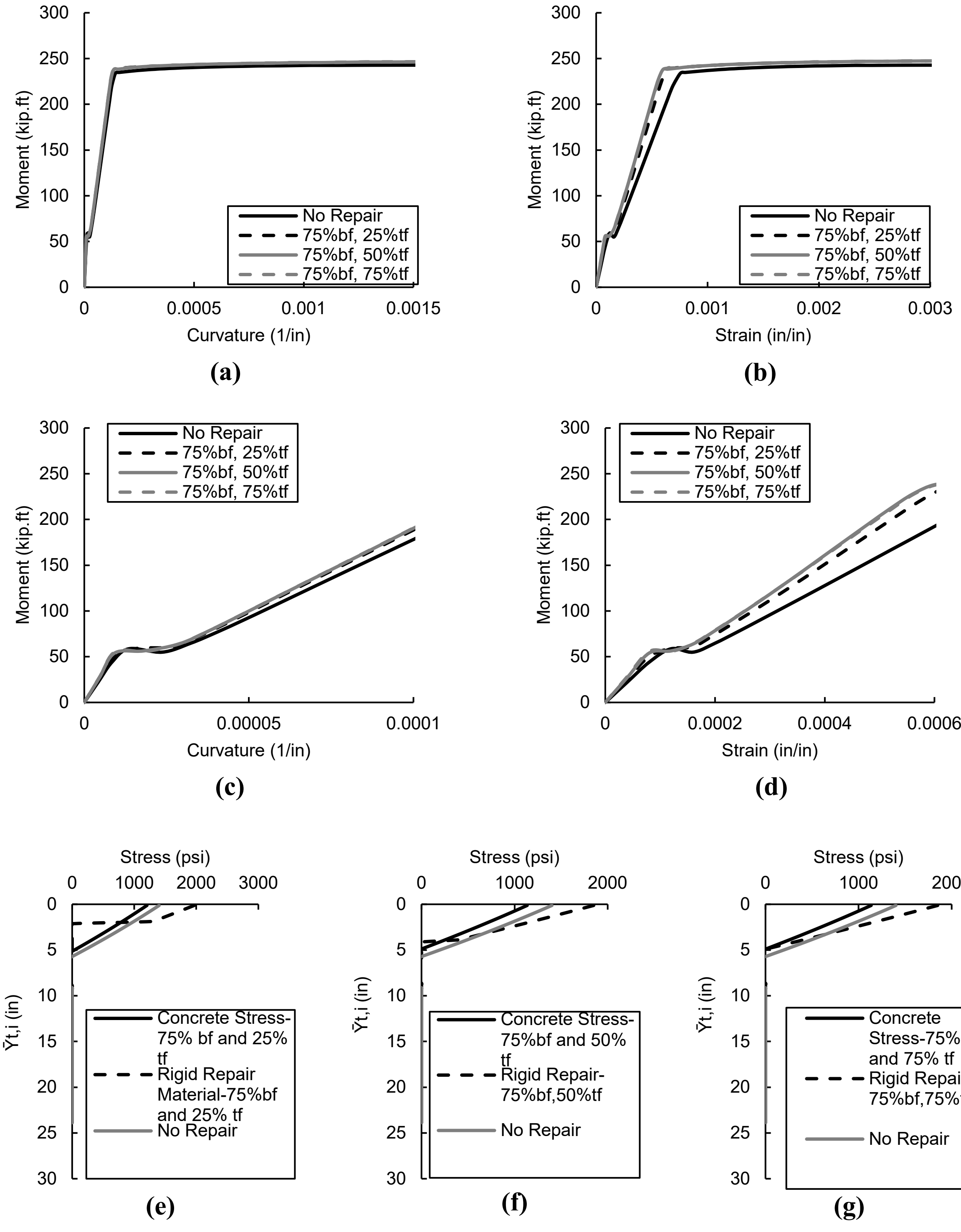


Figure Chapter 3.9 Effects of cement-based rigid repair materials on the flexural strength of a T-beam a)Complete moment-curvature curve and; b) moment-strain curve of a rigid repair material; c)elastic part of the moment-curvature curve; d)elastic part of the moment-strain curve; stress distribution in the concrete and the rigid repair material having a width equal to 75% of the width of the flange and e)25%; f)50%; and g)75% of the flange thickness

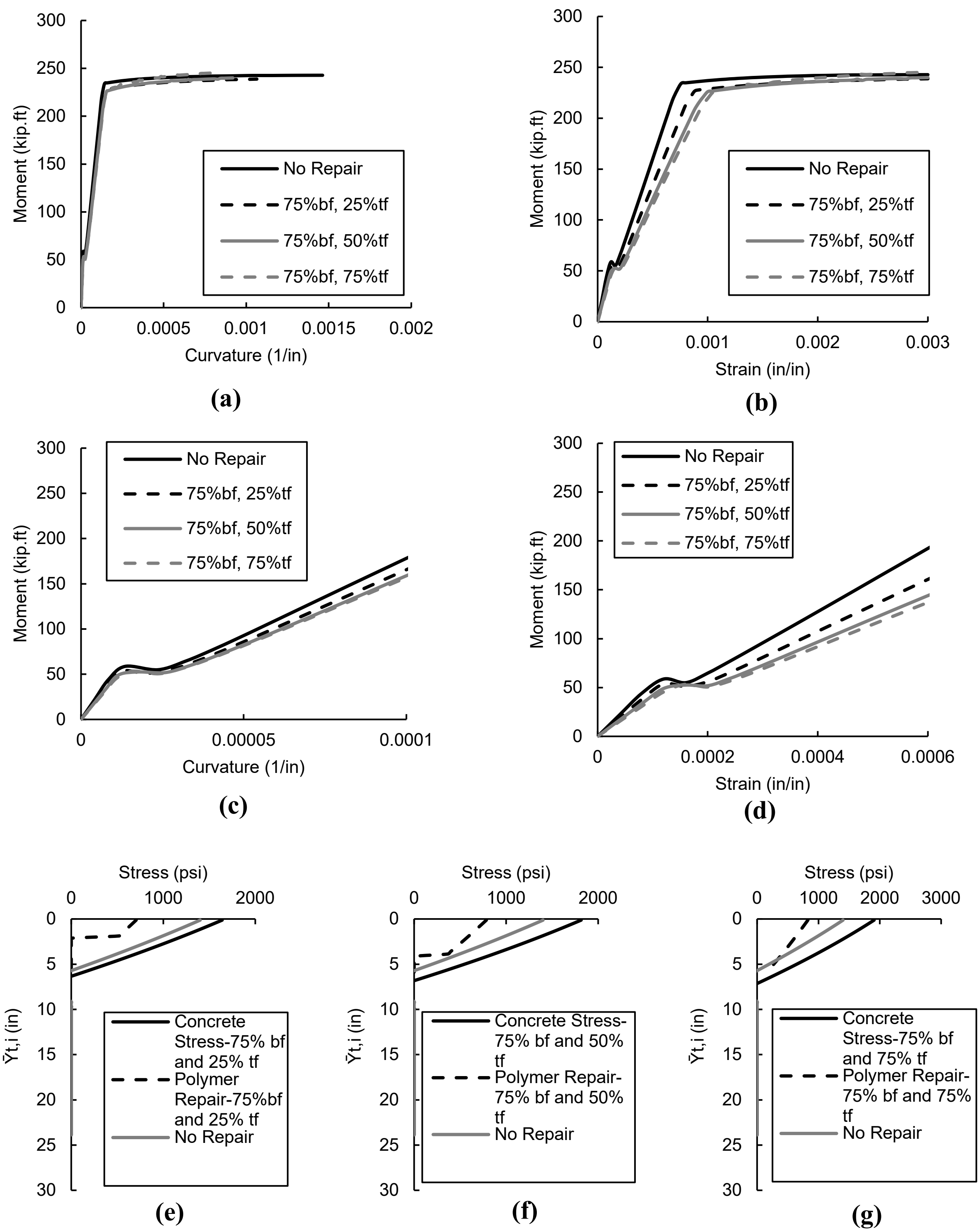


Figure Chapter 3.10 Effects of polymer repair materials on the flexural strength of a T-beam a)Complete moment-curvature curve and; b) moment-strain curve of a polymer repair material; c)elastic part of the moment-curvature curve; d)elastic part of the moment-strain curve; stress distribution in the concrete and the polymer repair material having a width equal to 75% of the width of the flange and e)25%; f)50%; and g)75% of the flange thickness

3.4 MnRoad Field Data Analysis

One of the few field studies found in the literature investigating the field performance of HES materials is research by Burnham et al. (Burnham et al., 2016) that investigated the field performance of 93 partial depth joint repairs for concrete pavement installed in 1993. Twenty-two HES materials were investigated in this study, and the performance of each material was evaluated over a period of three years. In this study, the authors introduced a six-point qualitative condition rating system that is shown in Table Chapter **3.4**. This system is based on visual observations made over the evaluation period. Since the evaluation of HES materials performance was solely qualitative, an attempt was made to analyze the collected field data and investigate potential relationships between the field data and the experimental data of different material properties.

Table Chapter 3.4 The condition rating system developed by MnDOT (Burnham et al., 2016)

Rating	Condition of patch material (visual observation)
5	Excellent condition, no random cracking
4	Very good condition, with a small number of tight random cracks
3	Good condition, with some random cracks, and limited material missing
2	Fair condition, with multiple wide random cracks, and some material missing
1	Poor condition, with substantial material missing, and some areas refilled
0	Failed patch, patch completely refilled

Experimental data for each HES material used was collected from either the NTPEP database or the product datasheet in case the material is not tested by NTPEP. Based on the condition rating given for each patch, the degradation rate of each material represented by the slope of the curve of the condition rating data and the age of repair was calculated. The rate of degradation data was then plotted against the one-hour, 3-hour, and 28-day compressive strength in addition to length change (shrinkage data). The results are shown in Figure Chapter **3.11** through Figure Chapter **3.15**, and show a weak correlation between the degradation rate and the early and 28-day compressive strength ($R^2_{1\ hour}$=0.1134, $R^2_{3\ hours}$=0.1157, $R^2_{28\text{-}days}$= 0.0416). The shrinkage data plotted against the rate of degradation show a low correlation between the length change data in air and the rate of degradation (R^2=0.3035). However, the length change in water data shows a possible relationship with the rate of degradation with a correlation coefficient (R^2) of 0.7211, but this seems to be heavily influenced by two points that dominate the R^2 weighting. The two materials, Akona NRRI and Akona NRRI with Taconite, seemed to affect the data disproportionately and strongly influenced the regression lines and R^2 values. The obtained results show that the relationship between the rate of degradation with different material properties is highly sensitive to the collected field data and the qualitative judgment of the evaluator on the repair condition.

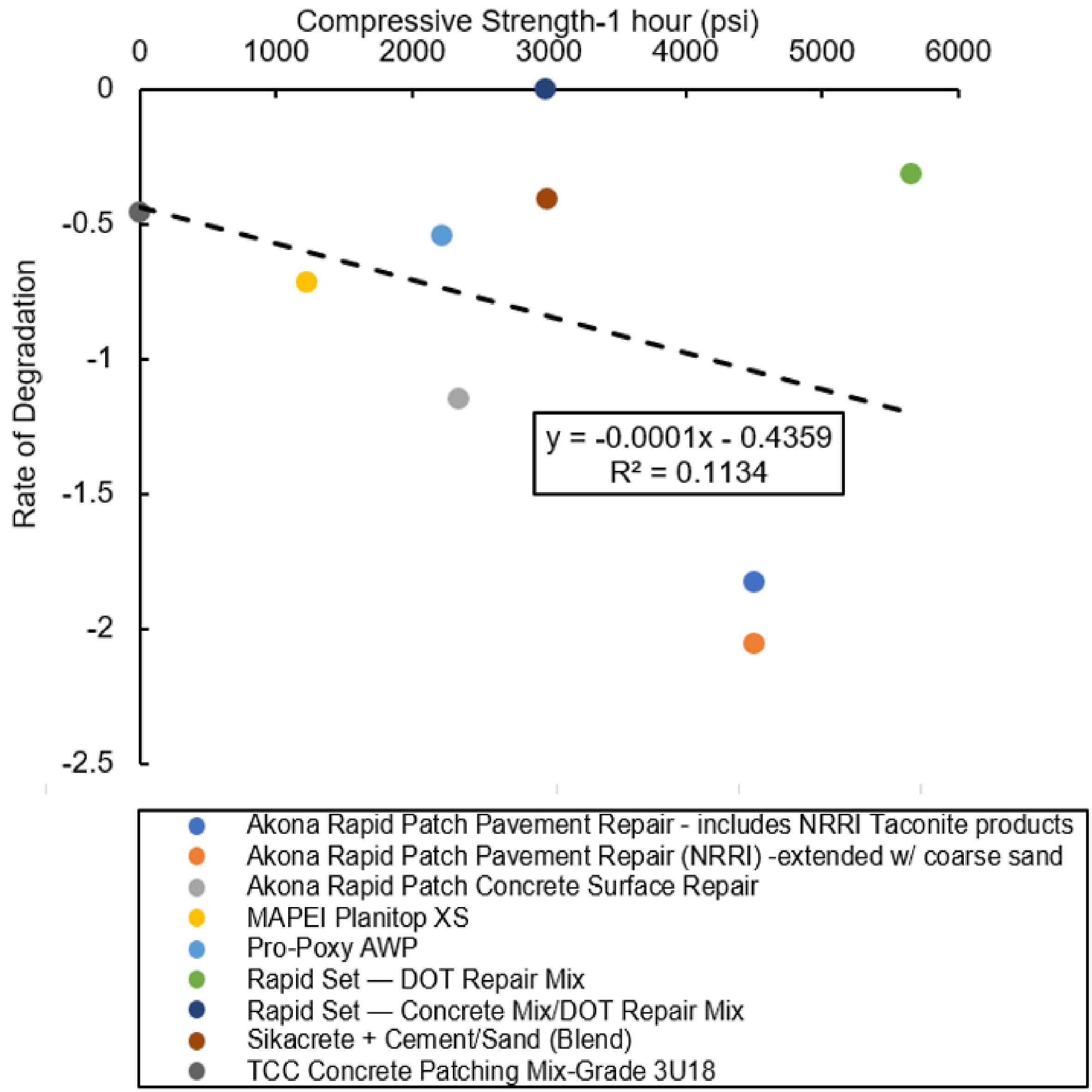


Figure Chapter 3.11 Early Compressive strength (1 hour) vs. the rate of degradation of field data collected by (Burnham et al., 2016)

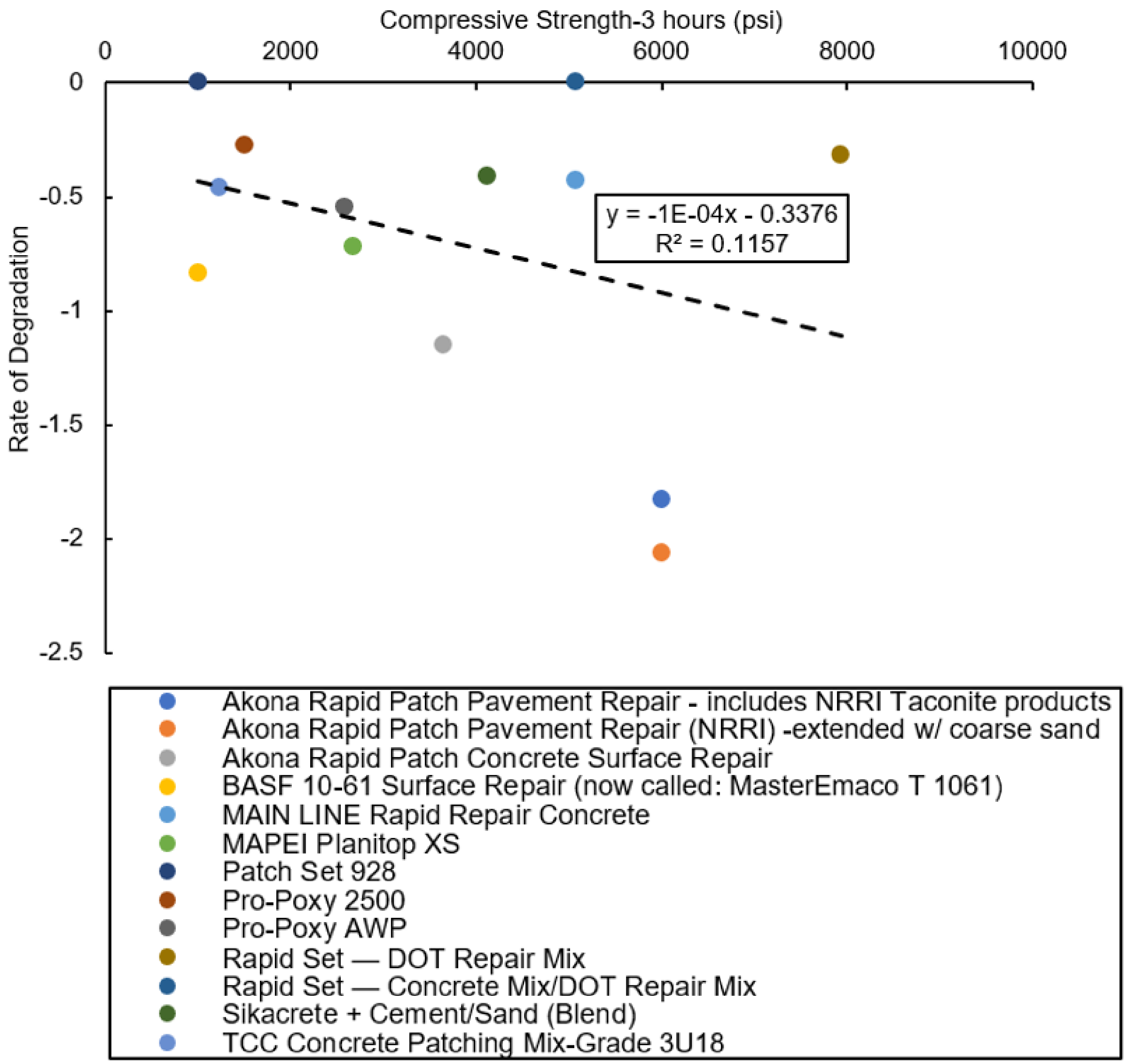


Figure Chapter 3.12 Early Compressive strength (3 hours) vs. the rate of degradation of field data collected by (Burnham et al., 2016)

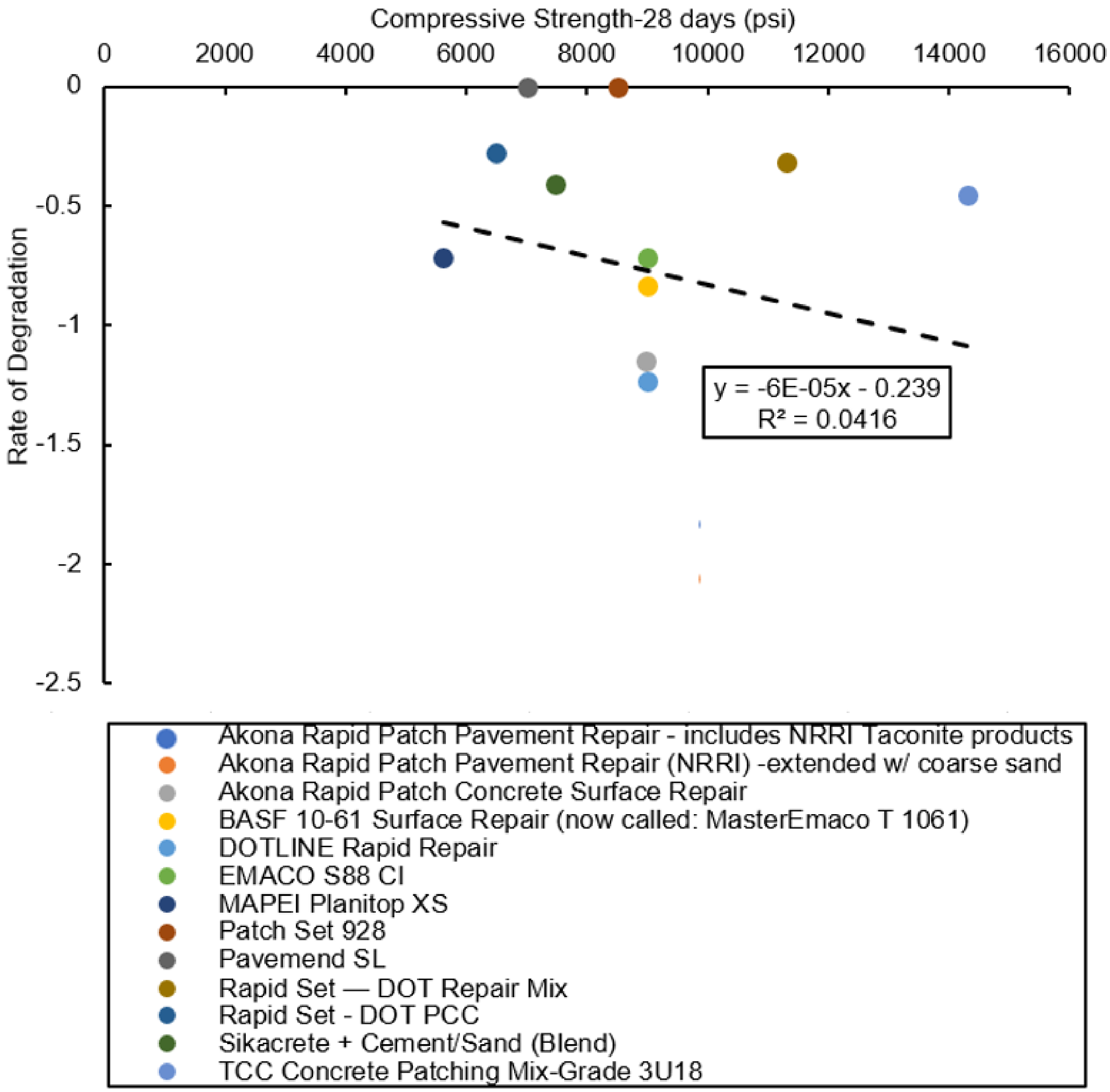


Figure Chapter 3.13 Compressive strength (28 days) vs. the rate of degradation of field data collected by (Burnham et al., 2016)

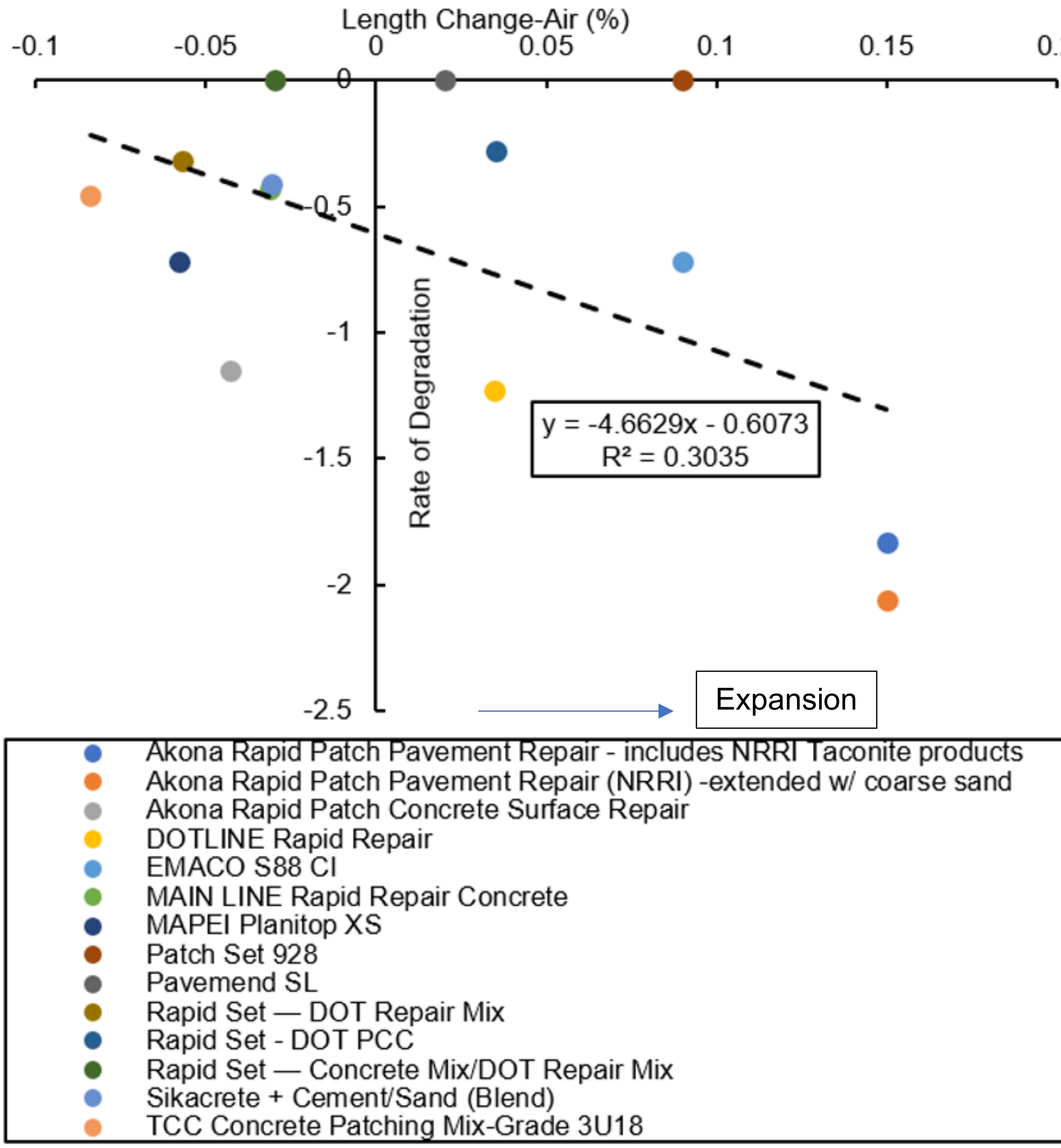


Figure Chapter 3.14 Length change in air vs. the rate of degradation of field data collected by (Burnham et al., 2016)

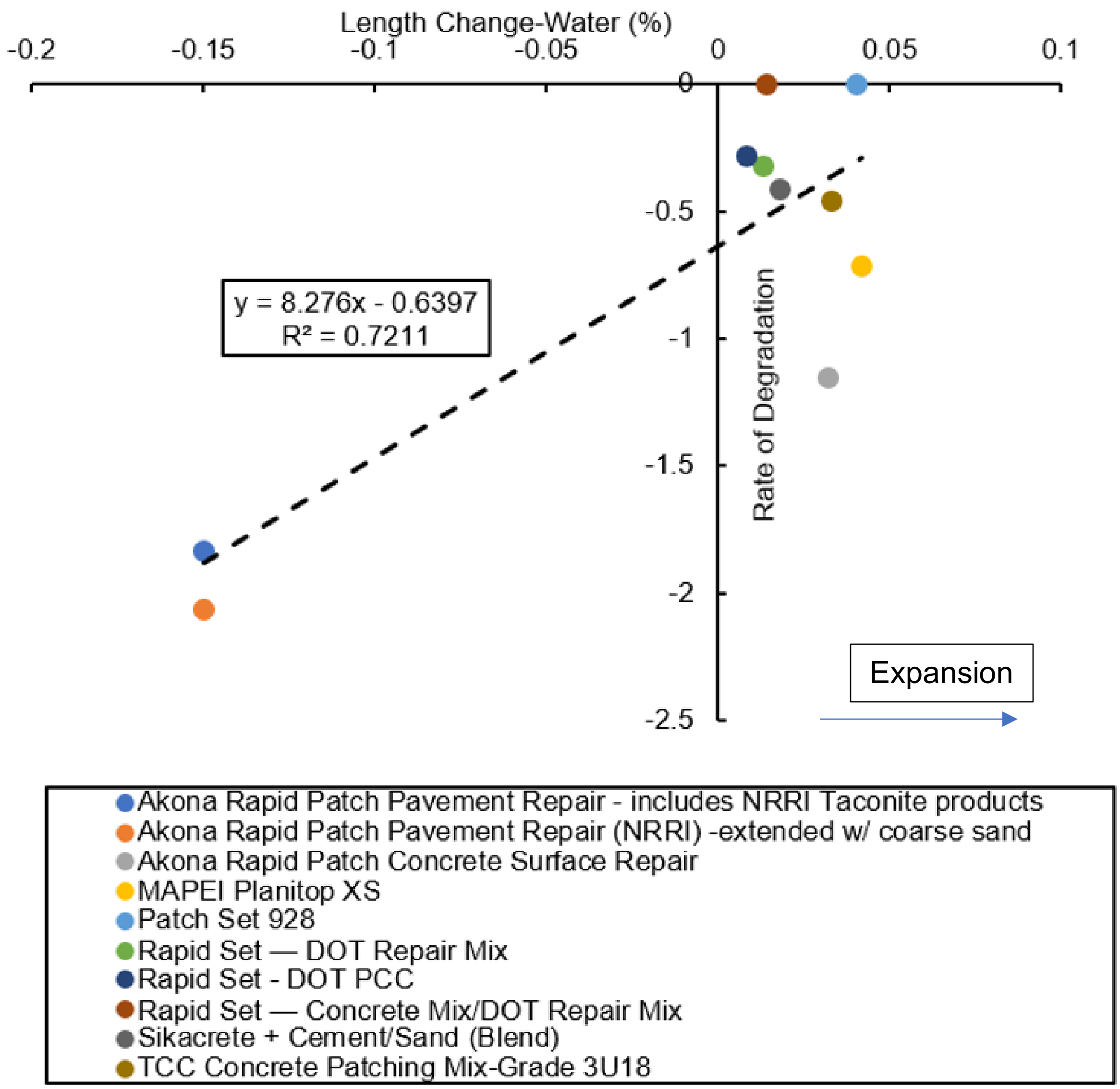


Figure Chapter 3.15 Length change in water vs. the rate of degradation of field data collected by (Burnham et al., 2016)

Chapter 4 Field Inspection

4.1 Introduction

Field inspections in multiple locations in districts one, two, and four were performed in the summer and fall of 2022. These districts contain the vast majority of instances of prebagged rapid-set, HES repair materials in Nebraska. A total of 24 bridges were visited in the three districts to assess the performance of multiple rapid-setting repair materials installed in each location. The performance of each repair material was evaluated using a six-point condition rating system that was introduced by a previous study published by the Minnesota Department of Transportation (Burnham et al., 2016). In addition, the number of cracks and the crack length of each repair were approximated. The collected field data were then plotted against different experimental data for multiple mechanical properties reported in the datasheet of each material, in addition to experimental data for the used repair materials provided by the National Transportation Product Evaluation Program (AASHTO, 2023).

4.2 NDOT Districts

The state of Nebraska is divided into eight districts by the NDOT. Each district has its own office and engineers responsible for performing maintenance and construction. Figure Chapter **4.1** shows the map of Nebraska and the borders of each district.

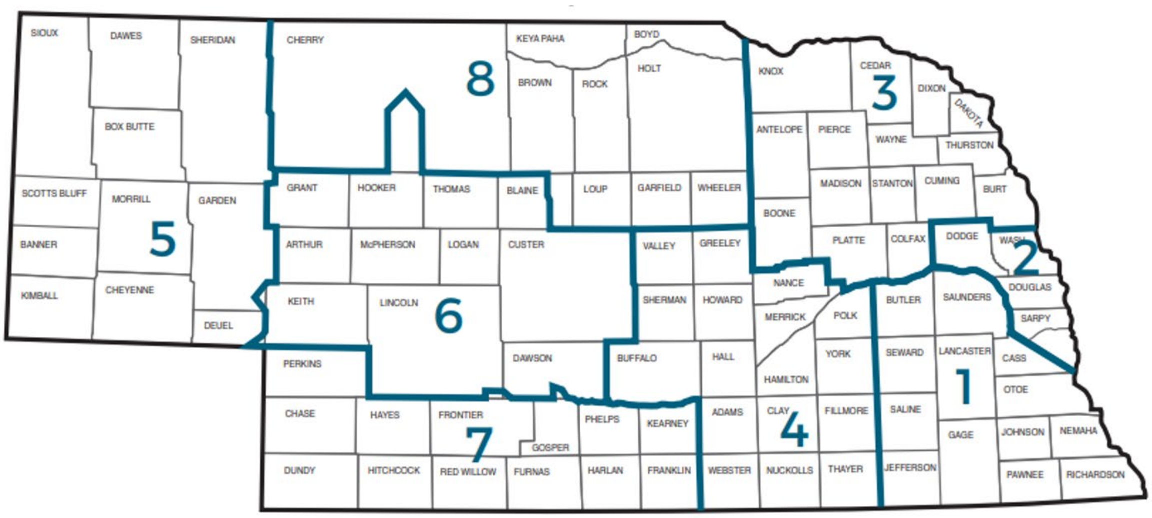


Figure Chapter 4.1 The distribution of districts in Nebraska state (NDOT, 2023)

<u>4.3 HES Materials Used in Inspected Districts</u>

4.3.1 District One

Three HES repair materials were primarily used in district one. The district switched to using Phoscrete HC rapid repair material in 2021. Before that, two repair materials manufactured by Master Builders Solutions were the primary rapid repair materials used in district one. All the repair materials used in district one are summarized in Table Chapter **4.1**

Table Chapter 4.1 Summary of the rapid-setting repair materials used in district one

Product Number	Product Name	Listed in NTPEP?	Product Description	Manufacturer
1	MasterEmaco T 545	No	Magnesium phosphate-based mortar	Master Builders Solutions
2	Phoscrete HC	Yes	Fiber-reinforced cementitious material	Phoscrete Corporation
3	MasterEmaco T 1060	No	Cement-based mortar	Master Builders Solutions

4.3.2 District Two

District two utilizes only two HES repair concrete products in the maintenance projects allocated in the district. These products are PPC 1121 polyester polymer concrete (often referred to as "Kwik Bond", which is its manufacturer) and Phoscrete HC. Note that reportedly the use of Kwik Bond is being phased out. Table Chapter **4.2** summarizes the repair materials used in District two.

Table Chapter 4.2 Summary of the rapid-setting repair materials used in district two

Product Number	Product Name	Listed in NTPEP?	Product Description	Manufacturer
1	PPC 1121 Polyester Polymer Concrete	No	Premixed polymer concrete	Kwik Bond Polymers
2	Phoscrete HC	Yes	fiber-reinforced cementitious material	Phoscrete Corporation

4.3.3 District Four

Multiple rapid-setting repair materials have been used in District four. These repair materials and all relevant information are summarized in Table Chapter **4.3**.

Table Chapter 4.3 Summary of the rapid-setting repair materials used in district four

Product Number	Product Name	Listed in NTPEP?	Product Description	Manufacturer
1	Commercial-grade FastSet repair mortar	Yes	Polymer modified	Quikrete Companies
2	Phoscrete HC	Yes	fiber-reinforced cementitious material	Phoscrete Corporation
3	FasTrac V/O Mortar	No	Polymer-modified, cement-based mortar	Western Material and Design
4	Sikacrete 321 FS	No	Portland cement concrete containing factory-blended coarse aggregate	Sika
5	Crete120	No	not found	not found
6	PPC 1121	No	Premixed polymer concrete	Kwik Bond Polymers
7	RepCon V/O	Yes	Polymer-modified, fiber-reinforced repair mortar	SpecChem

4.4 Field Inspection

4.4.1 Field Inspection Data

Field inspections were performed to assess the performance of the HES materials installed on several structures in districts one, two, and four. The structures inspected and all the relevant details related to each location are summarized in Table Chapter **4.4**, Table Chapter **4.5**, and Table Chapter **4.6**. In addition, photos were taken from each location to evaluate the current condition of each repair and to assess the performance of each rapid-setting repair material in service. General overview photos taken from each location can be found in the appendix of this report. Note that multiple materials were often used on a single structure, and several patches have even been repaired multiple times, sometimes with multiple materials.

Table Chapter 4.4 Summary of field inspection for structures in district one

Item	Structure Number	Repair material(s) used	Time of repair
1	508016	Phoscrete HC, MasterEmaco T 545	July 2022 (Phoscrete HC), 2017 (MasterEmaco T 545)
2	48048	MasterEmaco T 1060, Phoscrete HC, MasterEmaco T 545	2012 (MasterEmaco T 1060), 09/26/2022 (Phoscrete HC), 2017 (MasterEmaco T 545)
3	49665	Phoscrete HC, MasterEmaco T 1060, MasterEmaco T 545	09/27/22 (Phoscrete HC), not specified (MasterEmaco T 1060, MasterEmaco T 545)
4	49626	Phoscrete HC	10/11/2022
5	49047	Phoscrete HC	10/05/2022
6	05428	Phoscrete HC, MasterEmaco T 1060	04/05/2022 (Phoscrete HC), 2017 (MasterEmaco T 1060)
7	35911	Phoscrete HC	07/11/2022

Table Chapter 4.5 Summary of field inspection for structures in district two

Item	Structure Number	Repair material(s) used	Time of repair
1	44606	Mastic, PPC 1121, undefined black material	2019
2	44207 Westbound	PPC 1121	2020 or 2019
3	44207 East Bound	PPC 1121, hot mix	2021 (PPC 1121), hot mix (2022)
4	43922	47B-PR	Summer, 2021
5	44207	PPC 1121, hot mix	May 2021 (PPC 1121), July 2022 (Hot mix)
6	00604	PPC 1121, cold mix	2018 or 2017 (PPC 1121), 2019 (cold mix and second repair using PPC 1121)

Item	Structure Number	Repair material(s) used	Time of repair
7	S080-44572	PPC 1121, Phoscrete HC	2020 (PPC 1121), 2021 (Phoscrete HC)
8	Highway 50-8762	Phoscrete HC	May, 2022
9	S050-08894	47B-PR, PPC 1121, hot mix	2020 (47B-PR), 2019 (PPC 1121)

Table Chapter 4.6 Summary of field inspection for structures in district four

Item	Structure Number	Repair material used	Time of repair
1	0578	Commercial-grade FastSet repair mortar	Started in 2020 and finished in 2021
2	09667	Phoscrete HC and cold-patch.	2022
3	Rockville Ravenna North Highway 68	FastTrac VO	2020
4	Gibbon link bridge over Highway 30	FasTrac VO	Oct,2021
5	31263	Sikacrete 321 FS	2021
6	32815	Crete 120	2019
7	I-80 bridge Deck Aurora E&W	PPC 1121	Fall 2020
8	34413	RepCon V/O	Summer 2021

4.4.2 Condition Rating of the Installed HES Materials

The current state of the installed repair materials at each location was evaluated based on a six-point qualitative condition rating system developed by MnDOT (Burnham et al., 2016). The condition rating system used is shown in Table Chapter **4.7**.

Table Chapter 4.7 The condition rating system developed by MnDOT (Burnham et al., 2016).

Rating	Condition of patch material (visual observation)
5	Excellent condition, no random cracking
4	Very good condition, with a small number of tight random cracks
3	Good condition, with some random cracks, and limited material missing
2	Fair condition, multiple wide random cracks, some material missing
1	Poor condition, substantial material missing, some areas refilled
0	Failed patch, patch completely refilled

4.4.3 Condition Rating in District One

Table Chapter 4.8 Condition rating for the installed repair materials in District one inspected in November, 2022

Item	Structure Number	Material	Time of Repair	Condition Rating	Approximate Repair Area (ft^2)	Average Crack Length (in.)	The current condition of the installed repair materials
1	508016	Phoscrete HC	July 2022	5	42	-	
		Master Emaco T 545	2017	2	1.5	8	

Table 4.8 (continued) Condition rating for the installed repair materials in District one inspected in November, 2022

Item	Structure Number	Material	Time of Repair	Condition Rating	Approximate Repair Area (ft^2)	Average Crack Length (in.)	The current condition of the installed repair materials
2	48048	Master Emaco T 1060	2012	3	2	12	
		Phoscrete HC	09/26/2022	5	2.7	-	

Table 4.8 (continued) Condition rating for the installed repair materials in District one inspected in November, 2022

Item	Structure Number	Material	Time of Repair	Condition Rating	Approximate Repair Area (ft^2)	Average Crack Length (in.)	The current condition of the installed repair materials
2	48048	Master Emaco T 545	2017	2	5.83	14.2	

Table 4.8 (continued) Condition rating for the installed repair materials in District one inspected in November, 2022

Item	Structure Number	Material	Time of Repair	Condition Rating	Approximate Repair Area (ft^2)	Average Crack Length (in.)	The current condition of the installed repair materials
3	49665	Phoscrete HC	09/27/2022	3	21	12	
		Master Emaco T 1060	-	5	2.6	-	

Table 4.8 (continued) Condition rating for the installed repair materials in District one inspected in November, 2022

Item	Structure Number	Material	Time of Repair	Condition Rating	Approximate Repair Area (ft^2)	Average Crack Length (in.)	The current condition of the installed repair materials
3	49665	Master Emaco T 545	-	2	9.17	29	
4	49626	Phoscrete HC	10/11/2022	5	7	7	

Table 4.8 (continued) Condition rating for the installed repair materials in District one inspected in November, 2022

Item	Structure Number	Material	Time of Repair	Condition Rating	Approximate Repair Area (ft^2)	Average Crack Length (in.)	The current condition of the installed repair materials
5	49047	Phoscrete HC	10/05/2022	1	14.2	17	
6	05428	Master Emaco T 1060	2017	3	42.5	30	

Table 4.8 (continued) Condition rating for the installed repair materials in District one inspected in November, 2022

Item	Structure Number	Material	Time of Repair	Condition Rating	Approximate Repair Area (ft^2)	Average Crack Length (in.)	The current condition of the installed repair materials
7	35911	Phoscrete HC	07/11/2022	4	4.4	-	

4.4.4 Condition Rating in District Two

Table Chapter 4.9 Condition rating for the installed repair materials in District two inspected in June, 2022

Item	Structure Number	Material	Time of Repair	Condition Rating	Approximate Repair Area (ft^2)	Average Crack Length (in.)	The current condition of the installed repair materials
1	44606	PPC 1121	2019	1	7.5	7.227	
		Undefined black material, Mastic	2019	1	7		

Table 4.9 (continued) Condition rating for the installed repair materials in District two inspected in June, 2022

Item	Structure Number	Material	Time of Repair	Condition Rating	Approximate Repair Area (ft^2)	Average Crack Length (in.)	The current condition of the installed repair materials
2	44207 Westbound	PPC 1121	2020 or 2019	2	48	7	
3	44207 East Bound	Hot mix and PPC 1121 (The hot mix seems to be placed on top of PPC 1121)	2021 (PPC 1121) 2022 (Hot mix)	1	144	7.393	

Table 4.9 (continued) Condition rating for the installed repair materials in District two inspected in June, 2022

Item	Structure Number	Material	Time of Repair	Condition Rating	Approximate Repair Area (ft^2)	Average Crack Length (in.)	The Current condition of the installed repair materials
3	44207 East Bound	PPC 1121	2021	2	4	7.393	
4	43922	47B-PR	Summer, 2021	3	36	3.8	

Table 4.9 (continued) Condition rating for the installed repair materials in District two inspected in June, 2022

Item	Structure Number	Material	Time of Repair	Condition Rating	Approximate Repair Area (ft^2)	Average Crack Length (in.)	The Current condition of the installed repair materials
4	43922	47B-PR	Summer, 2021	4	50	3.8	
5	44207	PPC 1121 and hot mix	May 2021 (PPC 1121), July, 2022 (Hot mix)	1	74	5.31	

Table 4.9 (continued) Condition rating for the installed repair materials in District two inspected in June, 2022

Item	**Structure Number**	**Material**	**Time of Repair**	**Condition Rating**	**Approximate Repair Area (ft^2)**	**Average Crack Length (in.)**	**The Current condition of the installed repair materials**
5	44207	PPC 1121 and hot mix	May 2021 (PPC 1121), July, 2022 (Hot mix)	1	148	5.31	
6	00604	PPC 1121, cold mix	2018 or 2017 (PPC 1121), 2019 (cold mix and second repair using PPC 1121)	1	17.5	6.9	

Table 4.9 (continued) Condition rating for the installed repair materials in District two inspected in June, 2022

Item	Structure Number	Material	Time of Repair	Condition Rating	Approximate Repair Area (ft^2)	Average Crack Length (in.)	The Current condition of the installed repair materials
6	00604	PPC 1121, cold mix	2018 or 2017 (PPC 1121), 2019 (cold mix and second repair using PPC 1121)	1	24.5	6.9	
7	S080-44572	PPC 1121	2020	4	24	7	

Table 4.9 (continued) Condition rating for the installed repair materials in District two inspected in June, 2022

Item	Structure Number	Material	Time of Repair	Condition Rating	Approximate Repair Area (ft^2)	Average Crack Length (in.)	The Current condition of the installed repair materials
7	S080-44572	Phoscrete HC	2021	4	5	7	
8	Highway 50-8762	Phoscrete HC	May, 2022	3	12	4.9	

Table 4.9 (continued) Condition rating for the installed repair materials in District two inspected in June, 2022

Item	Structure Number	Material	Time of Repair	Condition Rating	Approximate Repair Area (ft^2)	Average Crack Length (in.)	The Current condition of the installed repair materials
9	S050-08894	47B-PR	2020	3	216	5.4	
	S050-08894	PPC 1121, hot mix	2019	1	24	5.4	

4.4.5 Condition Rating in District Four

Table Chapter 4.10 Condition rating for the installed repair materials in District four inspected in July, 2022

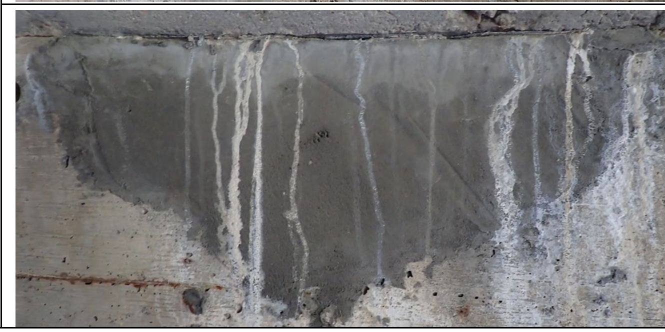
Item	**Structure Number**	**Material**	**Time of Repair**	**Condition Rating**	**Approximate Repair Area (ft^2)**	**Average Crack Length (in.)**	**The Current condition of the installed repair materials**
1	0578	Commercial -grade FastSet repair mortar	Started in 2020, and finished in 2021	4	6	8.4	
		Commercial -grade FastSet repair mortar	Started in 2020, and finished in 2021	4	3		

Table 4.10 (continued) Condition rating for the installed repair materials in District four inspected in July, 2022

Item	Structure Number	Material	Time of Repair	Condition Rating	Approximate Repair Area (ft^2)	Average Crack Length (in.)	The Current condition of the installed repair materials
2	09667	Phoscrete HC and cold-patch.	2022	2	6[a]	7.8	
3	Rockville Ravenna North Highway 68	FastTrac VO	2020	4	45[b]	8.2	

Table 4.10 (continued) Condition rating for the installed repair materials in District four inspected in July, 2022

Item	Structure Number	Material	Time of Repair	Condition Rating	Approximate Repair Area (ft^2)	Average Crack Length (in.)	The Current condition of the installed repair materials
3	Rockville Ravenna North Highway 68	FastTrac VO	2020	4	15	8.2	
4	Gibbon link bridge over Highway 30	FasTrac VO	Oct,2021	4	NC	13.5	

Table 4.10 (continued) Condition rating for the installed repair materials in District four inspected in July, 2022

Item	Structure Number	Material	Time of Repair	Condition Rating	Approximate Repair Area (ft^2)	Average Crack Length (in.)	The Current condition of the installed repair materials
5	31263	Sikacrete 321 FS	2021	4	NC	NC	
6	32815	Crete 120	2019	2	147	18.2	

Table 4.10 (continued) Condition rating for the installed repair materials in District four inspected in July, 2022

Item	Structure Number	Material	Time of Repair	Condition Rating	Approximate Repair Area (ft^2)	Average Crack Length (in.)	The Current condition of the installed repair materials
7	I-80 bridge Deck Aurora E&W	PPC 1121	Fall 2020	2	NC	11.75	

Table 4.10 (continued) Condition rating for the installed repair materials in District four inspected in July, 2022

Item	Structure Number	Material	Time of Repair	Condition Rating	Approximate Repair Area (ft^2)	Average Crack Length (in.)	The Current condition of the installed repair materials
8	34413	RepCon V/O	Summer 2021	4	10	NC	

[a] This value represents the area of the repair shown in the photo. Multiple circular-shaped repairs existed on the site with different sizes.
[b] This area represents the sum of the areas of three similar repairs along the side of the bridge.
c This value represents the approximate area of two repairs that existed on the site.
NC, the dimensions of the repair area are not clear.

4.5 Field Data Analysis

4.5.1 Setting Time and Compressive Strength of Repair Materials

To understand the performance of each material, data on different properties were tested and reported in the NTPEP database (AASHTO, 2023) for each repair material that was collected. Since some repair materials were not listed in the NTPEP database, their properties were obtained from the datasheet provided by the manufacturer of each material. For repair materials that have their properties tested and included on the NTPEP database and the manufacturer datasheet, the values of each property were compared between the two data sources. Figure Chapter **4.2** and Figure Chapter **4.3** show the data of two material properties that were tested and reported in both the NTPEP database and the datasheet of each repair material, namely, the setting time and the compressive strength. The data plotted on each of these figures indicate a variation between the data found in the NTPEP database and the data found in the datasheet of each repair material.

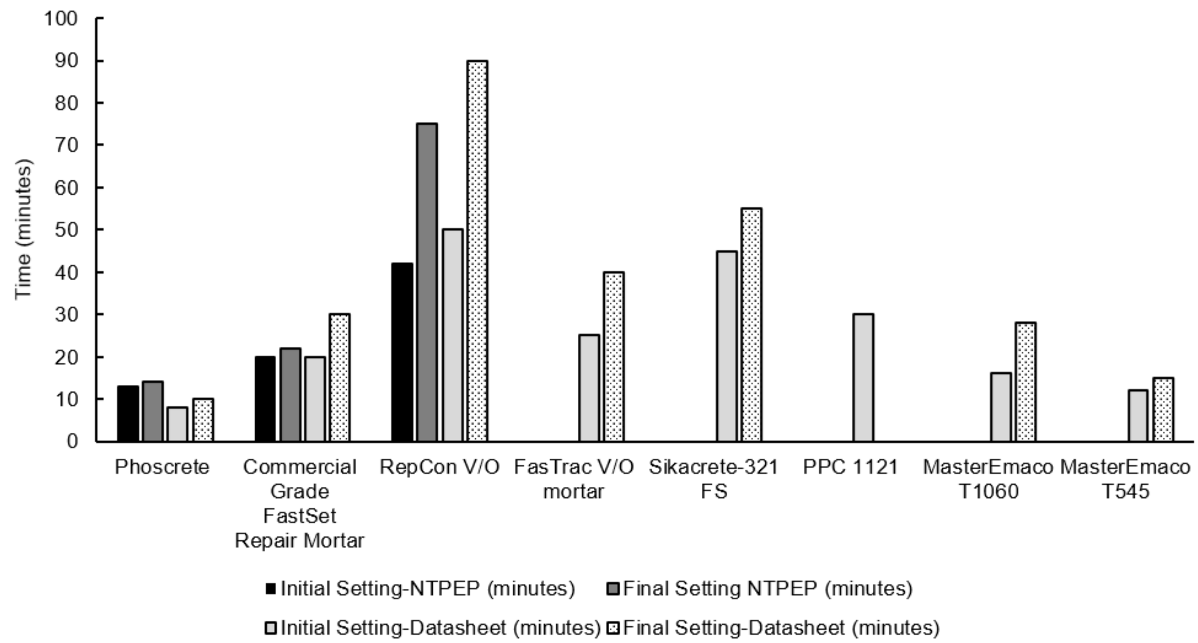


Figure Chapter 4.2 Setting time data of HES materials used in districts one, two, and four

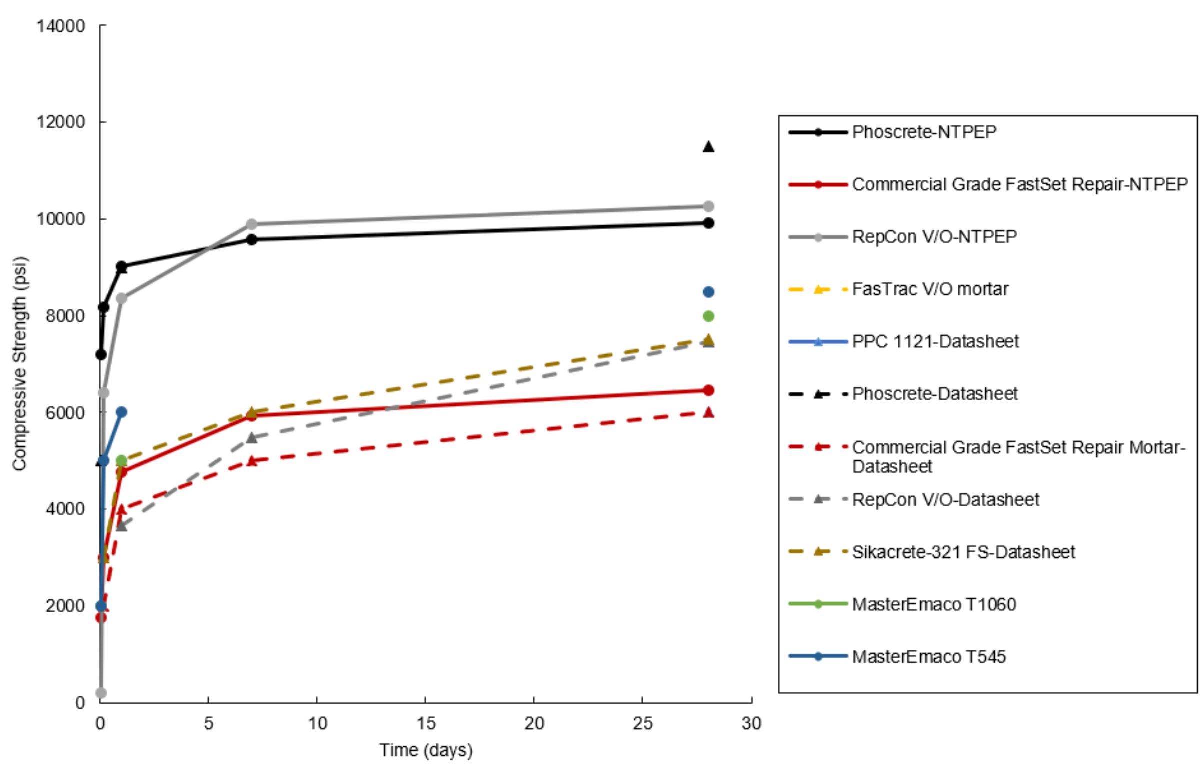


Figure Chapter 4.3 Compressive strength data of HES materials used in districts one, two, and four

4.5.2 Condition Rating and Rate of Degradation

A qualitative condition rating was assigned for each repair inspected in Districts one, two, and four, and the average condition rating for each repair material used in each district was calculated and is shown in Figure Chapter **4.4**. Note that this may not be a fair comparison because of the unequal numbers of repairs represented and the nonuniformity of the dataset. The results indicate that the highest condition rating was associated with locations that used Phoscrete HC, FastSet rapid mortar, FasTrac V/O, RepCon V/O, MasterEmaco T 1060, and Sikacrete 321 FS as repair materials. The repair material PPC 1121 had the lowest condition rating, which indicates that this repair material did not seem to perform as expected in the field. Based on the condition rating assigned for each repair inspected in the three districts, the rate of degradation was calculated, and the results are shown in Figure Chapter **4.5**. The highest rate of degradation was associated with the Phoscrete HC material, followed by PPC 1121. District one reported good conditions of current repairs that used Phoscrete HC; however, all of these repairs were installed a few months ago (less than one year) and cannot be solely used to conclude the field performance of this material.

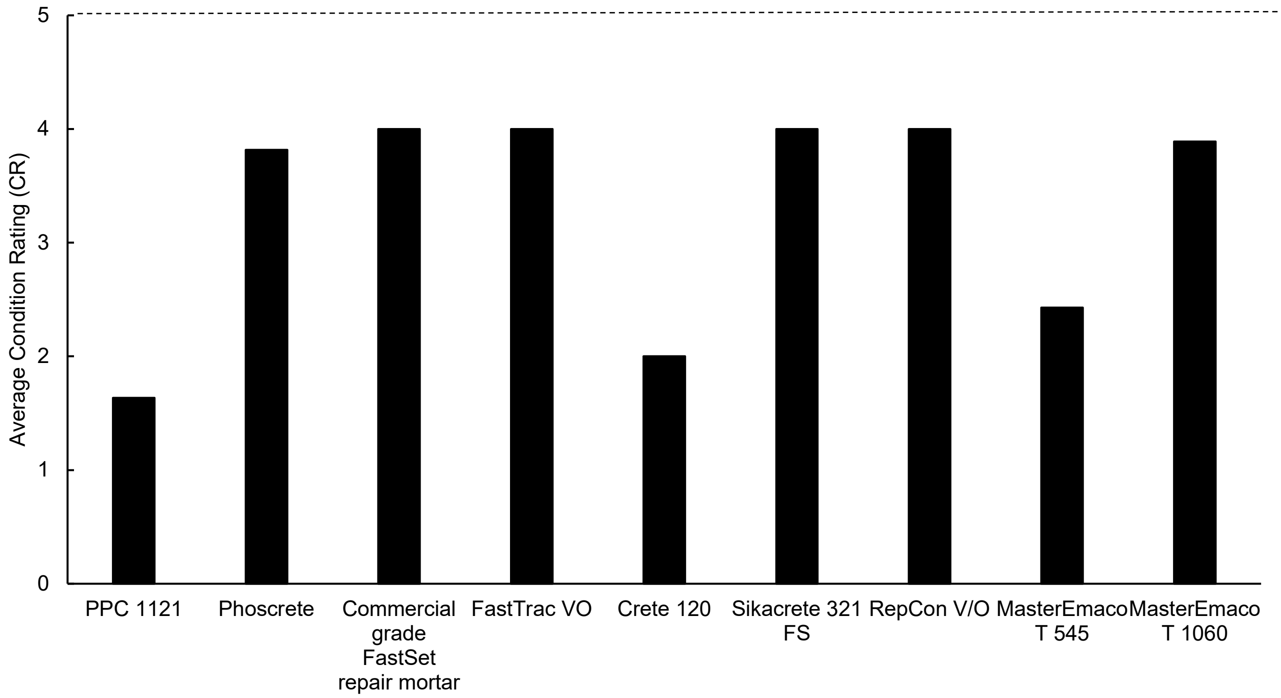


Figure Chapter 4.4 Average condition rating for HES materials used in districts one, two, and four

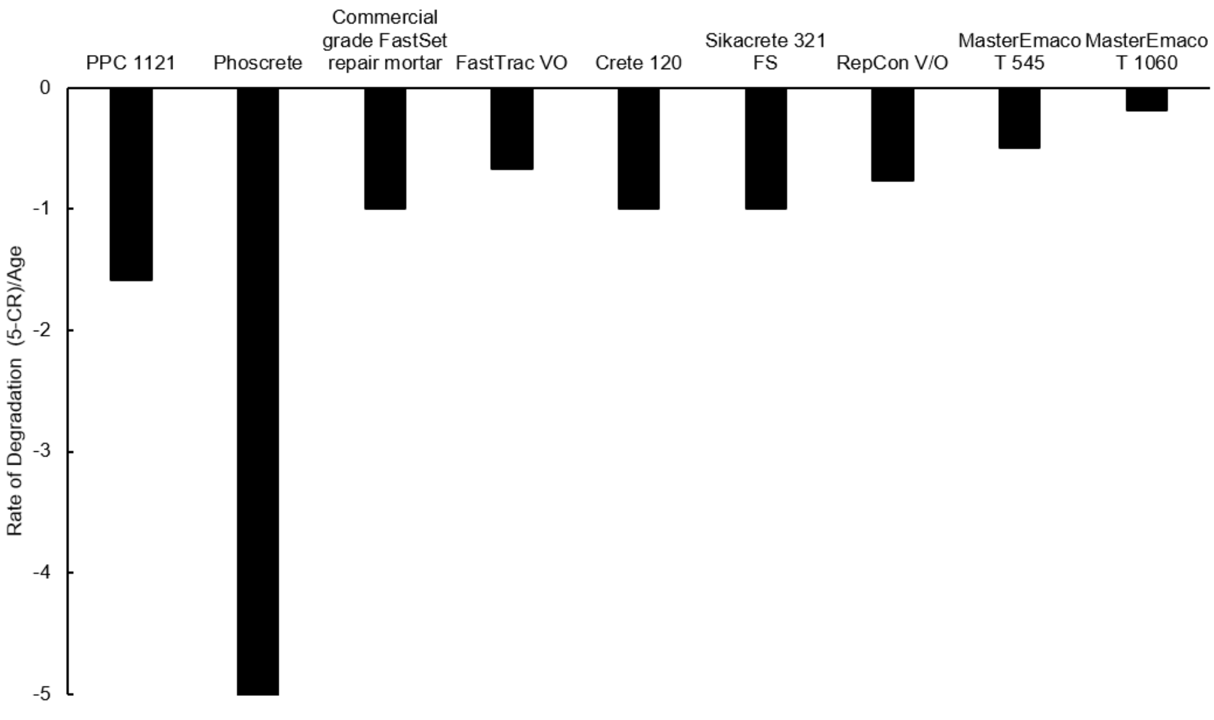
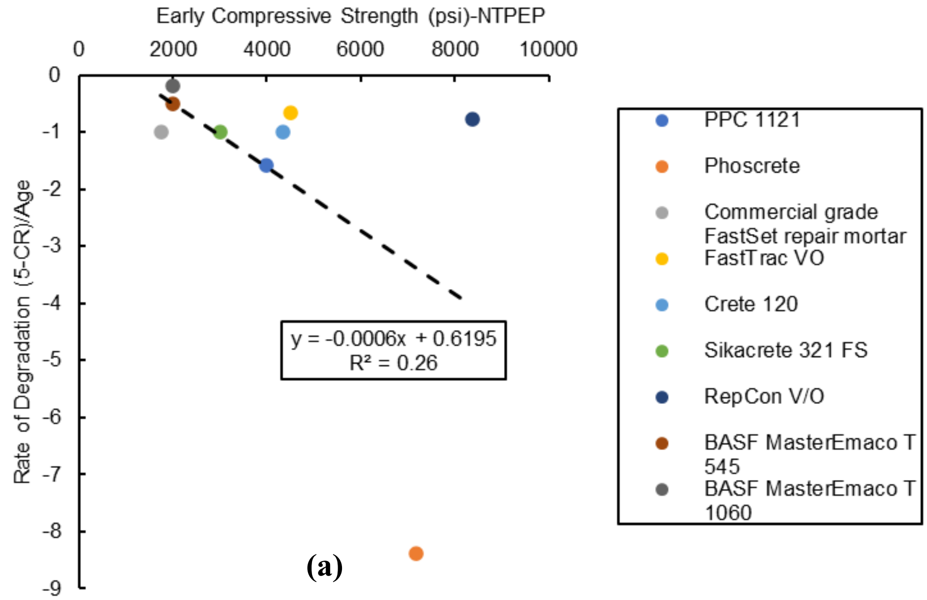


Figure Chapter 4.5 Average rate of degradation of HES materials used in districts one, two, and four

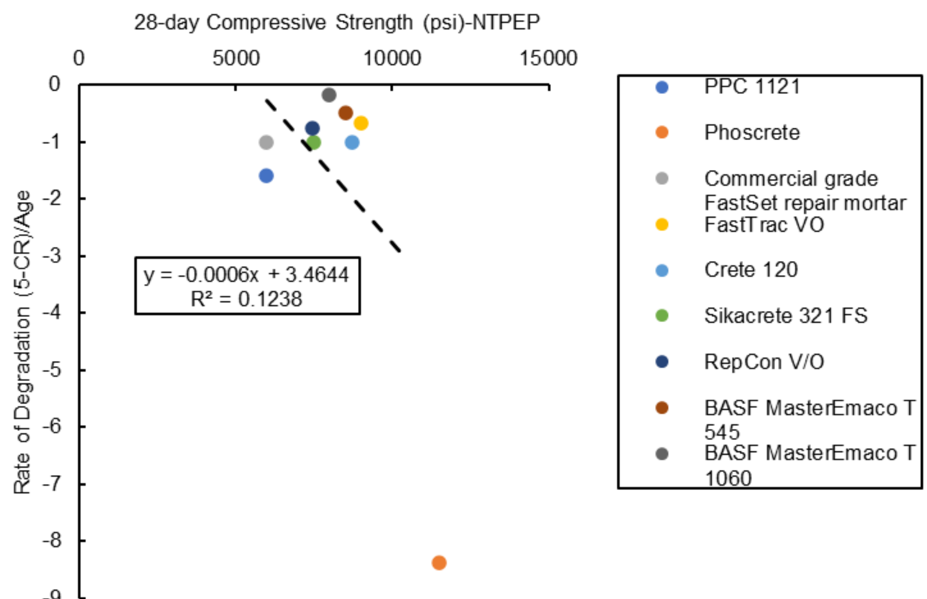
4.6 Correlation Between Field and Laboratory Data

4.6.1 Condition Rating Relationships

The main objective of this field investigation was to search for a possible correlation between a material's field performance and laboratory testing published on the NTPEP database or the datasheet provided (for materials not tested on NTPEP) by the manufacturer for each repair material. The early and 28-day compressive strength data were plotted with the rate of degradation data gathered from the field inspection, and the results are shown in Figure Chapter **4.6**. The early and 28-day compressive strength did not seem to be correlated with the rate of degradation based on the available data obtained from the field inspection. The Phoscrete data represented by the solid orange circle in Figure Chapter **4.6** drove this relationship and may be too influential in a small dataset.



(a)



(b)

Figure Chapter 4.6 a) Rate of degradation vs. early compressive strength (psi); b) Rate of degradation vs. 28-day compressive strength (psi)

The 28-day shrinkage strain data in air content (per ASTM C157) were also plotted against the average rate of degradation, and the results shown in Figure Chapter **4.7** shows a low correlation between the two variables (R^2=0.3569). This indicates that lower degradation rates corresponded to lower shrinkage values, except for FastTrac VO. In the NTPEP and datasheet data for these materials, it was unclear if they used a 24-hour demold time (per ASTM C157) or a 3-hour demold time, as is common for rapid-set materials.

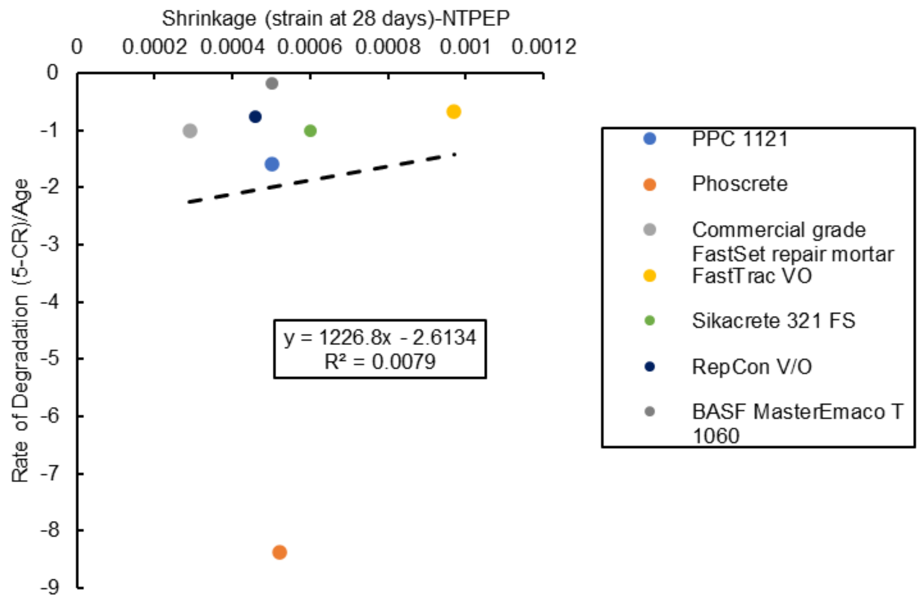
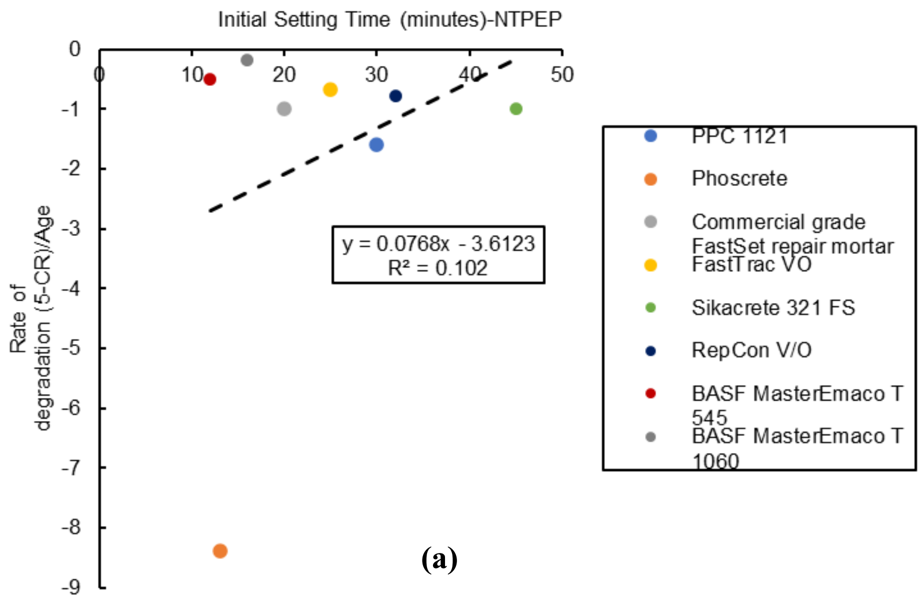


Figure Chapter 4.7 Shrinkage strain at 28 days vs. rate of degradation

Figure Chapter **4.8** shows the relationship between the average rate of degradation and the initial and final setting time data. The results indicate that the lowest average rate of degradation (-8.4/year) was associated with the material that had the shortest initial and final setting time (Phoscrete HC). This was anecdotally corroborated by a discussion with District two personnel that indicated that the two Phoscrete HC repairs might have been affected by this. A short setting time made it harder to maintain the quality of the performed repair, and if not expected, it may affect workmanship. Due to the limited dataset, it was not possible to draw factual findings for the relationship between the rate of degradation and the setting time, but setting time seemed to be as important a factor as found herein. Field inspection data for locations that incorporated Phoscrete had either a high or a low condition rating, which affected the final average rate of degradation and consequently affected potential relationships with the initial and final setting times.



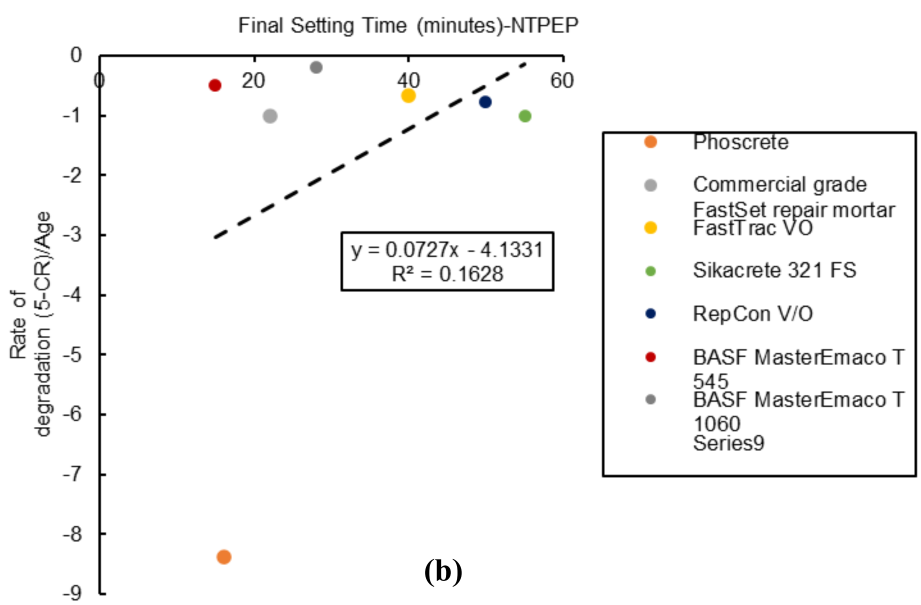


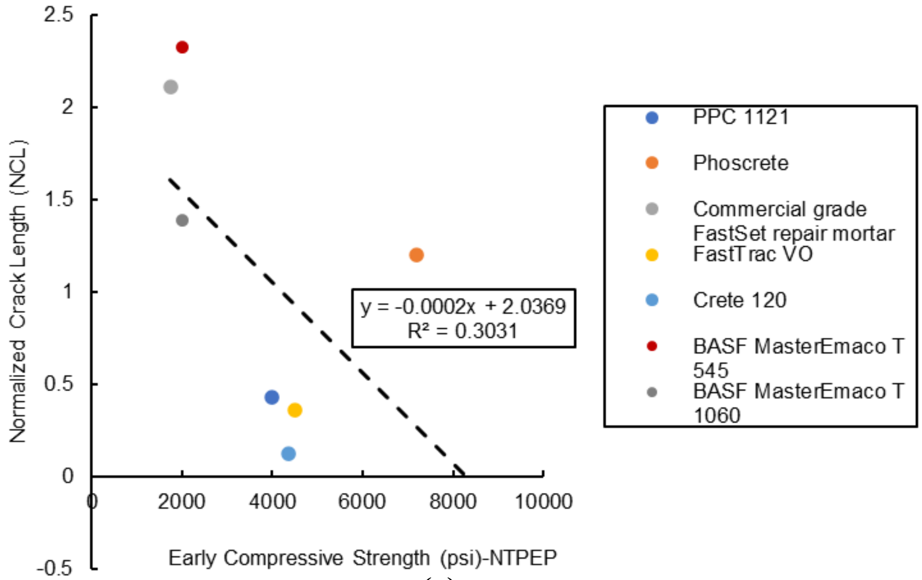
Figure Chapter 4.8 Rate of degradation vs. a) initial setting time; b) final setting time

4.6.2 Field-Observed Crack Length Relationships

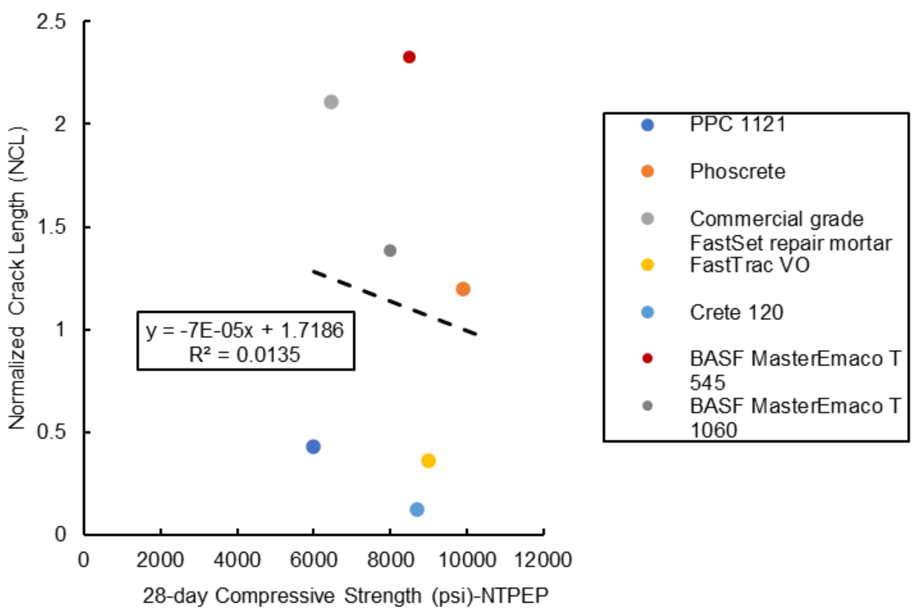
The number of cracks and the estimated crack lengths within a field repair were estimated for each repair location based on the field inspection. Figure Chapter **4.9** displays an example of one of the repairs with the cracks highlighted for clarity.

Figure Chapter 4.9 Highlighted cracks on one of the repair patches

The area of each repair was also measured and used to normalize the crack data by dividing the estimated total crack length by the estimated area of repair to obtain the normalized crack length (NCL). The NCL data were plotted against the early compression strength, 28-day compressive strength, 28-day shrinkage strain, and setting time data of each repair material. The laboratory test data were gathered from the NTPEP or datasheet if NTPEP data were not available. Based on the results shown in Figure Chapter **4.10**, the experimental data of the early and 28-day compressive strength did not seem to be correlated with the NCL based on the current dataset. However, there may be a potential relationship between the early compressive strength and the NCL if a larger and more representative dataset is used. The shrinkage and setting time data showed a potential relationship with the NCL, as shown in Figure Chapter **4.11**. Phoscrete data represented by a solid orange circle seemed to affect the relationship of the NCL with the different material properties investigated in this study. Since most of the Phoscrete data obtained from District one have been recently installed (less than a year in age), they seemed to negatively affect the relationship of the NCL with different material properties, especially the final setting time. The removal of Phoscrete data from the plot can improve the correlation up to an R^2 of 0.9701, as shown in Figure Chapter **4.12**. This explains how sensitive the relationship between the NCL and different material properties was to factors such as the age of the repair, number of data points, condition rating, and number of cracks.

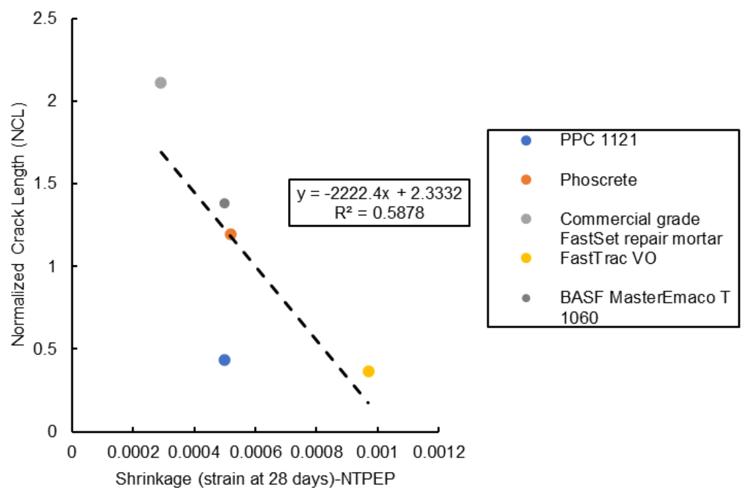


(a)

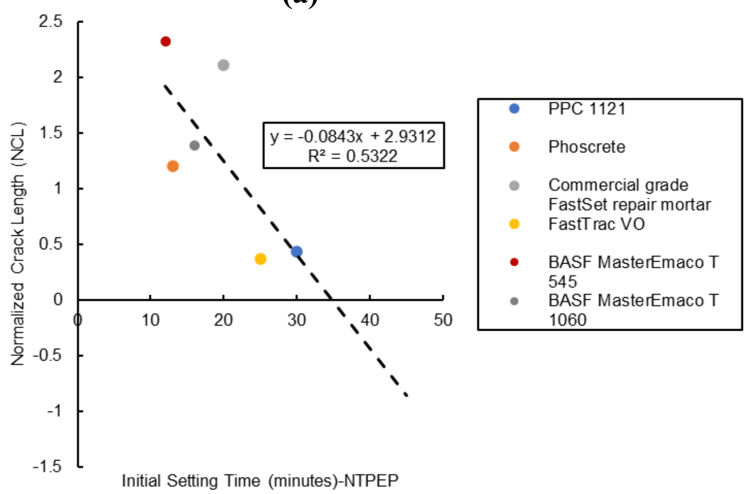


(b)

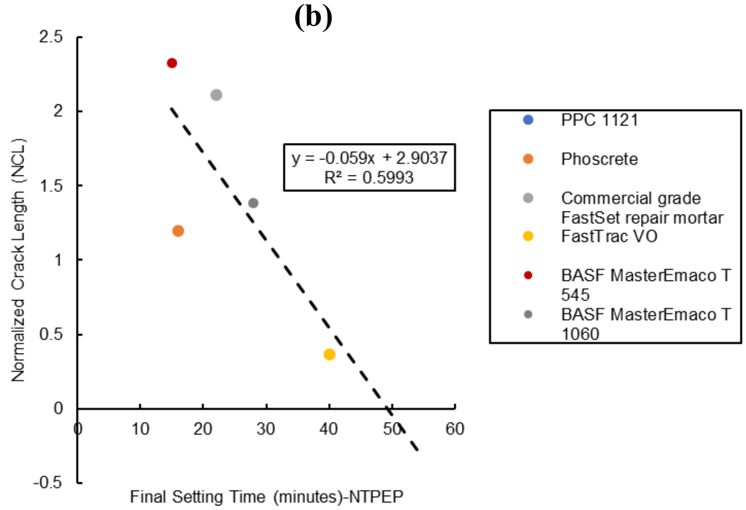
Figure Chapter 4.10 Normalized cracking length vs. a) early compressive strength (psi); b) 28-day compressive strength (psi)



(a)



(b)



(c)

Figure Chapter 4.11 Normalized crack length vs. a) shrinkage strain at 28 days; b) initial setting time; c) final setting time (minutes)

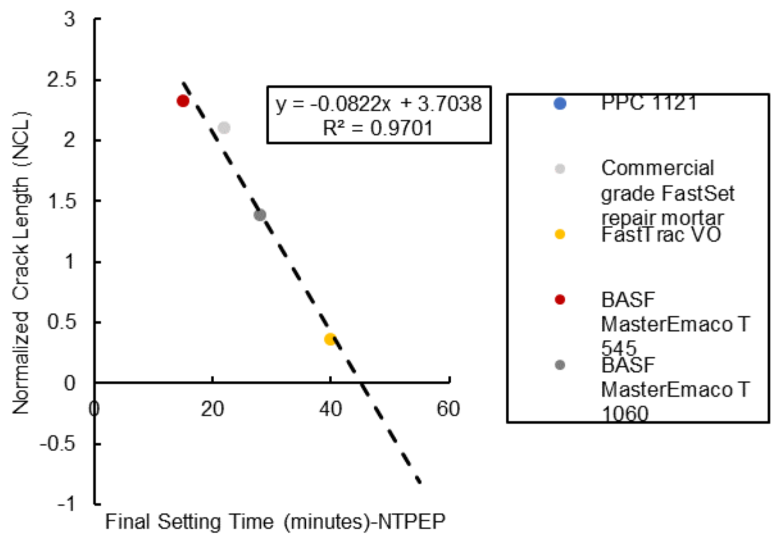


Figure Chapter 4.12 Normalized crack length data vs. final setting time (minutes) for data without Phoscrete

Chapter 5 Summary and Conclusions

The primary purpose of this research was to collect performance data on HES materials used in Nebraska and the surrounding states. A survey was prepared and distributed to the surrounding states of Nebraska to understand the common practices related to appropriate specifications of HES materials. In addition, field evaluation of multiple repair projects utilizing different HES products was performed, and the data was analyzed and compared to experimental data available on the NTPEP database and each product datasheet. Based on the analysis with the results obtained, the following conclusions were made regarding the use of HES and the possibility of predicting the durability of the repair material using the data:

- There is a significant difference in the experimental data of HES materials from the NTPEP database and the data included in the product datasheet.
- Installation of cement-based HES materials for concrete repair increases stresses in the repaired concrete, which leads to premature cracking and early deterioration in the cementitious repairs, as observed.
- Installation of polymer-based HES materials shifts stress to the substrate, which may increase deterioration in the substrate concrete and damage to the bond. This was corroborated by field observations where minor damage was observed in the polymer-based repairs, but the damage was observed at the interface and in the substrate, ultimately resulting in polymer-based repair debonding and spalling.
- Due to the varied number of proprietary products investigated, as well as the limited number of observations of each product in the field, statistical analyses were sensitive to outliers and scatter. This was observed both in the MnRoad data, and the Nebraska field collected data, as there was little overlap in materials encountered in both datasets.

- No significant relationships between compressive strength or length change and degradation rate were found in the MnRoad dataset due to the scatter of the available data and two materials obfuscating the regression analysis. However, the strongest trend indicated higher positive length change (expansion in air and in water) led to faster degradation.
- No significant relationship exists between the early-age and 28-day compressive strength, shrinkage, and setting time data (per NTPEP) with the field performance data of inspected HES materials represented by the observed rate of degradation, where the largest coefficient of determination was only 0.26.
- The relationship between the Normalized Crack Length (NCL) and measured material properties was improved over the Rate of Degradation with several coefficients of determination over 0.50.
- The strongest relationship was observed between NCL and setting time. The initial setting and final setting times had coefficients of determination of 0.53 and 0.60, respectively, and when Phoscrete (an outlier throughout the program) was omitted, the final setting time comparison with NCL coefficient of determination was 0.97. Higher setting times indicated lower NCL.
- Early-age strength (coefficient of determination at 0.30) had a greater relation to NCL than 28-day strength (coefficient of determination at 0.01), with higher early-age strength indicating lower NCL.
- Shrinkage strain data from NTPEP indicated higher shrinkage resulted in a lower cracking tendency of field repairs when compared to NCL. This result was counterintuitive but resulted in a coefficient of determination of 0.59. This was a reminder that the low power

and scatter in the relatively small amount of field data may cause spurious relationships, and strongly indicated more data among more products is needed.

Chapter 6 Recommendations

Based on the research findings, the following recommendations can be made:

- Utilization of HES materials in maintenance projects should be restricted to only those tested and included in the NTPEP database due to the discrepancies in the manufacturer-reported values.
- There is a need to develop an internal database to document HES repair projects performed in the state of Nebraska using HES materials. This database can then be used to document the long-term behavior of the installed repairs and all the relevant details. NDOT is currently participating in a monitoring project with NTPEP. It is recommended that an internal program begin to monitor new HES repairs over time to track their performance and useful life.
- Polymer-based HES repair materials have not performed well on NDOT structures. This may be due to several unknown factors, but NDOT has been moving away from them due to poor performance, and the field inspection supports this.
- Based on the NCL field investigations, longer setting time may be a strong performance indicator. This is likely due to the material with lower setting times being harder to work with and, thus, a surrogate quantitative measure of workmanship. A minimum initial setting time of 30 minutes is recommended as it is the approximate median setting time of the field-observed materials. According to observations, this change will improve the median NCL and, hopefully the functional life of the repair. This should be revisited after several years to determine if an even longer setting time is needed.
- While the relationship between NTPEP-measured shrinkage and repair material was counterintuitive, other states (see Table 3.2) make it part of the approval process. Because

of the lack of data to support a restriction on shrinkage, it is not recommended to place a limit on shrinkage for approval of HES material at this time.

- Best practices outlined in the literature review indicate that the elastic modulus of the repair and substrate materials should be as close as possible. This was further supported by the analysis in Section 3.3 that showed low modulus (even though they were high strength) repairs shift load significantly to the substrate concrete, which may already be somewhat distressed. For this reason, it is recommended that the 24-hour strength of the repair be restricted to the lowest reasonable value, which will likely be around 4000 psi. Such materials did perform well in NCL. This may also ideally result in lower 28-day strengths to obtain as close as reasonable elastic moduli; however, placing an upper limit on the strength of the repair may be warranted. A suggested upper limit is 8000 psi for 28-day strength, as it could result in an approximately 40% difference in elastic modulus with the typical bridge concrete.
- Best practices indicate that the CTE should also match between repair and substrate. In lieu of requiring matching CTE due to the lack of quantitative evidence herein, it is recommended that, when extended with aggregate, all HES materials be extended with the local bridge deck aggregate to help maintain similar CTE.
- Anecdotal reports from district maintenance indicate that familiarity with a material plays a significant role in field installation and performance. It is recommended that external contractors should be required to undergo additional observation and inspection while they gain familiarity with the way a new (to the contractor) pre-bagged HES repair material behaves during installation.

References

AASHTO. (2023). *National Transportation Product Evaluation Program (NTPEP)*. https://data.ntpep.org/RSCP/Products

Alice, S. E. (2014). *"Selection of High Performance Repair Materials for Pavements and Bridge Decks"*. Cleveland State University.

American Concrete Pavement Association. (2004). *"Concrete Crack and Partial-Depth Spall Repair Manual"*.

Ansari, F., Luke, A. C., Vitillo, N., Blank, N., & Turhan, I. (1997). "*Developing Fast Track Concrete for Pavement Repair*". Concrete International, 19, 24–29.

Barde, A., Parameswaran, S., Chariton, T., Weiss, J., & Cohen, M. D. (2006). *"Evaluation of Rapid Setting Cement Based Materials for Patching and Repair"*.

Bentz, D., & Peltz, M. (2008). "*Reducing Thermal and Autogenous Shrinkage Contributions to Early-Age Cracking*". Aci Materials Journal, 105, 414–420.

Bescher, E., & Kim, J. (2019). "*Belitic Calcium Sulfoaluminate Cement: History, Chemistry, Performance, and Use in the United States*". 1st International Conference on Innovation in Low Carbon Cement and Concrete Technology.

Broomfield, J. P. (2003). *"Corrosion of Steel in Concrete: Understanding, Investigation and Repair"* (2nd ed.). Taylor & Francis Group.

Burnham, T. R., Johnson, E., & Worel, B. J. (2016). *"Performance of Various Partial-Depth Repair Materials at the MnROAD Facility"*. Minnesota Department of Transportation, Research Services & Library.

Burris, L. E., & Kurtis, K. E. (2018). "*Influence of Set Retarding Admixtures on Calcium Sulfoaluminate Cement Hydration and Property Development*". Cement and Concrete Research, 104, 105–113. https://doi.org/10.1016/j.cemconres.2017.11.005

California Department of Transportation. (2008). "*Chapter 8 - Full Depth Concrete Repair in Maintenance*". In *Rigid Pavement Preservation* (2nd ed.).

California Department of Transportation. (2015). *"Standard Specifications for Road and Bridge Construction"*.

Cervo, N. M., & Schokker, A. J. (2008). *"Bridge deck patching materials"*.

Colorado Department of Transportation. (2011). *"Standard Specifications for Road and Bridge Construction"*.

Colorado Department of Transportation. (2022). *"Notice to Manufacturer's Handbook"*.

Cordon, W. A. (1966). "*Freezing and Thawing of Concrete-Mechanisms and Control"*.

Cramer, S. M., Pham, L. T., & Snyder, M. B. (2017). *"Better Concrete Mixes for Rapid Repair in Wisconsin"*.

Delatte, N. (2008). *"Concrete Pavement Design, Construction, and Performance"*. Taylor & Francis Group.

Delaware Department of Transportation. (2014). *"Supplemental Specifications to the August 2001 Standard Specifications"*.

Ding, Z., & Li, Z. (2005). "*High-Early-Strength Magnesium Phosphate Cement With Fly Ash*". ACI Materials Journal, 102(6), 375.

Dornak, M., Zuniga, J., Garcia, A., Drimalas, T., & Folliard, K. J. (2015). *"Development of Rapid, Cement-Based Repair Materials for Transportation Structures"*.

Elhindy, E., Chevalier, F., & Khayat, K. H. (1996). "*Airfield Pavement Repair Using High-early Strength Concrete: Experience*". In *Concrete in the Service of Mankind: Concrete for Infrastructure and Utilities* (1st ed.). CRC Press.

Emberson, N. K., & Mays, G. C. (1990). "*Significance of Property Mismatch in the Patch Repair of Structural Concrete Part 1: Properties of Repair Systems*". Magazine of Concrete Research, 42(152), 147–160.

Emmons, P. H. (1993). *"Concrete Repair and Maintenance Illustrated: Problem Analysis, Repair Strategy, Techniques"*. RSMeans.

Emmons, P. H., Vaysburd, A. M., & McDonald, J. E. (1993). "*A Rational Approach to Durable Concrete Repairs*". Concrete International.

Emmons, P. H., Vaysburd, A. M., Poston, R. W., & McDonald, J. E. (1998). *"Performance Criteria for Concrete Repair Materials, Phase II Field Studies"*. Army Engineer Waterways Experiment Station.

Falls, A. J. (2019). *"Evaluation of Concrete Spall Repair Materials"*. Engineer Research and Development Center.

Farha, M. H., Hassan, Y., Abd El Halim, A. O., Razaqpur, A. G., El-Desouky, A., & Mostafa, A. (2002). "*Effects of New Deicing Alternatives on Airfield Asphalt Concrete Pavements*". Federal Aviation Administration Technology Transfer Conference.

Frentress, D. P., & Harrington, D. S. (2012). *"Guide for Partial-Depth Repair of Concrete Pavements"*. Iowa State University Institute for Transportation.

Georgia Department of Transportation. (2013). *"Standard Specifications Construction of Transportation Systems"*.

Ghafoori, N., Najimi, M., & Maler, M. (2017). "*High-Early-Strength High-Performance Concrete for Rapid Pavement Repair"*.

Gholami, S., Hu, J., & Kim, Y.-R. (2019). *"Development of High-Performance Rapid Patching Materials for Pavement Repair"*.

Gillespie, T. (1999). *"New Method to Predict Performance of Concrete Repair Materials in the Field"*.

Glasser, F. P., & Zhang, L. (2001). "*High-Performance Cement Matrices Based on Calcium Sulfoaluminate-Belite Compositions*". Cement and Concrete Research, 31(12), 1881–1886. https://doi.org/10.1016/S0008-8846(01)00649-4

Grove, J. D., Jones, K. B., Bharil, K. S., Abdulshafi, A., & Calderwood, W. (1990). "*Fast Track and Fast Track II, Cedar Rapids, Iowa*". Transportation Research Record 1282, *1282*, 1–7.

Hall, K., & Tayabji, S. (2011). *"Coefficient of Thermal Expansion in Concrete Pavement Design"*.

Hauggaard, A. B., Damkilde, L., Hansen, P. F. ., Pedersen, E. S. ., & Nielsen, A. (1997). *"HETEK: Control of Early Age Cracking in Concrete - Phase 4 and 5: Material Modelling - Continuum Approach"*.

Heiman, J., & Koerstz, P. (1991). "*Performance of Polymer Modified Cementitious Mortars in Chloride Contaminated Concrete*". Trans. Inst. Eng. Austral Civ. Eng., 3, 169–175.

Hewlett, P. C., & S.A., H. (1985). "*Repair Materials Selection and Testing*". Proceedings of the Second International Conference on Structural Faults and Repair.

Hu, C., Hou, D., & Li, Z. (2017). "*Micro-Mechanical Properties of Calcium Sulfoaluminate Cement and the Correlation with Microstructures*". Cement and Concrete Composites, 80, 10–16. https://doi.org/10.1016/j.cemconcomp.2017.02.005

Illinois Department of Transportation. (2012). *"Standard Specifications for Road and Bridge Construction"*.

Iowa Department of Transportation. (2023). "*Inspection & Acceptance Rapid-Setting Concrete Patching Materials"*. https://iowadot.gov/erl/current/IM/content/491.20.htm

Janotka, I., & Mojumdar, S. C. (2007). "*Performance of Sulphoaluminate-Belite Cement With High C~ 4A~ 3S Contents*". Ceramics Silikaty, 51(2), 74.

Kansas Department of Transportation. (2015). "*1716-Rapid-Set Concrete Patching Material*". In *Standard Specifications for State Road & Bridge Construction*.

Kirchner, H. W. (2001). "*Using Deicers Correctly*". Salt Institute (Www. Saltinstitute. Org), 24.

Knutson, M., & Riley, R. (1987). "*Fast-Track Concrete Paving Opens Door to Industry Future*".

Concrete Construction, 19–22.

Koehler, A., Neubauer, J., & Goetz-Neunhoeffer, F. (2022). "*How C12A7 influences the early hydration of calcium aluminate cement at different temperatures*". Cement and Concrete Research, 162, 106972. https://doi.org/10.1016/j.cemconres.2022.106972

Kohn, S. D., & Tayabji, S. (2003). *"Best Practices for Airport Portland Cement Concrete Pavement Construction (Rigid Airport Pavement)"*.

Kuo, S.-S., Carlo, L., & Kuenzel, C. (1999). *"Evaluation of Patching Materials and Placement Techniques for Rigid Pavements and Bridge Decks"*.

Lee, E. B., Lamour, V., Pae, J. H., & Harvey, J. (2003). *"Analysis of Sensitivity of Plain Jointed Concrete Pavement in California to Early-age Cracking using HIPERPAV"*.

Li, J., Zhang, W., & Cao, Y. (2014). "*Laboratory Evaluation of Magnesium Phosphate Cement Paste and Mortar for Rapid Repair of Cement Concrete Pavement*". Construction and Building Materials, 58, 122–128.

Li, M., & Li, V. C. (2011). "*High-Early-Strength Engineered Cementitious Composites for Fast, Durable Concrete Repair—Material Properties*". ACI Materials Journal, 108(1), 3–12. https://doi.org/10.14359/51664210

Luca, B., Bernhard, E., Pietro, P., & Rob, P. (2004). "*Corrosion of Steel in Concrete: Prevention, Diagnosis, Repair*". Bedin: Wiley—VCH.

Marosszeky, M. (1991). "*Stress Performance in Concrete Repairs*". ACI-SP126, 467–473.

Mauricio Ruiz, J., Rasmussen, R. O., Chang, G. K., Dick, J. C., & Nelson, P. K. (2005). *"Computer-Based Guidelines for Concrete Pavements Volumn II-Design and Construction Guidelines and HIPERPAV II User's Manual"*.

McDaniel, R. S., Olek, J., Behnood, A., Magee, B., & Pollock, R. (2014). *"Pavement Patching Practices"* (Issue Project 20-05, Topic 44-04).

McRory, J. W., Pozo-Lora, F. F., Benson, Z., Tawadrous, R., & Maguire, M. (2022). "*Behavior of Hybrid Reinforced Concrete Bridge Decks under Static and Fatigue Loading*". Polymers, 14(23), 5153. https://doi.org/10.3390/polym14235153

Mehta, P. K., & Burrows, R. W. (2001). "*Building Durable Structures in the 21st Century*". Concrete International, 23(3), 57–63.

Mihashi, H., Nishiyama, N., Kobayashi, T., & Hanada, M. (2002). "*Development of a Smart Material to Mitigate Thermal Stress in Early Age Concrete*". Control of Cracking in Early Age Concrete, 385–392.

Missouri Department of Transportation. (2023). *"JSP0210-Rapid Set Concrete Patching Material-Horizontal Repair"*.

Morency, M., Vaysburd, A., Von Fay, K., & Bissonnette, B. (2005). *"Development of a Test Method to Evaluate Cracking Tendency of Repair Materials, Phase I Report"*.

Morgan, D. R. (1996). "*Compatibility of Concrete Repair Materials and Systems*". Construction and Building Materials, 10(1), 57–67.

Murray, C. D., Floyd, R. W., & Ramseyer, C. C. E. (2019). "*Using Belitic Calcium Sulfoaluminate Cement for Precast, Prestressed Concrete Beams.*". PCI Journal.

NCDOT. (2012). *"Standard Specifications for Roads and Structures"*.

NDOT. (2023). *Divisions and Districts*. https://dot.nebraska.gov/about/divisions-districts/

Nebraska Department of Transportation. (2017). *"Standard Specifications for Highway Construction"*.

New York Department of Transportation. (2014). *"Standard Specifications for Roads and Bridges"*.

Pearson, R. I. (1988). "*Fast-Track Concrete Paving*". Concrete International, 10(8), 33–35.

Pelletier, L., Winnefeld, F., & Lothenbach, B. (2010). "*The Ternary System Portland cement–Calcium Sulphoaluminate Clinker–Anhydrite: Hydration Mechanism and Mortar Properties*". Cement and Concrete Composites, 32(7), 497–507. https://doi.org/10.1016/J.CEMCONCOMP.2010.03.010

Péra, J., & Ambroise, J. (2004). "*New Applications of Calcium Sulfoaluminate Cement*". Cement and Concrete Research, 34(4), 671–676. https://doi.org/10.1016/j.cemconres.2003.10.019

Plum, D. (1991). "*Materials-What to Specify*". International Journal of Construction Maintenance and Repair, 5, 3–7.

Poulsen, E., & Mejlbro, L. (2010). *"Diffusion of Chloride in Concrete: Theory and Aapapplication"*. CRC Press.

Quezada, I., Thomas, R. J., & Maguire, M. (2019). *"Rapid Concrete Repair"*.

Ram, P. V., Olek, J., & Jain, J. (2013). *"Field Trials of Rapid-Setting Repair Materials"*. https://doi.org/10.5703/1288284315185

Ram, P. V., Smith, K. D., Shah, A., Olek, J., Van Dam, T., & Sutter, L. (2019). *"Non-Cementitious Repair Materials Study"*.

Russell, H. G. (2004). "*NCHRP Synthesis of Highway Practice 333: Concrete Bridge Deck Performance*". Transportation Research Board of the National Academies, Washington, DC.

Saucier, F., & Pigeon, M. (1991). "*Durability of New-to-Old Concrete Bondings*". ACI Symposium Publication, 128, 689–706. https://doi.org/10.14359/2066

Shin, A. K.-C., & Walker, D. (2020). *"Development of Rapid Pavement Repair Materials"*.

Sprinkel, M. M., Hossain, M. S., & Ozyildirim, C. (2019). *"Premature Failure of Concrete Patching: Reasons and Resolutions"*.

Thomas, R. J., Maguire, M., Sorensen, A. D., & Quezada, I. (2018). "*Calcium Sulfoaluminate Cement*". Concrete International, 40(4), 65–69.

Todd, N. T. (2015). *"Assessing Risk Reduction of High Early Strength Concrete Mixtures"*. Purdue University.

Van Dam, T. J., Peterson, K. R., Sutter, L. L., Panguluri, A., Sytsma, J., Buch, N., Kowli, R., & Desaraju, P. (2005). *"Guidelines for Early-Openning-to-Traffic Portland Cement Concrete for Pavement Rehabilitation"*.

Virginia Department of Transportation. (2016). *"Road and Bridge Specifications"*.

Washington Department of Transportation. (2016). *"Standard Specifications for Road, Bridge, and Municipal Construction"*.

Whiting, D., Nagi, M., & Okamoto, P. A. (1994). "*Early Strength Gain of Rapid Highway Repair Concrete*". Concrete International, 16(8), 28–35.

Whitmore, D. W. (2005). "*Galvanic Corrosion Protection Systems for Concrete Bridges*". Bridges, 8(2).

Wilkinson, G. C. M. and W. B. (1987). "*Polymer Repairs to Concrete: Their Influence on Structural Performance*". ACI Symposium Publication, 100. https://doi.org/10.14359/2618

Wilson, T. P., Smith, K. L., & Romine, A. R. (1999). *"Materials and Procedures for Rapid Repair of Partial-Depth Spalls in Concrete Pavements"*.

Woodson, R. D. (2011). "*Concrete Repair Preperation*". In *Concrete Portable Handbook*. Butterworth Heinemann.

Wyoming Department of Transportation. (2021). *"Standard Specifications for Road and Bridge Construction"*.

Yuan, Y. ., & Marosszeky, M. (1991). "*Major Factors Influencing the Performance of Structural Repair*". ACI Symposium Publication, 128, 819–838. https://doi.org/10.14359/3460

Zayed, A., Riding, K. A., Sedaghat, A., Mapa, D., Markandeya, A., Shanahan, N., Nosouhian, F., & Williams, A. (2018). "*Performance Improvement of High Early Strength (HES) Concrete for Pavement Replacement Slabs"*.

Zuniga, J. R. (2013). *"Development of Rapid, Cement-Based Repair Materials for Transportation Structures"*. University of Texas at Austin.

Appendix A

District One

Location 1

Bridge Number: 508016
Time of repair: July 2022 (Phoscrete HC), 2017 (MasterEmaco T 545)
Type of repair materials: Phoscrete HC, MasterEmaco T 545

(a)

(b)

Figure Appendix A.1 Current state of repair material installed in location 1

Location 2

Bridge number: 48048

Time of repair: 2012 (MasterEmaco T 1060), 09/26/2022 (Phoscrete), 2017 (MasterEmaco T 545)

Type of repair materials: MasterEmaco, Phoscrete, MasterEmaco T 545

(a)

(b)

(c)

Figure Appendix A.2 Current state of repair material installed in location 2

(d)

(e)

Figure A.2 (continued) Current state of repair material installed at location 2

Location 3

Bridge number: 49665

Time of repair: 09/27/2022 (Phoscrete HC), the repair time is not mentioned for the repairs utilizing MasterEmaco T 545 and MasterEmaco T 1060.

Type of repair materials: Phoscrete HC, MasterEmaco T 1060, MasterEmaco T 545

(a)

(b)

Figure Appendix A.3 Current state of repair material installed at location 3

(c)

(d)

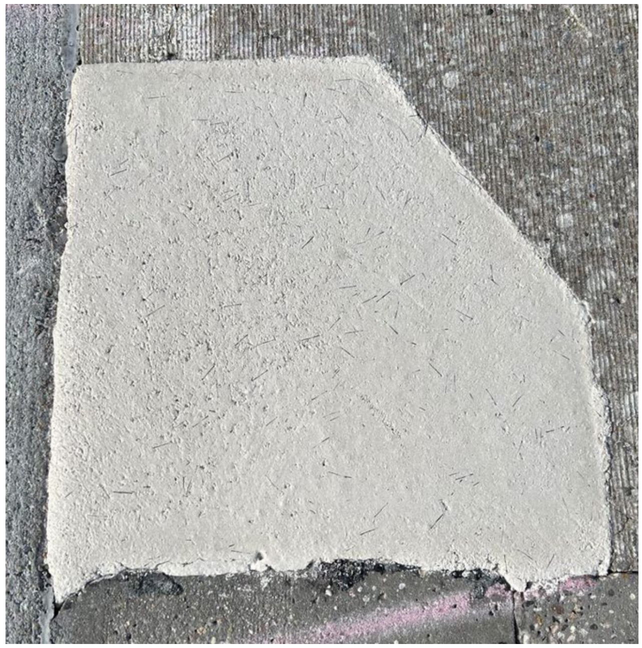
Figure A.3 (continued) Current state of repair material installed at location 3

(e)

(f)

Figure A.3 (continued) Current state of repair material installed at location 3

Location 4
Bridge number: 49626
Time of repair: 10/11/2022
Type of repair materials: Phoscrete HC



(a)

(b)

Figure Appendix A.4 Current state of repair material installed at location 4

(c)

(d)

Figure A.4 (continued) Current state of repair material installed at location 4

Location 5
Bridge number: 49047
Time of repair: 10/05/2022
Type of repair materials: Phoscrete HC


(a)


(b)


(c)

Figure Appendix A.5 Current state of repair material installed at location 5

Location 6

Bridge number: 05428

Time of repair: 04/05/2022 (Phoscrete HC), 2017 (MasterEmaco T 1060)

Type of repair materials: Phoscrete HC, MasterEmaco T 1060

(a)

(b)

Figure Appendix A.6 Current state of repair material installed at location 6

Location 7

Bridge number: 35911

Time of repair: 07/11/2022

Type of repair materials: Phoscrete HC

(a)

(b)

(c)

Figure Appendix A.7 Current state of repair material installed at location 7

District Two

Location 1

Bridge number: 44606

Time of repair: 2019

Type of repair materials: mastic on the side, black material unknown (light porous or porous, not sure), Kwik bond on the side

(a)

(b)

Figure Appendix A.8 Current state of repair material installed in location 1

(c)

(d)

(e)

Figure A.8 (continued) Current state of repair material installed in location 1

Location 2
Bridge number: 44207 West bound
Time of repair: 2019–2020
Type of repair materials: Kwik bond
Note: Photos were taken inside the car.

(a)

(b)

Figure Appendix A.9 Current state of repair material installed in location 2

Location 3

Bridge number: 44207 East bound

Time of repair: 2021

Type of repair materials: Kwik bond (2021) on the sides of the lane and hot mix (2022) in the middle

(a)

(b)

Figure Appendix A.10 Current state of repair material installed at location 3

(c)

(d)

(e)

Figure A.10 (continued) Current state of repair material installed at location 3

(f)

Figure A.10 (continued) Current state of repair material installed at location 3

Location 4

Bridge number: 43922
Time of repair: Summer 2021
Type of repair materials: 47B-PR (done by contractor)

(a)

Figure Appendix A.11 Current state of repair material installed at location 4

(b)

(c)

(d)

Figure A.11 (continued) Current state of repair material installed at location 4


(e)

Figure A.11 (continued) Current state of repair material installed at location 4

Location 5
Bridge number: 44207
Time of repair: May 2021 (Kwik bond), May 2022 (hot mix)
Type of repair materials: Kwik bond (NDOT) and hot mix asphalt


(a)

Figure Appendix A.12 Current state of repair material installed at location 5

(b)

(c)

(d)

Figure A.12 (continued) Current state of repair material installed at location 5

(e)

(f)

(g)

Figure A.12 (continued) Current state of repair material installed at location 5

Location 6
Bridge number: 00604
Time of repair: 2017–2018 (Kwik bond), 2019 (cold mix), 2019 (Kwik bond)
Type of repair materials: Kwik bond and cold mix

(a)

(b)

(c)

Figure Appendix A.13 Current state of repair material installed at location 6

(d)

(e)

(f)

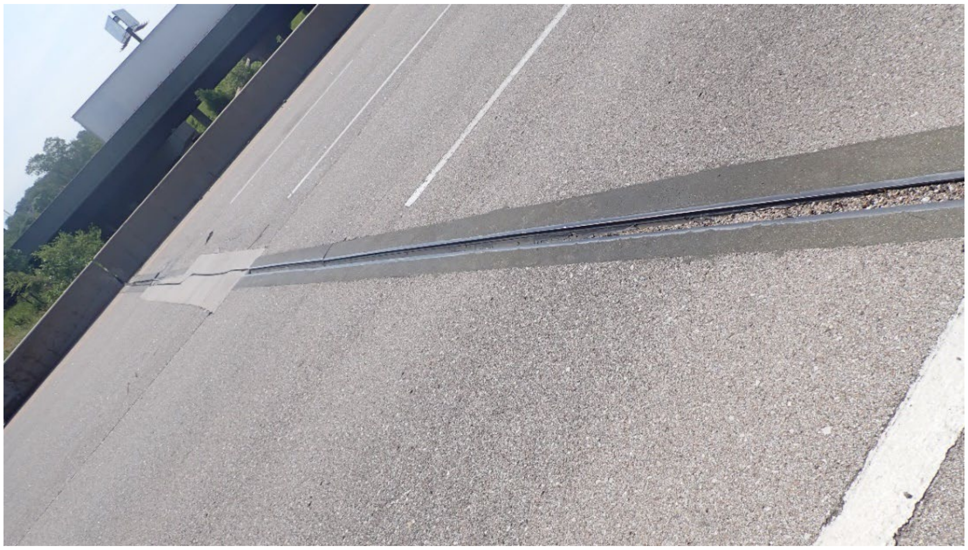
Figure A.13 (continued) Current state of repair material installed at location 6

Location 7

Bridge number: S080-44572

Time of repair: 2020 (Kwik bond), (2021) Phoscrete HC

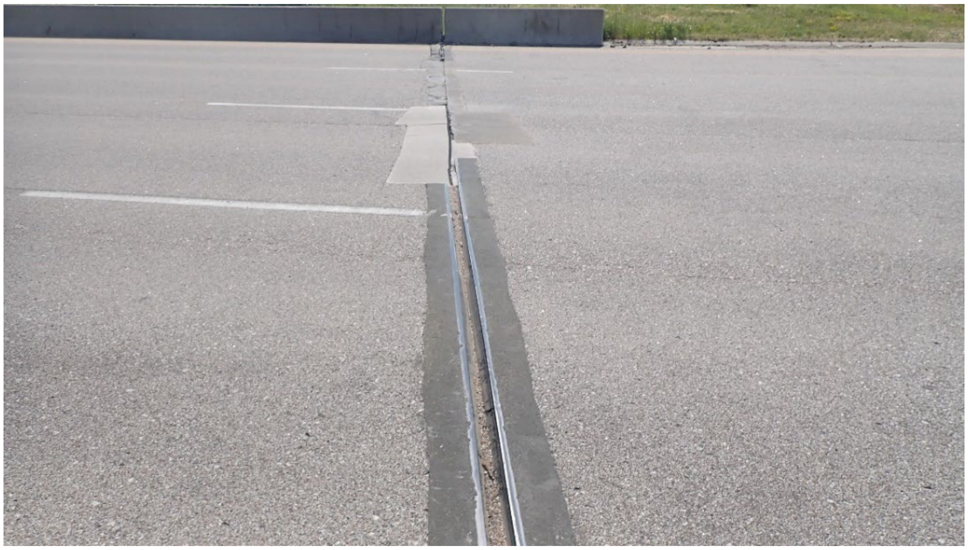
Type of repair materials: Kwik bond and Phocrete in the middle



(a)

(b)

Figure Appendix A.14 Current state of repair material installed at location 7



(c)

(d)

Figure A.14 (continued) Current state of repair material installed at location 7

Location 8

Bridge number: Highway 50- 8762

Time of repair: May 2022

Type of repair materials: Phoscrete HC, hot mix

(a)

(b)

(c)

Figure Appendix A.15 Current state of repair material installed at location 8

(d)

(e)

Figure A.15 (continued) Current state of repair material installed at location 8

Location 9

Bridge number: S050-08894

Time of repair: 2020 (47B-PR), 2019 (Kwik bond), older unknown (hot mix)

Type of repair materials: 47B-PR, Kwik bond, and hot mix (patching over the older repair material)

Note: It might have been patched in 2022 without removing the old material.

(a)

(b)

(c)

Figure Appendix A.16 Current state of repair material installed at location 9

(d)

(e)

(f)

Figure A.16 (continued) Current state of repair material installed at location 9

(g)

Figure A.16 (continued) Current state of repair material installed at location 9

District Four

Location 1

Bridge number: 0578
Location: Bridge Osceola East & West Project
Time of repair: 2020–2021
Type of repair materials: Commercial grade FastSet repair mortar
Notes: The repair was performed on the bottom of the bridge deck. It looked good. Some parts had an eco-sound.

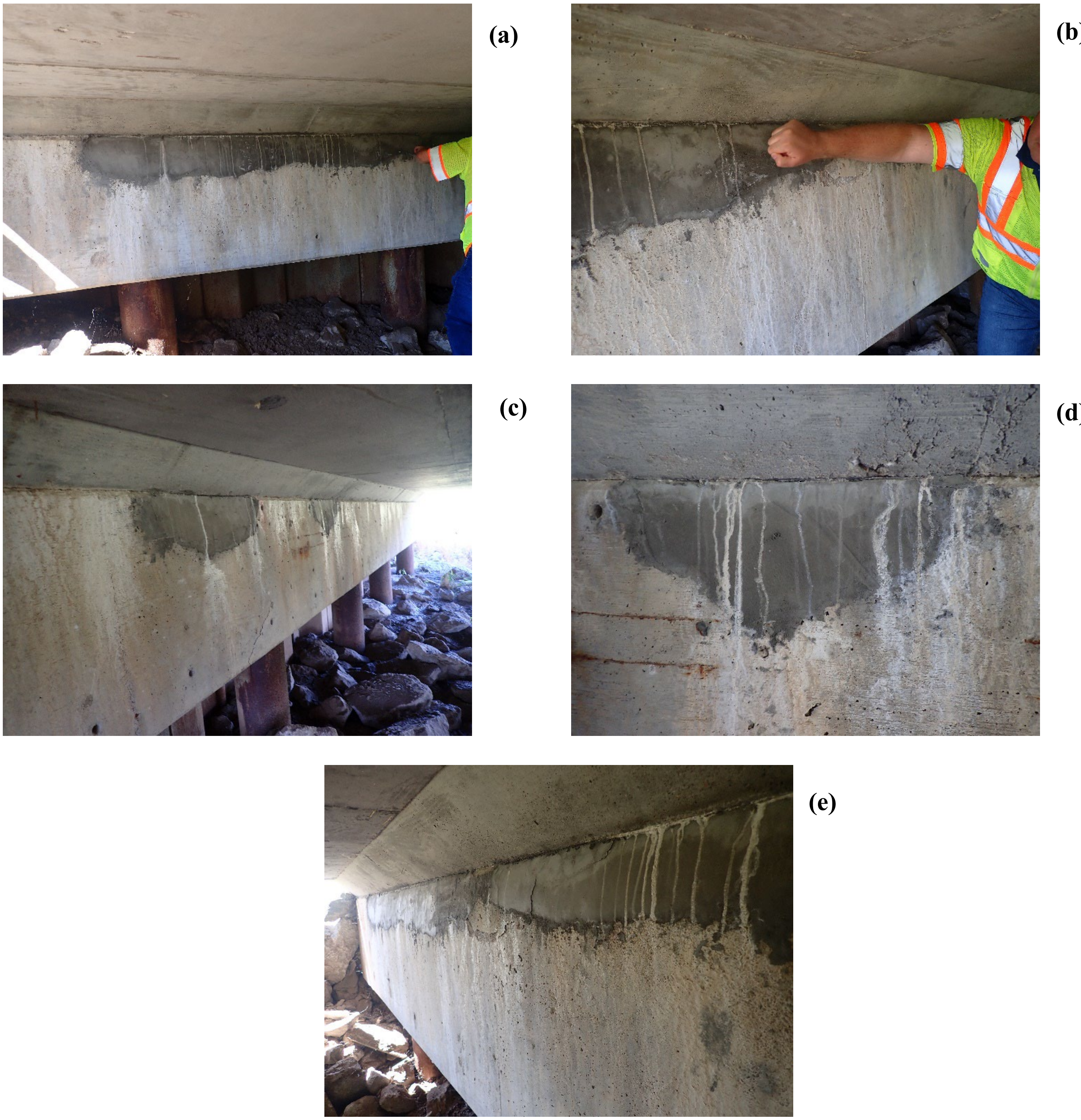


Figure Appendix A.17 Current state of the repair material installed at location 1

Location 2

Bridge number: 09667

Location: Saint Paul, MN

Time of repair: 2022

Type of repair material: a mixture between Phoscrete HC and cold-patch

(a)

(b)

(c)

(d)

(e)

(f)

gure Appendix A.18 Current state of repair material installed in location 2


(g)


(h)


(i)

Figure A.18 (continued) Current state of repair materials installed at location 2

Location 3

Location: Rockville Ravenna North Highway 68

Time of repair: 2020

Type of repair material: FastTrac VO

(a)

(b)

(c)

(d)

Figure Appendix A.19 Current state of repair materials installed at location 3

Location 4

Location: Gibbon link bridge over highway 30.
Time of repair: October 2021
Type of repair material: FasTrac VO


(a) (b)

Figure Appendix A.20 Current state of the repair material used in location 4

Location 5

Bridge number: 31263
Time of repair: 2021
Type of repair material: Sikacrete 321 FS


(a)

Figure Appendix A.21 Current state of repair material installed at location 4

(b)

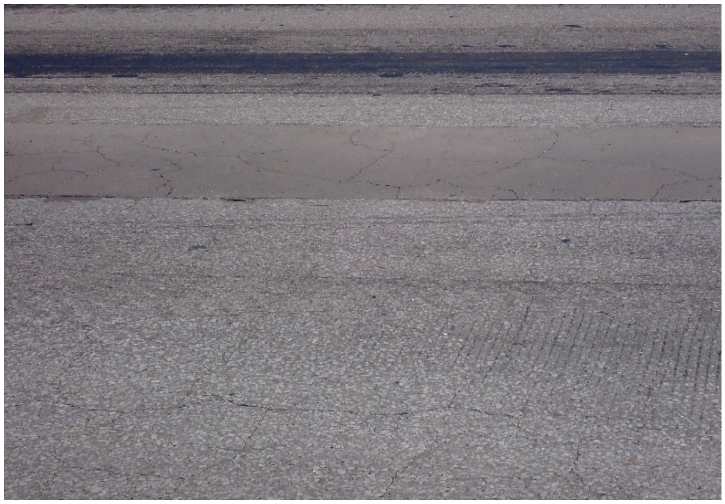
Figure A.21 (continued) Current state of the repair material at location 4

Location 6

Bridge number: 32815
Time of repair: 2019
Type of repair material: Crete 120
Note: It has cracks all over.

(a)

Figure Appendix A.22 Current state of repair material installed at location 6



(b)

(c)

Figure A.22 (continued) Current state of the repair material used in location 6

Location 7

Location: I-80 bridge Deck Aurora E&W

Time of repair: Fall 2020

Type of repair material: PPC 1121 (Polyester Polymer Concrete)

(a)

(b)

Figure Appendix A.23 Current state of repair material installed at location 7

(c)

(d)

Figure A.23 (continued) Current state of repair material installed at location 7

(e)

Figure A.23 (continued) Current state of the repair material used in location 7

Location 8

Bridge number: 34413

Time of repair: Summer 2021

Type of repair material: RepCon V/O

(a)

Figure Appendix A.24 Current state of repair material installed at location 8

(b)

(c)

(d)

Figure A.24 (continued) Current state of repair material installed at location 8

(e)

Figure A24 (continued) Current state of the repair material used in location 8

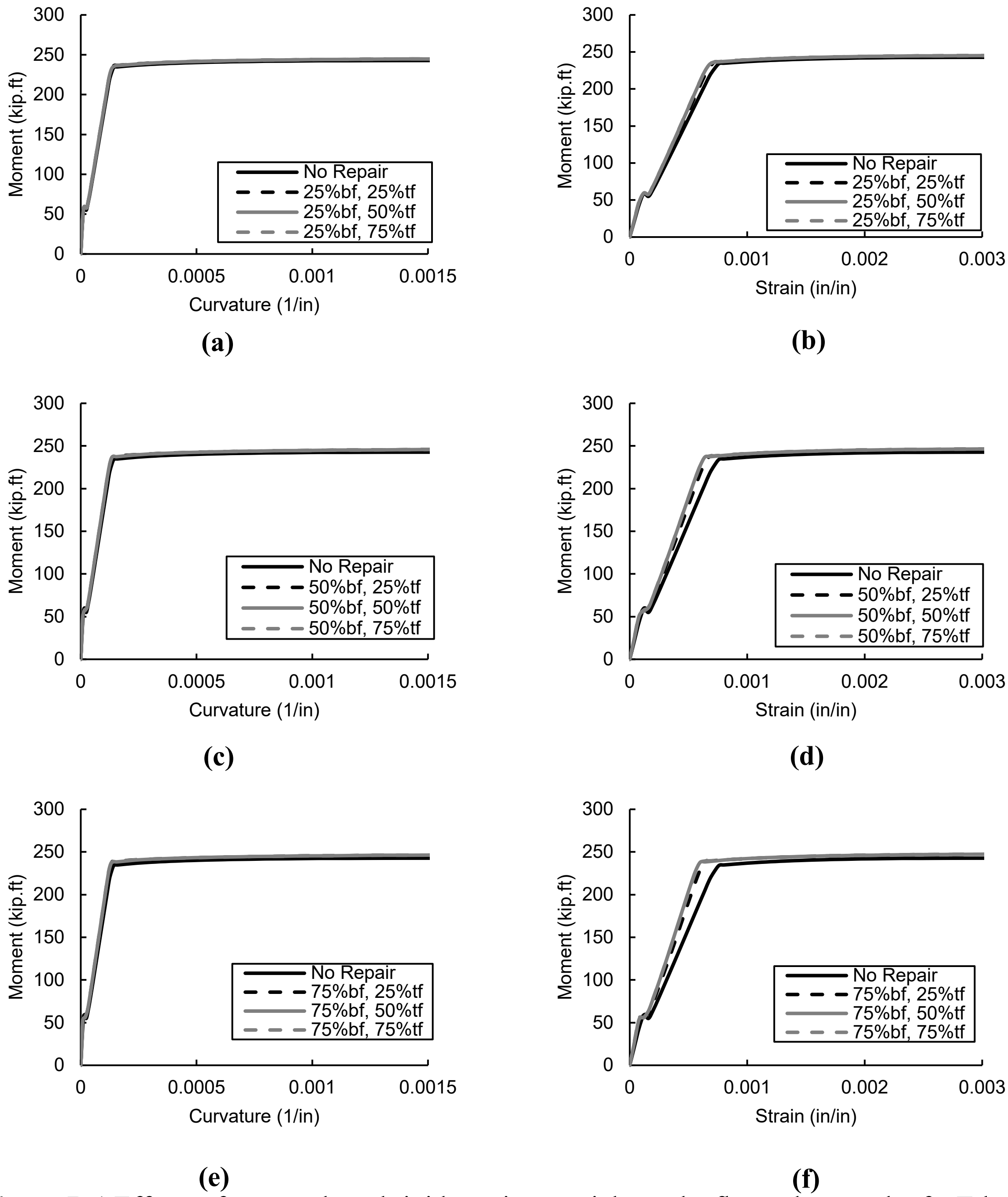


Figure B.1 Effects of cement-based rigid repair materials on the flexural strength of a T-beam a)moment-curvature curve for a 25%b_f repair width; b) moment-strain curve for a 25%b_f repair width; c) moment-curvature curve for a 50%b_f repair width; d) moment-strain curve for a 50% b_f repair width; e) moment-curvature curve for a 75%b_f repair width; f) moment-strain curve for a 75%b_f repair width. Each case covers a certain width with a depth of 25%, 50%, and 75%t_f

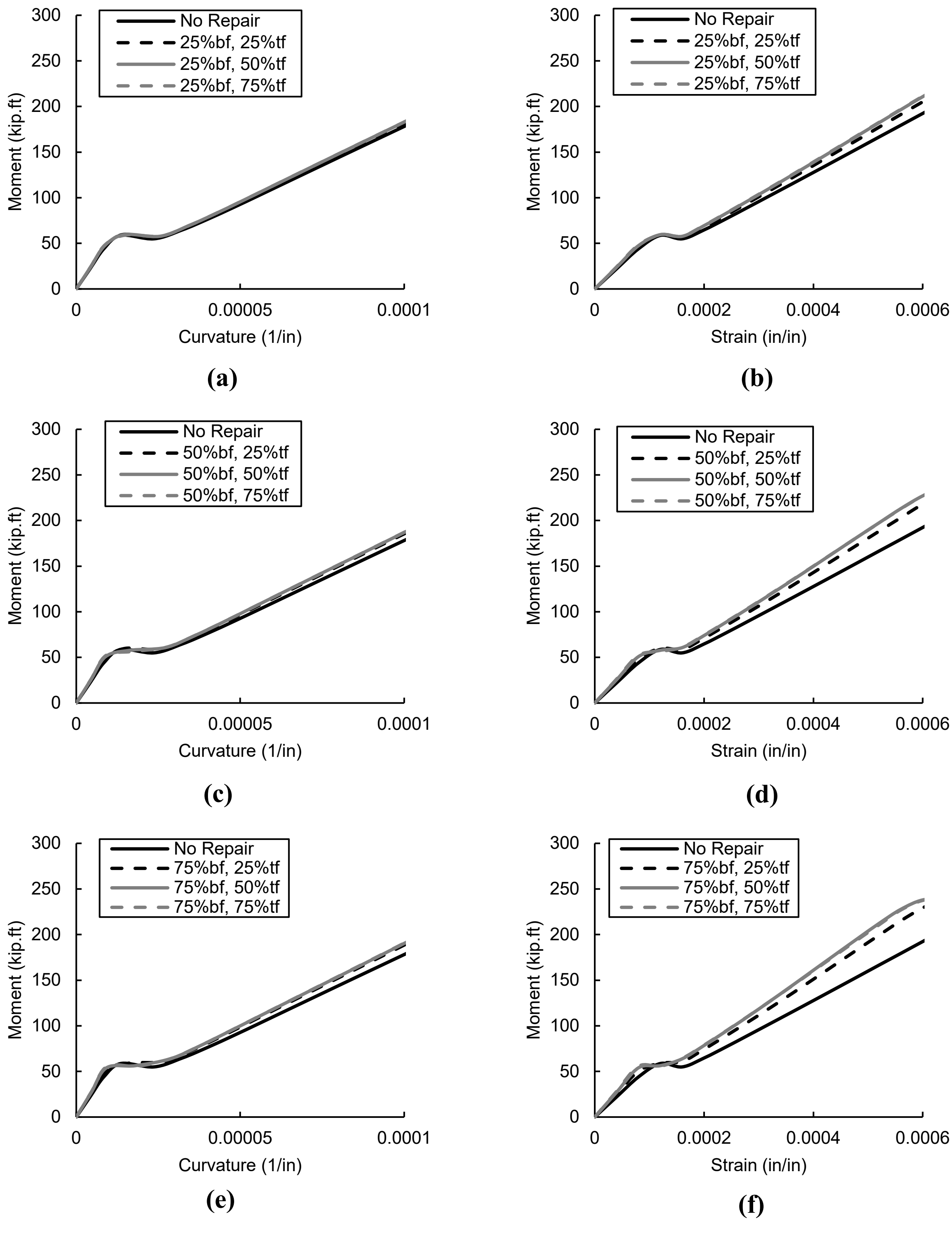


Figure B.2 The elastic part of a cement-based rigid repair material moment-curvature and moment-strain curves a)moment-curvature curve for a 25%b_f repair width; b) moment-strain curve for a 25%b_f repair width; c) moment-curvature curve for a 50%b_f repair width; d) moment-strain curve for a 50% b_f repair width; e) moment-curvature curve for a 75%b_f repair width; f) moment-strain curve for a 75%b_f repair width. Each case covers a certain width with a depth of 25%, 50%, and 75%t_f

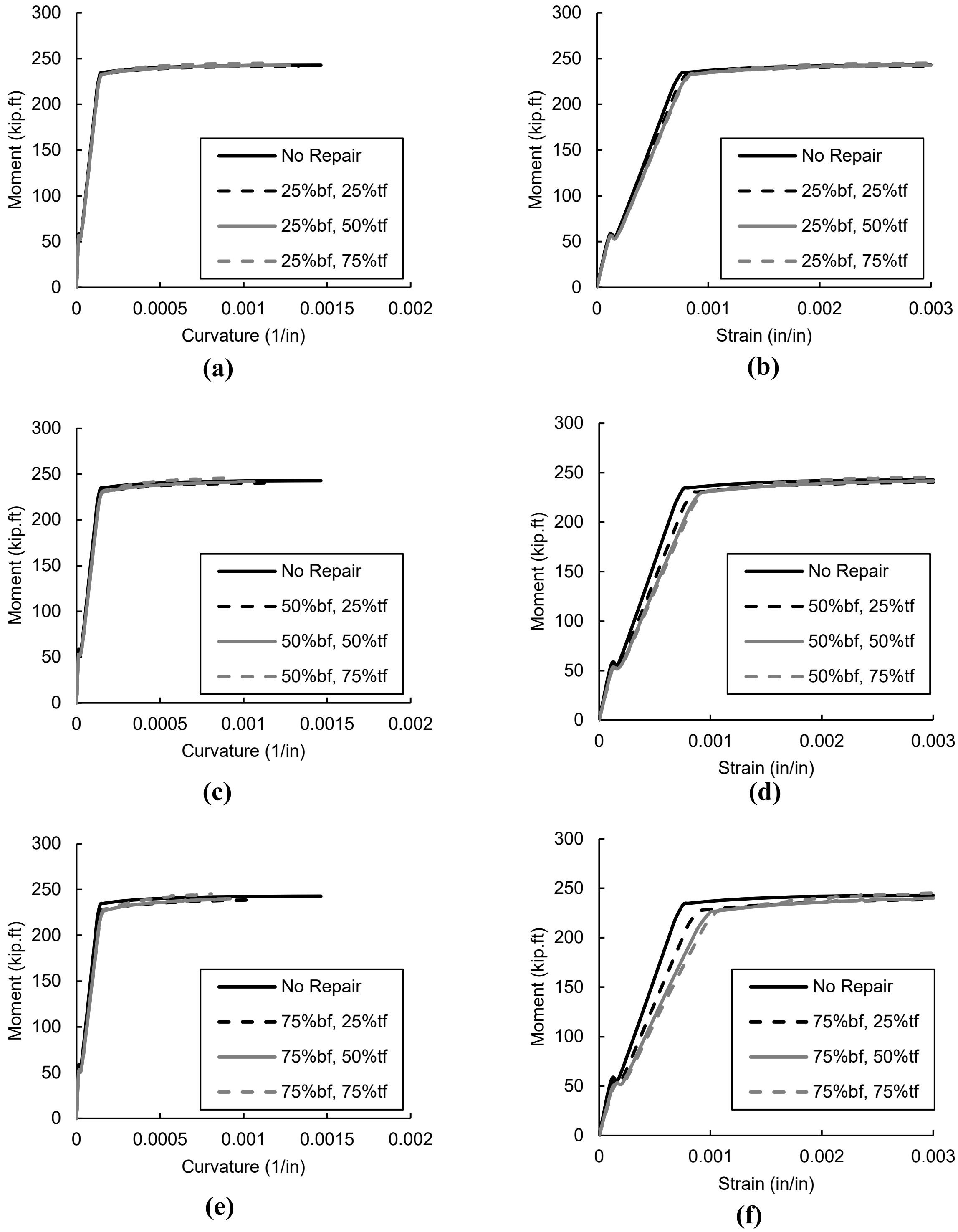


Figure B.3 Effects of polymer repair materials on the flexural strength of a T-beam a)moment-curvature curve for a 25%b_f repair width; b) moment-strain curve for a 25%b_f repair width; c) moment-curvature curve for a 50%b_f repair width; d) moment-strain curve for a 50% b_f repair width; e) moment-curvature curve for a 75%b_f repair width; f) moment-strain curve for a 75%b_f repair width. Each case covers a certain width with a depth of 25%, 50%, and 75%t_f

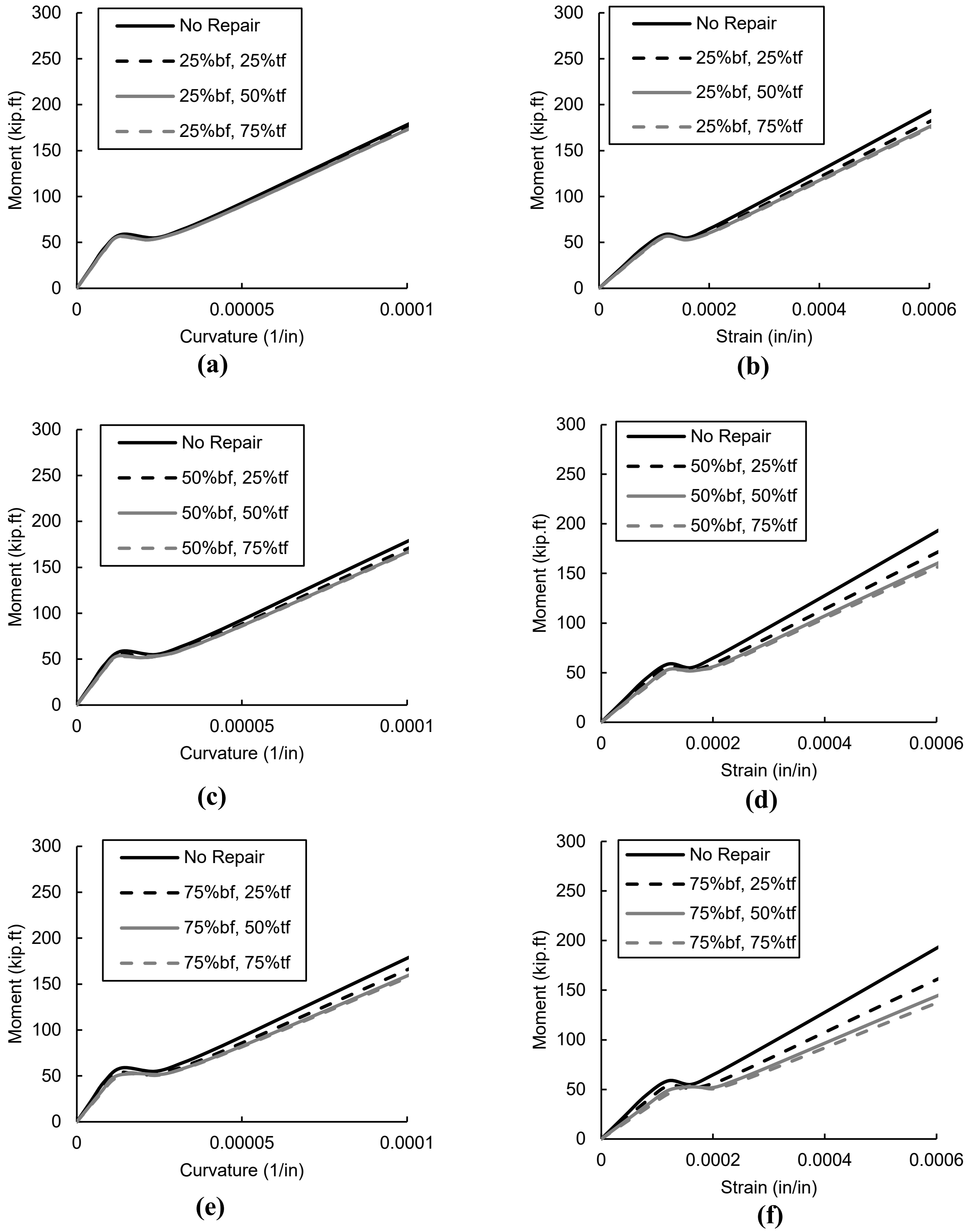


Figure B.4 The elastic part of a polymer-based HES material moment-curvature and moment-strain curves a)moment-curvature curve for a 25%b_f repair width; b) moment-strain curve for a 25%b_f repair width; c) moment-curvature curve for a 50%b_f repair width; d) moment-strain curve for a 50% b_f repair width; e) moment-curvature curve for a 75%b_f repair width; f) moment-strain curve for a 75%b_f repair width. Each case covers a certain width with a depth of 25%, 50%, and 75%t_f