

Sustainability and Resiliency of Concrete Rapid Repairs Utilizing Advanced Cementitious Materials: Freeze/Thaw Loads

FINAL REPORT
October 2019

Submitted by:

Matthew P. Adams, Ph.D., F.ACI
Assistant Professor

Matthew J. Bandelt, Ph.D., P.E.
Assistant Professor

Noah Thibodeaux
Graduate Research Assistant

John A. Reif, Jr. Department of Civil and Environmental Engineering
Newark College of Engineering
New Jersey Institute of Technology
University Heights, Newark, NJ 07102

External Project Manager

Richard Jones
NYC Department of Transportation

In cooperation with

Rutgers, The State University of New Jersey
And
U.S. Department of Transportation

Disclaimer Statement

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. This document is disseminated under the sponsorship of the Department of Transportation, University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.

The Center for Advanced Infrastructure and Transportation (CAIT) is a Regional UTC Consortium led by Rutgers, The State University. Members of the consortium are Atlantic Cape Community College, Columbia University, Cornell University, New Jersey Institute of Technology, Polytechnic University of Puerto Rico, Princeton University, Rowan University, SUNY - Farmingdale State College, and SUNY - University at Buffalo. The Center is funded by the U.S. Department of Transportation.

1. Report No. CAIT-UTC-REG 2A		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Sustainability and Resiliency of Concrete Rapid Repairs Utilizing Advanced Cementitious Materials: Freeze/Thaw Loads				5. Report Date October 2019	
				6. Performing Organization Code CAIT/NJIT	
7. Author(s) Matthew P. Adams https://orcid.org/0000-0002-3298-2913 , Matthew J. Bandelt https://orcid.org/0000-0001-6681-2376 , Noah Thibodeaux https://orcid.org/0000-0001-7306-8178				8. Performing Organization Report No. CAIT-UTC-REG 2A	
9. Performing Organization Name and Address John A. Reif, Jr. Department of Civil and Environmental Engineering Newark College of Engineering New Jersey Institute of Technology University Heights, Newark, NJ 07102				10. Work Unit No.	
				11. Contract or Grant No. 69A3551847102	
12. Sponsoring Agency Name and Address Center for Advanced Infrastructure and Transportation Rutgers, The State University of New Jersey 100 Brett Road Piscataway, NJ 08854				13. Type of Report and Period Covered Final Report 09/01/2018 - 08/31/2019	
				14. Sponsoring Agency Code	
15. Supplementary Notes U.S. Department of Transportation/OST-R 1200 New Jersey Avenue, SE Washington, DC 20590-0001					
16. Abstract This report provides a review of advanced cementitious materials that can be used in transportation infrastructure to resist freeze-thaw loading durability conditions. The report begins by providing a literature review of the mechanical and durability properties of rapid repair systems. A summary of discussion points held during a workshop held on rapid-repair systems at New Jersey Institute of Technology is presented. A proposed methodology for assessing the performance of rapid-repair systems in partial depth repair systems is explored when subjected to freeze-thaw loading. Recommendations for future research to improve the state of knowledge on repair systems are discussed.					
17. Key Words Concrete, Freeze-thaw, alternative cements, portland cement, overlay, rapid repair, bond				18. Distribution Statement	
19. Security Classification (of this report) Unclassified		20. Security Classification (of this page) Unclassified		21. No. of Pages 40	22. Price

Acknowledgments

The research team would like to acknowledge the support of this work from the Center for Advanced Infrastructure and New Jersey Institute of Technology. Additionally, we would like to thank Lafarge-Holcim, Imerys Aluminates, Quikrete, Mapei, and Weldon for generously donating supplies.

Table of Contents

1. Introduction.....	1
1.1 Description of the Problem.....	1
1.2 Approach.....	2
1.3 Organization of Report	2
2. Literature Review.....	3
2.1 Partial Depth Repairs	3
2.2 Rapid Repair Materials.....	4
2.2.1 Calcium Aluminate Cements.....	4
2.2.2 Calcium Sulfoaluminate Cements	6
2.2.3 Blended Cement Systems	7
2.3 Repair Surface Preparation.....	8
2.4 Bond Zone and Dimensional Stability.....	11
2.4.1 Volume stability and drying shrinkage.....	11
2.4.2 Thermal Compatibility	12
2.5 Deterioration Mechanisms	12
2.5.1 Freeze-Thaw Attack	13
2.5.2 Corrosion	15
2.5.2.1 Carbonation	16
2.5.2.2 Chloride Ingress.....	17
2.5.3 Salt Scaling.....	18
3. Workshop on Rapid Repair Systems	20
3.1 Overview.....	20
3.2 Format and Layout.....	20
3.3 Advertisement, Attendance, and Feedback.....	21
4. Methodology and Findings for Guidelines for Rapid Repair Systems for Freeze-thaw Loading	22
4.1 Intent of Guideline	22
4.2 Substrate Preparation	22
4.3 Overlay Placement and Testing	24
4.4 Recommended Conditioning Intervals	25
4.5 Preparation for ASTM C1583.....	26
4.6 Pull-off strength testing and interpretation of results	28
5. Summary, Conclusions, and Recommendations.....	30
5.1 Summary and Conclusions	30

5.2	Recommendations for Future Research	30
-----	---	----

List of Figures

Figure 2.1: Representation of definitions of pavement preservation, rehabilitation, and reconstruction [1].....	4
Figure 2.2: Hydration reactions of monocalcium aluminate [17].....	6
Figure 2.3: Schematic strength development of calcium aluminate cements at a water cement ratio of about 0.4 [17].	6
Figure 2.4: Strength development of PC and CAC based systems [18]	8
Figure 2.5: Length change of concrete prisms submitted to drying conditions [32]	12
Figure 2.6: Crack patterns of damaged specimens by freezing and thawing at low magnification (SEM-backscattered, 15X) [33].....	14
Figure 2.7: Freeze-Thaw durability of alternative cement systems subjected to ASTM C666 [9]	15
Figure 2.8: Relative volume of corrosion products [7].....	16
Figure 2.9 : Chloride penetration after 40 and 180 days [18].....	18
Figure 3.1 : Rapid Repair Cements Workshop Flyer.....	20
Figure 4.1 (a) & (b): Substrate casting setup	23
Figure 4.2: Substrate preparation.....	24
Figure 4.3: Freeze-thaw chamber	24
Figure 4.4: Freeze-thaw specimen procedure	26
Figure 4.5: Preparation of a specimen for ASTM C1583 by core drilling	27
Figure 4.6: Pull-off test modification for ASTM C666 specimens	27
Figure 4.7: Controls Group™ pull-off strength load cell.....	28
Figure 4.8: Failure modes of specimens tested according to ASTM C1583 [45].....	29

List of Tables

Table 2.1: Methods for preparing concrete surfaces for overlays	10
---	----

Chapter 1

Introduction

1.1 Description of the Problem

Highway and road infrastructure are prone to various deterioration mechanisms that reduce their service life [1], [2]. Concrete is susceptible to deterioration mechanisms resulting in premature cracking and spalling, reduced strength, and overall deterioration. In highway roads and bridge decks, premature cracking and spalling of the roadway surface can result in potentially hazardous road conditions.

Freeze-thaw attack is one such deterioration mechanism that engineers must design to resist. Cyclic freezing and thawing causes significant cracking in concrete structures as water entrapped in the pore matrix expands when temperatures drop below the freezing point of water [3], [4]. Another common deterioration mechanism comes in the form of corrosion of the reinforcement, which leads to cracking and spalling as the corrosion products form at a volume that is multiple times that of the reinforcement, exerting tensile stresses on the concrete matrix [5]–[7]. Corrosion can be the result of carbonation or chloride ingress. Salt scaling is another form of deterioration in roadways subjected to deicing salts in combination with cyclic freezing and thawing. This form of deterioration takes place when deicing salts placed on the road surface go into solution and infiltrate the pore structure of the concrete [8]. Once these ions penetrate the concrete, they can interact chemically with the cementitious matrix, breaking down the hydration products. The breakdown of hydration products can lead to peeling and delamination of the finished surface. Due to the need for public safety, highly corrosive deicing salts are commonly used to maintain road conditions that are safe for drivers when freezing conditions exist on bridges, overpasses and road structures.

The previously mentioned deterioration mechanisms require regular maintenance to keep transportation infrastructure operational. Construction materials that can be rapidly installed at deteriorated sites can extend the service life of a structure without requiring complete demolition and reconstruction [1]. In the area of concrete, rapid repair systems are generally described by their quick strength-gaining performance. Due to their unique system chemistries, rapid repair materials exhibit different mechanical and durability properties than that of Ordinary Portland Cement (OPC) concretes. While various rapid repair blends are utilized for the repair of deteriorated concrete pavements, their mechanical and durability properties are not well documented in the context of partial depth repair (PDR) applications and failures are relatively common [9].

1.2 Approach

The overall objective of this project is to investigate the use of rapid-repair materials for retrofit of transportation infrastructure systems. To achieve this objective, the following research tasks were completed:

- Task 1 – Investigate the chemical makeup, mechanical properties, durability behavior, and applications of rapid repair systems through a comprehensive literature review.
- Task 2 – Engage researchers, engineers, contractors, transportation officials, and other stakeholders through a workshop on rapid-repair systems for transportation infrastructure.
- Task 3 – Develop a methodology to physically test rapid repair materials under freeze-thaw conditioning in order to assess their performance in partial depth repair projects for transportation infrastructure.

1.3 Organization of Report

This report is organized into five chapters, including this introductory chapter. The major topics of each chapter are summarized below.

Chapter 2 provides a background on partial depth repairs in pavements and bridge decks, rapid repair materials, and deterioration mechanisms. An emphasis is placed on the chemical composition of rapid repair materials, and their associated in-service properties.

Chapter 3 provides a summary of a workshop held on rapid repair systems as part of this research project. An overview of the workshop is provided, along with a summary of attendees, and lessons-learned during the presentations, demonstrations, and roundtable discussions.

Chapter 4 summarizes a series of proposed methodology for evaluating the effectiveness of rapid-repair systems when subjected to freeze-thaw loading. An emphasis is placed on evaluating the bond-zone behavior between rapid repair systems and existing concrete substrates.

Chapter 5 summarizes the main contributions of this research project. Recommendations for future research on evaluating the bond zone of rapid-repair systems under freeze-thaw conditioning for in-service are documented.

Chapter 2

Literature Review

2.1 Partial Depth Repairs

The presence of deterioration mechanisms coupled with traffic loading necessitates the use of repair materials to effectively increase the service life of a structure without complete reconstruction. Reconstruction of a road surface can be costly and time consuming, leading to lane closures and delays on road infrastructure. For this reason, concrete resurfacing practices are used in areas where deterioration has compromised the pavement structure. A repair solution can consist of a bonded or unbonded overlay system; where bonded systems are utilized in situations where the existing pavement is in fair structural condition and the repair thickness is 2 – 6 in. [2]. Partial depth repairs (PDRs) are bonded systems that are effective in rehabilitating areas of localized spalling, thereby restoring the performance of the pavement and extending its service life [10]. PDRs are useful when deterioration is limited to joint failures between pavements and in areas where a third or less of the total depth of the pavement structure is determined to be unsound [1]. PDRs involve the removal and replacement of small sections of deteriorated concrete pavement, effectively slowing or eliminating the spread of damage that tends to occur due to thermal stress, freezing and thawing, and traffic loading [4]. There are different types of PDRs that fall into different categories according to the FHWA concrete preservation guide [1]:

- Type 1: Spot repair of cracks, joints and spalls
- Type 2: Joint and crack repairs
- Type 3: Bottom-half repairs

Partial depth repairs can extend the service life of a structure at a cost well below that of reconstruction while enabling lane closures to be relatively short [1], [2], [11]. Figure 2.1 graphically demonstrates various maintenance and repair definitions for damaged pavement structures as a function of time. PDRs are also useful in emergency situations where there is not ample time to procure and place a new concrete paver. One of the issues facing transportation agencies when repairing overpass and bridge pavement structures is the limited amount of time that lanes can be closed without having adverse impacts on traffic flow. The presence of traffic and delays on critical arterial roads has long been considered to have significant economic impacts [12], [13]. As such, there is a need for repair materials that can work effectively in a short period of time. Rapid repair materials must exhibit high early strength gain properties to maintain an adequate bond to the existing substrate while sustaining mechanical loads from traffic shortly after placement. For this reason, traditional OPC systems are generally insufficient

for rapid repairs. In addition to rapid strength gain, a material for use on a PDR is suitable when it exhibits a reasonable cost, high workability, short curing time, high bonding strength, long-term durability, and thermal compatibility with the existing concrete [14]. While many rapid repair materials have been used extensively for PDRs, their long-term durability has not been well quantified in the presence of freeze thaw and sulfate attack. A study on the properties of a few selected rapid repair materials found the freeze thaw durability of many of them to be unacceptable, especially in severe exposure conditions [15]. Due to the geometry of PDRs and the stresses they undergo while in service, it is important to understand and assess their strength and adhesion properties in the context of durability.

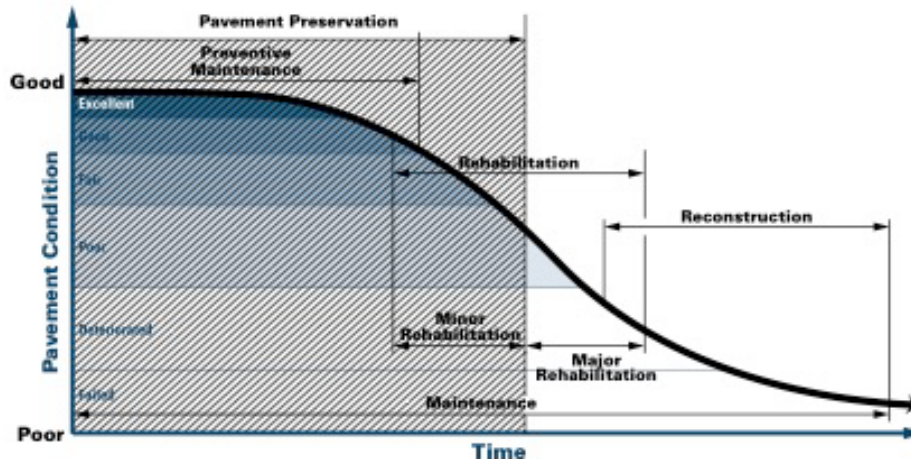


Figure 2.1: Representation of definitions of pavement preservation, rehabilitation, and reconstruction [1]

2.2 Rapid Repair Materials

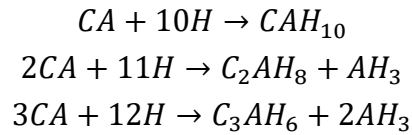
There exists a number of recognized rapid repair cements for use on PDRs that exhibit rapid strength gain properties, allowing for short lane closure times. Many of these systems attain high early strength as a result of the predominance of ettringite formation. Most rapid repair materials are made up of a blend of alternative cement chemistries. Some of the primary alternative cement chemistries are described herein.

2.2.1 Calcium Aluminate Cements

Calcium aluminate cements came about in the late 19th and early 20th centuries in Europe, originally intended to be resistant to the presence of high sulfate concentrations and seawater [9]. Upon further development, Jules Bied developed a blend of CAC low in silica and high in alumina and patented the blend as Ciment Fondu Lafarge in 1908 [16]. CAC is approximately four to five times more expensive compared to OPC [9], [17]. These cements exhibit superior heat refractive properties when compared to OPC and, as such, are best utilized in applications where high temperatures exist. CACs are also used in blends to produce mixtures with self-

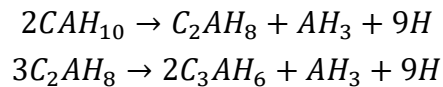
leveling properties and rapid strength gain properties [9]. The high early strength properties of CACs make them suitable for rapid repair applications.

Calcium aluminate cement (CAC) is the product of pulverized clinker consisting of mainly hydraulic calcium aluminates, a product obtained from fusing a mixture of aluminous and calcareous materials, namely limestone and bauxite [17], [18]. The production of CACs utilize a reverberatory open-hearth furnace, and in some cases a rotary or top-loader kiln [18]. The principal oxides of CACs are CaO and Al₂O₃, with little or no silica as compared to OPC systems. Combination of these oxides results in monocalcium aluminate (CA) as the primary active phase, which gives calcium aluminate hydrates when mixed with water [17]. The main products of CACs are formed according to the reactions shown [9]:



The hydration of CACs is highly temperature dependent. In general, higher curing temperatures result in earlier strength gain. CAC systems can achieve 100% of their ultimate strength when cured at temperatures between 40 and 50 C in less than 6 hours [19].

One of the biggest concerns with CACs is the inevitable process known as conversion. Calcium Aluminate Cements go through a process known as conversion wherein the metastable hydrates, CAH₁₀ and C₂AH₈ convert to stable hydrates, C₃AH₆ and AH₃ [17]. These reactions are given below [9].



These conversion reactions can occur slowly on the order of decades if the w/c is high and the temperature is below 95 °F or in a few days if the w/c is low and the temperature upon initial curing is above 150 °F [9]. Figure 2.2 represents the conversion process as a function of both temperature and time. The hydrates generated in the initial reaction is highly temperature dependent. Due to the high heat of hydration of CACs, large sections will undergo conversion much faster as the mass concrete will retain the heat generated from the hydration [17].

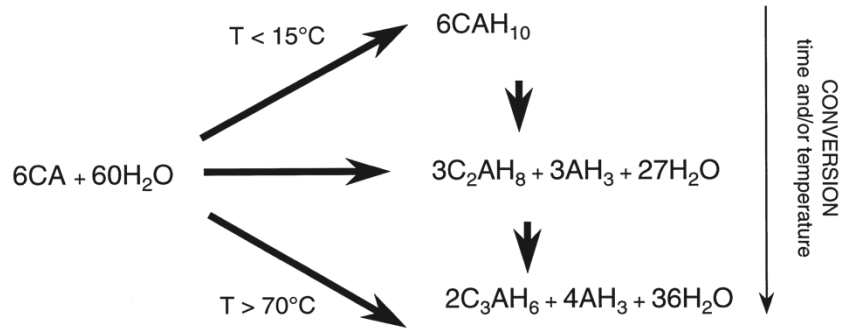


Figure 2.2: Hydration reactions of monocalcium aluminate [17]

The conversion of pure CAC systems is associated with a loss of long-term strength due to the nature of the stable hydrates [17], [19]. The stable hydrates are denser than the metastable hydrates, resulting higher porosity [17]. This is especially true at higher w/cm ratios of greater than 0.5. For this reason, CACs produced at a w/cm of about 0.4 decreases the loss of solid volume and, therefore, the porosity [17]. Formation of stable hydrates as a result of conversion is an inevitable process, and this necessitates unique long-term design considerations when utilizing CAC systems for structural members. Figure 2.3 represents the strength characteristics of CAC over time for sections of different size.

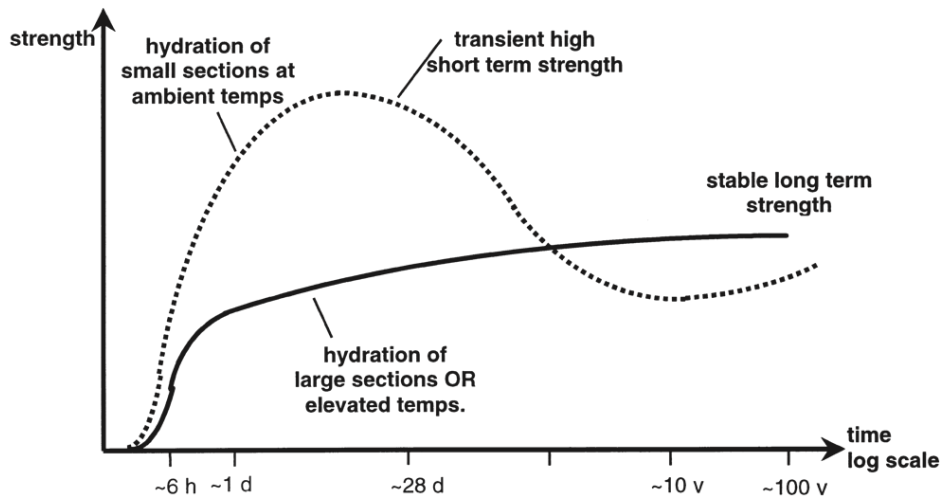
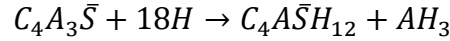


Figure 2.3: Schematic strength development of calcium aluminate cements at a water to cement ratio of about 0.4 [17].

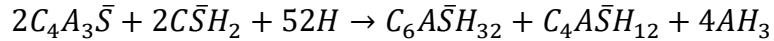
2.2.2 Calcium Sulfoaluminate Cements

Calcium Sulfoaluminate Cement (CSA) is a low-CO₂ producing cement made from calcium sulfate, limestone, and bauxite at a temperature of 1250 °C [20]. The production of

clinkers rich in CSA does not require as much limestone or input energy when compared to the production of Portland cement clinkers [21]. These cements contain belite (C_2S), yeelimite or tetracalcium trialuminate sulfate ($C_4A_3\bar{S}$) and gypsum ($C\bar{S}H_2$) as their primary phases [22]. Hydration characteristics of these cements is primarily dependent on calcium sulfate and/or calcium hydroxide [18]. A mixture of pure $C_4A_3\bar{S}$ and water will form monosulfate ($C_4A\bar{S}H_{12}$) and aluminum hydroxide (AH_3) [18].



The presence of calcium hydroxide and gypsum results in the formation of ettringite ($C_6A\bar{S}_3H_{32}$) and more monosulfate, depending on the molar ratio. The reaction is written as:



Systems interground with OPC and gypsum will produce ettringite alone [18], [23]. CSA cements exhibit rapid strength gain and heat evolution primarily as a result of ettringite formation. These systems can attain strengths of 20 MPa or greater in 3 hours [18]. XRD analyses show the formation of ettringite 15-20 minutes after mixing, a primary source of early-age strength [24]. The continuous increase of strength at later ages observed in CSAs results from the hydration of other phases such as belite as gypsum is rapidly consumed [24].

2.2.3 Blended Cement Systems

Due to the various advantages and disadvantages of pure alternative cement systems, most available products utilize a blend of different cement chemistries to achieve a product that will meet the demanding requirements of PDRs. Systems made up of a blend of various cement chemistries result in a material with unique hydration, strength and durability properties. By harnessing the potential of various systems, a fast-setting material with superior strength and durability properties can be achieved.

For example, one of the benefits of producing a blend involving Calcium Aluminate Cement (CAC) and Calcium Sulfate ($C\bar{S}$) with OPC is the possibility of eliminating conversion effects normally experienced by pure CAC systems. The formation of metastable and stable hydrates is replaced with the early formation of ettringite followed by calcium aluminate hydrates as well as hydrated phases normally found in OPC [25]. Figure 2.4 shows a comparison of the compressive strength development of ettringite-based systems to that of OPC while also comparing it to a pure CAC system. It can be observed that the ternary blend comprised of PC-CAC- $C\bar{S}$ exhibits both high early and long-term strength.

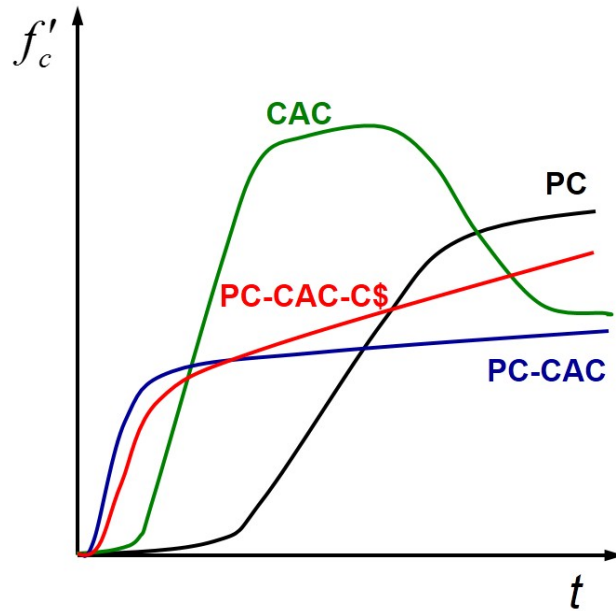


Figure 2.4: Strength development of PC and CAC based systems [18]

2.3 Repair Surface Preparation

The FHWA Concrete Preservation Guide details some of the field procedures for preparation of patch repairs [1]. A partial-depth repair involves the removal of small sections of deteriorated concrete that are then filled in with a suitable repair material. Proper preparation of the substrate is essential to ensure that the repair boundary is appropriate based on the condition of the concrete and to ensure an adequate bond between the existing concrete and the repair area.

Repair Boundaries

The repair boundary is generally determined by “sounding” the concrete with a steel rod, a heavy chain, or a ball-peen hammer [1]. A sharp metallic ringing is associated with sound concrete as the impact energy is transferred almost entirely back into the instrument used for sounding. A dull or hollow thud is associated with unsound concrete as delaminated sections will respond to impact without transferring energy back into the sounding tool. The repair areas are marked keeping in mind the minimum repair dimension requirements of 10 in. long and 4 in. wide for cementitious materials. Because manufacturers often specify minimum dimensions for their blends, those requirements should be adhered to as well. The FHWA Concrete Preservation Guide recommends that the repair boundaries exceed the visibly damaged or unsound area by 3 in.

Concrete Removal

After the repair boundaries are determined, the next step involves removal of the deteriorated material. Most repairs involving cementitious binders should be at least 2 in. deep to

ensure volume and weight stability [1]. Most proprietary blends will have a minimum depth requirement specified; these dimensions should control the design considerations. There are several methods employed for the removal of deteriorated concrete:

- Saw-and-patch (Type 1 repairs)
- Chip-and-patch (Type 1 and 3 repairs)
- Mill-and-patch (Type 1 and 2 repairs)
- Clean-and-patch (emergency Type 1 repairs)
- Hydrodemolition (all types)

These procedures (except for Clean-and-patch) create a rough surface. A rough surface exhibits a high surface area. This ensures that the bond area is maximized and that a repair material is able to bond sufficiently.

Repair Area Preparation

When placing a PDR, it is essential that proper concrete removal procedures have taken place to ensure an rough surface. Surface preparation ensures that a sound, clean, and suitably roughened surface is achieved and that laitance, dirt, oil, films, paint, coatings, sound and unsound concrete, and other materials [310-2R]. Surface roughness is one of the most important attributes of a prepared substrate [26]–[28]. Many methods exist for measuring the degree of roughness [29]. According to the ICRI, there are several methods that can be used to prepare a concrete surface for an overlay, they are summarized in Table 1.

Table 2.1: Methods for preparing concrete surfaces for overlays

Surface preparation method	Concrete Surface Profile									
	CSP 1	CSP 2	CSP 3	CSP 4	CSP 5	CSP 6	CSP 7	CSP 8	CSP 9	CSP 10
Detergent scrubbing	■									
Low-pressure water cleaning	■									
Grinding	■	■								
Acid etching	■	■	■							
Needle scaling		■	■	■						
Abrasive blasting		■	■	■	■	■	■			
Shotblasting		■	■	■	■	■	■	■	■	
High- and ultra-high-pressure water jetting		■	■	■	■	■	■	■	■	■
Scarifying			■	■	■	■	■			
Surface retarder (1)				■	■	■	■	■	■	■
Rotomilling					■	■	■	■	■	■
Scabbling						■	■	■	■	■
Handheld concrete breaker							■	■	■	■

(1) Only suitable for freshly placed cementitious materials

Once the area has been prepared, it must be cleaned to ensure debris generated from surface cutting, grinding, or milling do not impact the bond performance. A properly prepared surface ensures good bond development between the repair material and the existing substrate. Some of the methods for area preparation include dry sweeping, light sandblasting, and compressed air blasting [1].

Joint Preparation

Joint repairs tend to be subject to compression failure. PDRs that interact with transverse joints and cracks can undergo failure due to crushing when slabs expand [1]. In addition, failure may occur when the material flows into the joint below the bottom of the repair, preventing slab movement and proper joint function. Placing a strip of compressible material such as polystyrene, polyethylene, asphalt-impregnated fiberboard [1]. This type of inset is often referred to as a bond breaker or joint reformer and prevents these failures. This strip also serves to

provide a reservoir into which joint sealant can be placed. In addition to preplacement operations, there are procedures that must be taken after the rapid repair material has sufficiently hardened. Any PDR placed across a joint or crack must have the crack reestablished by utilizing compressible materials or saw cutting of the repair.

Bonding Agent Application

Many rapid repair cements require the placement of a bonding agent to ensure a strong bond is developed. Cement grouts are commonly used but epoxy grouts can also be used for faster opening times. Prior to the application of cement grout, the repair surface should be in a saturated surface dry (SSD) condition. Manufacturers often specify preparation instructions.

2.4 Bond Zone and Dimensional Stability

One of the primary concerns with patch repairs such as PDRs is the integrity of the bond zone at the interface of the repair material and the existing substrate. The long-term effectiveness of a repair is limited by the quality and durability of the bond zone [30]. For this reason, all bonded overlays are designed and constructed in a manner that establishes a good bond between the substrate and the overlay [2]. The stresses experienced by a repair material are unique due to the geometry of the bond zone between the repair and the existing substrate. Because it is essential that the existing pavement and the repair overlay behave as one structure to achieve desired performance, the dimensional stability and movement related properties must be understood [2].

2.4.1 Volume stability and drying shrinkage

Many cementitious materials undergo shrinkage throughout their service life. Concrete can undergo volume reductions due to drying shrinkage, especially in an exposed environment where temperature and moisture fluctuations exist in addition to high levels of carbon dioxide from vehicle emissions. It is important that the repair material exhibits a relatively low shrinkage compared to the substrate so that high stresses do not develop at the bond zone. The shrinkage compatibility of the substrate and the repair is critical in order to prevent premature failure of the repair. Additionally, a repair material should be dimensionally stable relative to the substrate [31]. Pure CAC systems experience drying shrinkage greater than that of OPC systems whereas pure CSA systems experience drying shrinkage less than that of OPC [32]. Figure 2.5 demonstrates this comparison. Blended systems will exhibit various levels of shrinkage based on the particular chemistry of the mix.

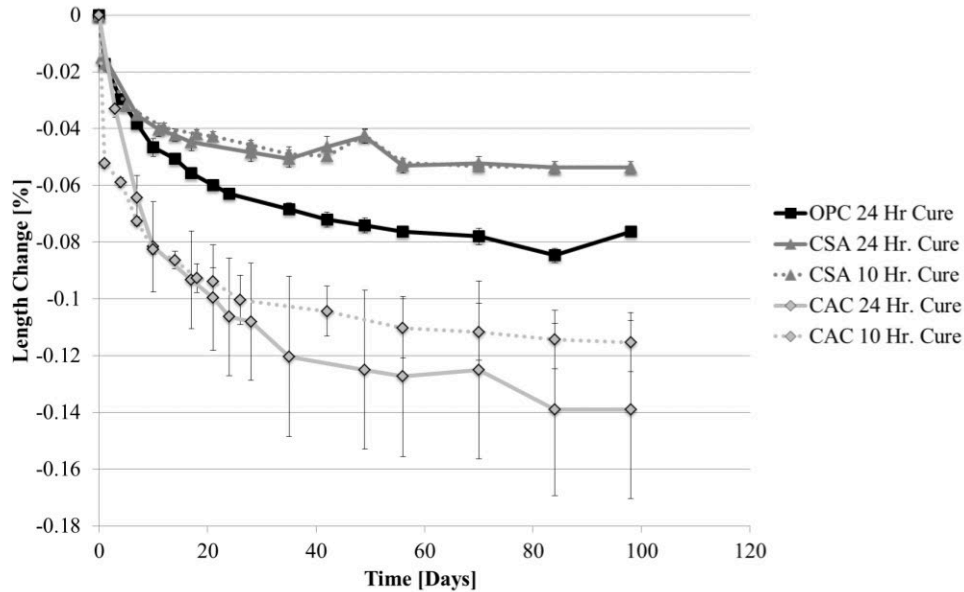


Figure 2.5: Length change of concrete prisms submitted to drying conditions [32]

Concrete utilizing a low water-to-cement ratio (w/cm) generally results in less drying shrinkage. As a result, it would follow that utilizing a low w/cm in a rapid repair material will result in less shrinkage. It has been observed, however, that high strength and high-early strength concretes are more susceptible to cracking due to increased autogenous shrinkage, increased stiffness, increased brittleness, and decreased creep [31]. These factors can be exasperated in rapid repair materials due to higher paste volumes and a high rate of material property development.

2.4.2 Thermal Compatibility

Due to the need for dimensional stability of rapid repair materials, it is important that a repair material has a coefficient of thermal expansion (CTE) that is similar to that of the substrate [31]. OPC concrete exhibits CTE values ranging from 8 – 12 $\mu\epsilon/^\circ\text{C}$ [9]. Typically, the aggregate used in the mixture will largely define the CTE of a mix as the aggregate represents the majority of the volume content. Limestone aggregates have lower CTE values compared to siliceous aggregates [9]. Any proprietary blend utilized in a repair scenario needs to be evaluated with the aggregate that will be used in the repair.

2.5 Deterioration Mechanisms

Concrete structures exposed to environmental conditions are often subject to various deterioration mechanisms. The deterioration of roadway infrastructure is widespread across the United States. Every four years, the American Society of Civil Engineers (ASCE) rates the condition of American infrastructure across all major categories in the form of a report card. The

current state of infrastructure scores a D+, with bridges scoring a C+ and roads scoring a D. There is a need, therefore, to assess the long-term durability of both future and current infrastructure. The usefulness of a repair technology to extend the service life of an existing structure is limited by its durability characteristics. Corrosion of reinforcing steel, shrinkage cracking, freezing and thawing, and chemical attack (such as chloride ingress) are some of the primary deterioration mechanisms observed in concrete structures. In all of these cases, water is either the primary damage initiator, or the transport medium whereby damaging agents are transported through the pore matrix [33]. For this reason, deterioration mechanisms and their probability of occurrence are often studied relative to the transport properties of concrete.

2.5.1 Freeze-Thaw Attack

Concrete exposed to temperatures above and below freezing are subject to cracking and spalling as a result of tensile stresses that develop upon the freezing of water existing in the pore structure. Joints are especially susceptible to cyclic freezing and thawing due to the prevalence of moisture saturation in these zones [2]. Water expands upon freezing, increasing in volume by approximately 9% [9]. The freeze-thaw durability of a cementitious system is largely based on the permeability and transport properties of the material. The freezing point and amount of ice formed in the pore structure of concrete is closely related with the volume, radius and size distribution of pores [4]. A particular effect often observed in pavements in need of repair is the failure of joints. This particular type of damage is observed as either crack development parallel to the joint or spalling and cracking from the bottom of a saw cut to the surface of the pavement [34]. Unfortunately, this type of damage is not often observed at the surface until significant damage has already occurred.

It has been long observed that air-entrainment of concrete prevents premature deterioration as the water absorbed in the concrete matrix is given room to expand into the pore structure as it freezes [35]. While increasing the air content of concrete can delay the initiation of freeze-thaw damage, it is evident that this measure alone cannot entirely eliminate the possibility of premature deterioration due to the effects of cyclic freezing and thawing [34], [35]. Figure 2.6 shows the cracking in saturated concrete subjected freezing and thawing. The specimen shown was made using Type I Portland cement with an air entraining admixture to achieve an air content of 8%.

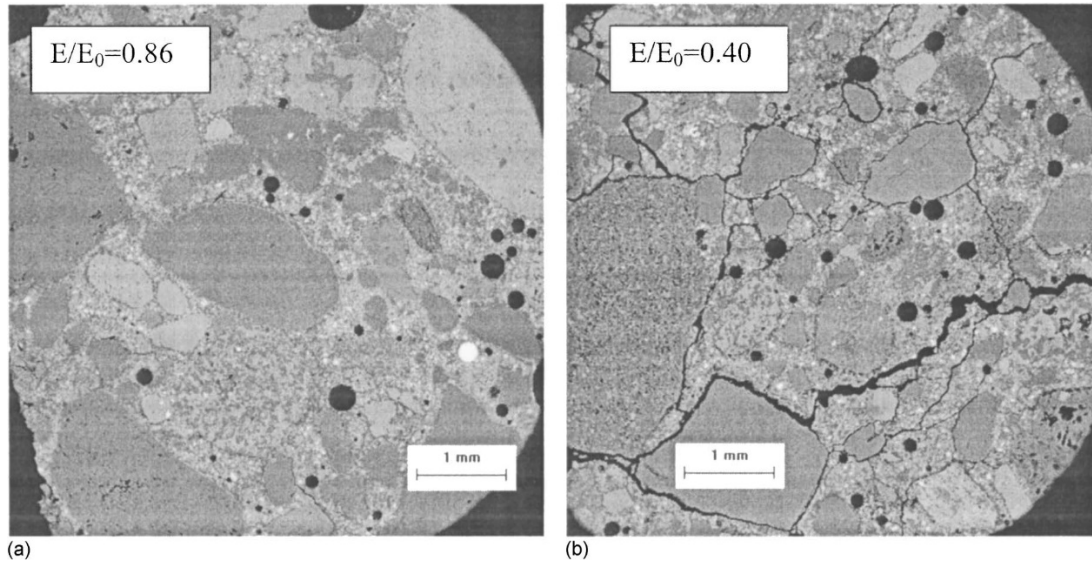


Figure 2.6: Crack patterns of damaged specimens by freezing and thawing at low magnification (SEM-backscattered, 15X) [33]

Alternative cement systems exhibit different freeze-thaw durability characteristics due to their unique pore structures. In a study performed on various patch repair materials, many of the systems did not perform satisfactorily, exhibiting a relative dynamic modulus of less than 60% after 300 cycles [15]. In a report published for the Texas Department of Transportation to evaluate the durability properties of alternative cement binders, ASTM C666 was followed to obtain a “durability factor” for the various cementitious materials used [9]. The durability factor prescribed by ASTM C666 is given by:

$$DF = PN/M$$

Where:

DF = durability factor of the test specimen

P = relative dynamic modulus of elasticity at N cycles, %

N = number of cycles at which P reaches the specified minimum value for discontinuing the test or the specified number of cycles at which the exposure is to be terminated, whichever is less

M = specified number of cycles at which the exposure is to be terminated

Figure 2.7 shows the results of this study, indicating both Calcium Aluminate Cement (CAC) and Calcium Sulfoaluminate Cement (CAC) systems can exhibit high resistance to freeze-thaw cycles, depending on their specific makeup. Any mix denoted with a “P” represents a proprietary blend.

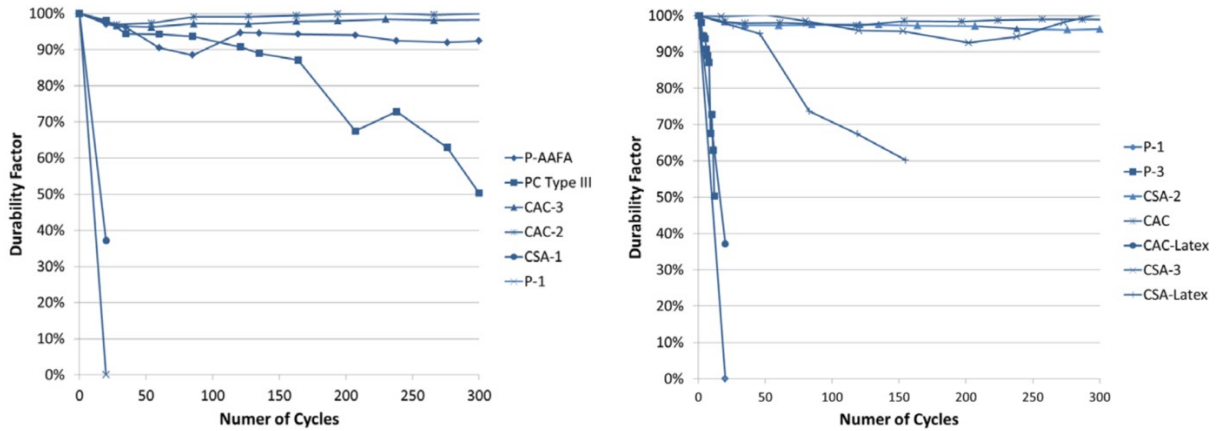


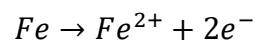
Figure 2.7: Freeze-Thaw durability of alternative cement systems subjected to ASTM C666 [9]

The bond of a repair material to an existing substrate will be affected by cyclic freezing and thawing. A study on the bond performance of OPC concrete repaired with both concrete using type II cement and concrete containing microsilica demonstrated that after 100 cycles, the bond strength had decreased by 85.6% and 61.2%, respectively [3].

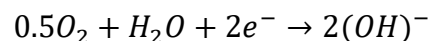
2.5.2 Corrosion

Corrosion of metal is a natural phenomenon that occurs due to environmental conditions that include the presence of water and oxygen. When metals such as steel are produced from the processing of minerals and ore, they are put in a higher energy state. Corrosion is essentially a return of the material to its original energy state because the material itself is thermodynamically unstable [7]. Corrosion of steel in concrete is an almost inevitable consequence due to the inherent instability of the material in an environment where water and oxygen are present.

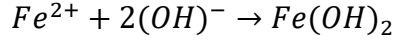
Corrosion is an electrochemical reaction involving the flow of electrons and ions. The existence of an electrochemical cell requires that an anode and cathode be established. The anodic reaction for iron (Fe), which is abundant in steel reinforcing bars is given as:



The existence of corrosion requires that both water (H₂O) and oxygen (O₂) are present. The reduction of water and oxygen gives the cathodic reaction, resulting in the evolution of hydroxyl ions:



These half-cell reactions take place at the surface of the reinforcement and yield iron oxide (Fe(OH)₂), or “rust.” This is an inevitable product of the interaction between Fe²⁺ and 2(OH)⁻ ions. The reinforcement itself acts as the circuit while the pore solution establishes the presence of an electrolyte [7]. The products of the two half-cell reactions combine as follows:



This is the most simplified form of oxidation. Further oxidation can occur, however, resulting in the evolution of different ferric oxides and hydroxides. These products can occupy up to six times the original volume of steel, resulting in high tensile strain within the concrete matrix and eventual cracking and spalling [18]. Figure 2.8 represents the relative volumes of the different corrosion products.

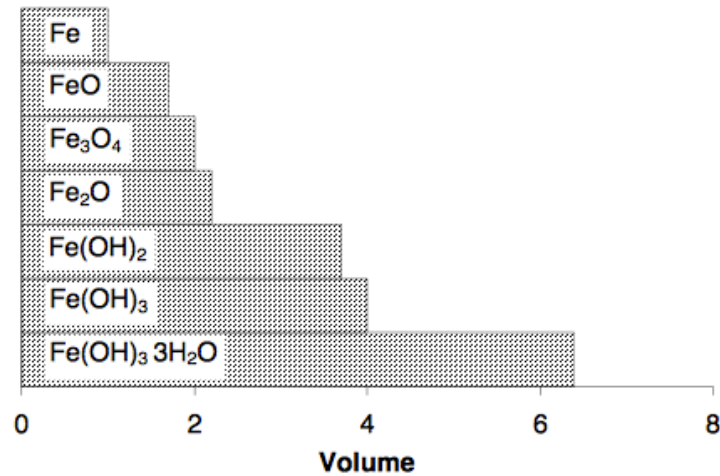
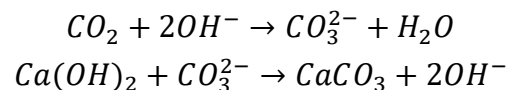


Figure 2.8: Relative volume of corrosion products [7]

OPC concrete has a high alkalinity (pH>13.0) due to the evolution of hydroxide (OH⁻) upon hydration. The interaction between steel reinforcement and the high alkalinity of OPC causes a passive film of iron oxide (γ -Fe₂O₃) to form around the reinforcement. In the presence of a highly alkaline solution, the passive current density, i_p (the amount of charge that can transfer through the passive film) drops to a value negligible enough to prevent corrosion from occurring [5]. The dense passive film that exists can be broken down by the progression of a carbonation front or the existence of chlorides in solution near the passive film.

2.5.2.1 Carbonation

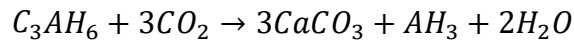
Carbonation in concrete occurs when the calcium bearing phases such as CH, C-S-H, ettringite (Aft) and monosulfate (AFm) are attacked by carbon dioxide (CO₂) existing in the atmosphere, causing these phases to be converted to calcium carbonate. When carbon dioxide dissolves to form carbonic acid, this acid reacts with Ca(OH)₂ and leads to the formation of CaCO₃ [36], [37].



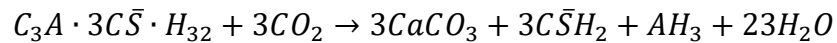
Carbonation results in a drop in the pH of concrete near the surface, causing depassivation of the steel reinforcement and subsequent corrosion [37]–[39]. Additionally,

carbonation of concrete causes an acceleration of chloride ingress, making carbonated reinforced concrete more susceptible to damage from de-icing salts [40].

One of the perceived benefits of carbonation of non-reinforced (or where sufficient cover exists in large reinforced members) OPC concrete is the densification that takes place upon carbonation [37]. The conversion of calcium-bearing hydrates resulting in calcium carbonate represents an 11% volume increase of hydrates within the pore structure [18], [39], [41]. This results in a marked decrease in porosity associated with densification of the hydrated phases. While the effects of carbonation of Portland cement concrete have been widely studied, carbonation on alternative cement systems is not as well documented. Calcium aluminate cement (CAC) systems form calcite and alumina gel as a result of carbonation due to the carbonation of hydrogarnet [18].



Unlike OPC systems where carbonation results in a decrease in permeability, ettringite-based systems experience an increase in permeability. Carbonation in these systems causes a drop in pH below ~10.6, resulting in the dissolution of ettringite, leading to the formation of calcite, gypsum, and alumina gel [41].



The formation of calcite, gypsum, and alumina gel upon carbonation take up less volume than ettringite, resulting in increased porosity and a decrease in mechanical properties [18].

2.5.2.2 Chloride Ingress

An abundance of chlorides in reinforced concrete results in Chloride-induced corrosion. This deterioration mechanism is the result of high concentrations of chloride ions reaching the reinforcing steel through diffusion, convection and absorption [18]. The existence of chlorides can be internal or external. Chlorides may exist in concrete upon mixing due to the use of chloride accelerators, use of seawater in the mix, or the use of chloride contaminated aggregates [6]. Chlorides can also penetrate the concrete from the surface due to the presence of external sources. Exposure to a marine environment, application of deicing salts, or exposure to other chloride containing chemicals can all result in the diffusion of chlorides into the pore matrix. It is well known that the susceptibility of concrete to chloride penetration is dependent on the transport properties. The transport properties of concrete arise from the pore structure (size, connectivity, and tortuosity of pores). As a result, any measure to increase the resistance of a mix to chloride penetration is essentially an attempt to create a less porous matrix through the reduction of the w/cm ratio, use of supplementary cementing materials (SCMs), and the implementation of proper construction practices to ensure consolidation and prevent cracking that can occur during curing times [18].

Alternative cement systems exhibit different chloride penetration characteristics due to their unique transport properties. Additionally, these systems have different chloride binding

characteristics when compared to OPC. Ettringite has been observed to lack chloride binding capacity due to its inability to form Friedels salt [42], [43]. The transport properties of these systems result in different chloride diffusion coefficients and, therefore, susceptibility to chloride induced corrosion. Alternative blended cement systems develop pore structures that are unique based on their compositions. Figure 2.9 shows results from five concrete mixtures immersed in a 165 g/L NaCl solution for 40 and 180 days, respectively. From observation, the PC-CAC-C \bar{S} and C \bar{S} A(2)-PC showed the least amount of chloride penetration while the C \bar{S} A(1)-C2S system exhibited high levels of chloride ingress. This demonstrates that different blends result in highly variable pore structures and transport characteristics.

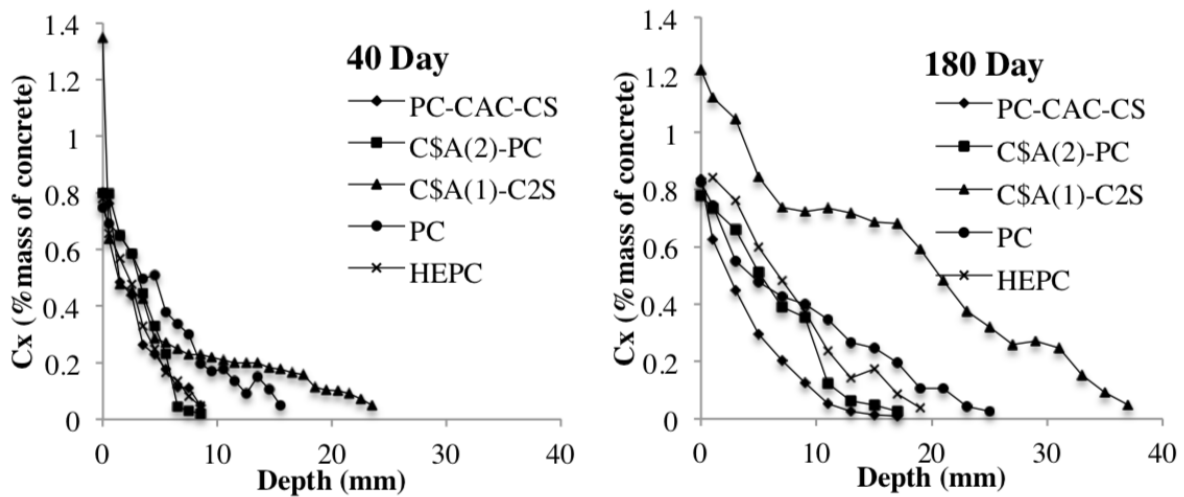


Figure 2.9 : Chloride penetration after 40 and 180 days [18]

2.5.3 Salt Scaling

One of the primary durability concerns related to concrete road pavements is scaling resulting from the use of de-icing salts [1], [11]. Salt scaling results in a damaged surface, with sections flaking or peeling as a result of the effects of freezing and thawing when there is an abundance of deicing salts. After sufficient cyclic freezing and thawing in the presence of deicing salts, the surface will begin to disintegrate. Scaling primarily results in the removal of paste or mortar from the surface. This will have an effect on the finished surface but not on the bulk mechanical properties of the system. In some cases, pieces of aggregate can scale off.

The scaling performance of a cementitious system, like many other durability properties, is highly dependent on the pore structure. Many studies have established the fact that the water-to-cementitious ratio (w/cm) is an important parameter that controls the mechanical and durability properties of a mix. A decrease in w/cm leads to increased salt scaling resistance. It

has been observed that poor surface-finishing practices can significantly alter the scaling resistance of a material due to the localized increase in the w/cm that can occur [9].

Chapter 3

Workshop on Rapid Repair Systems

3.1 Overview

On February 25, 2019 a day-long workshop on rapid repair cement systems was held on the campus of New Jersey Institute of Technology. This session was attended by students and industry personnel. It included lectures from preeminent scientists and engineers in the field of rapid repair cements as well as hands on demonstrations for casting and testing of rapid repair cement systems. The following section describe this workshop in detail.

3.2 Format and Layout

The workshop began at 9:00 AM and lasted until 6:00 PM. The flyer used to advertise the event as well as describe the agenda can be seen in Figure 3.1.

NJIT **RUTGERS**
New Jersey Institute of Technology Center for Advanced Infrastructure and Transportation

FEB. 25, 2019
RAPID REPAIR CEMENTS

One Day Seminar and Demonstration
Highlighting Chemistry, Durability, and Use of Rapid Repair Cements

Speakers:

 **Dr. Edward G. Moffatt, Independent Consultant**

 **Dr. Michael Thomas, Professor of Civil Engineering at the University of New Brunswick**

 **Dr. Matthew P. Adams, Assistant Professor of Civil Engineering at the New Jersey Institute of Technology**

Schedule of Events:	
9:00 AM	Introduction and Overview of Rapid Repair Cements
10:00 AM	Portland Cement Based Rapid Repair Cements
11:00 AM	Ettringite Based Rapid Repair Cements
12:30 PM	Lunch Break
2:00 PM	Calcium Aluminate Based Rapid Repair Cements
3:00 PM	Laboratory Demonstration: Casting with fast setting cements
5:00 PM	Wrap-up, Questions, Dinner

Cost: \$30 - covers coffee, lunch and dinner
Space is Limited
RSVP by Feb. 19th

NEW JERSEY INSTITUTE OF TECHNOLOGY
Campus Center Room 240
RSVP by Feb. 19th to
Matthew P. Adams
Adams@njit.edu

Figure 3.1 : Rapid Repair Cements Workshop Flyer

The speakers at the workshop included Dr. Michael Thomas, Professor at the University of New Brunswick; Dr. Edward G. Moffatt, an Independent Consultant and Research Scientist with the Military College of Canada; and Dr. Matthew P. Adams, Assistant Professor at New Jersey Institute of Technology. Dr. Thomas lead the sessions concerning a history of rapid repair cements, as well as portland cement based rapid repair cements. Dr. Moffatt lead the section on

ettringite based rapid repair cements. Dr. Adams lead the section on calcium aluminate cement rapid repair cements. Dr. Moffatt and Dr. Adams co-lead the hands-on laboratory demonstration on casting with fast cements. The Session ended with a roundtable discussion featuring all three speakers and answering questions about rapid repair systems. The lectures covered the history, cement chemistry, hydration chemistry, mechanical properties, durability, uses, and specification of many different types of rapid repair cements.

During the hands-on demonstration three different concrete systems were cast using both calcium aluminate cement based systems and calcium sulfoaluminate cement based systems. Attendees were able to learn how mixing and casting of these systems differed compared to ordinary portland cement systems including issues with workability and rapid setting. In addition, samples were cast and tested in compression within 3 hours of being cast so attendees could experience how quickly the cements gained strength.

3.3 Advertisement, Attendance, and Feedback

The workshop was advertised through e-mail blasts to the speakers contact groups. Additionally, it was advertised on the NJIT Civil Engineering Department's website and the events page of the Center for Advanced Infrastructure and Transportation's website. Over 20 people attended the workshop from the region. This group included students and industry personnel. Artifacts (such as power point slides and handouts) were provided for all attendees. Feedback from the attendees was positive and they noted that they particularly enjoyed learning about the way that rapid repair systems can differ in their chemistry and behavior and the hands-on demonstrations.

Chapter 4

Methodology and Findings for Guidelines for Rapid Repair Systems for Freeze-thaw Loading

4.1 Intent of Guideline

This portion of the report provides a guideline to assess the bond-zone behavior of rapid repair systems used as an overlay to existing concrete substrates. In particular, recommendations for benchmarking how freeze-thaw conditioning influences the bond-zone behavior is discussed. To achieve freeze-thaw conditioning, specimens will undergo cycles of freezing and thawing according to ASTM C666 [44]. These specimens will then undergo tensile pull off testing according to ASTM C1583 [45]. The guideline aims to follow testing procedures outlined by both of these standards as closely as possible while making some modifications to the standards to fit the needs of the current study.

One of the main goals for the guideline is to develop a consistent methodology of preparing specimens that conform closely to the geometry and curing required for specimens undergoing freeze-thaw cycling while being suitable for pull-off strength testing. The next goal is to modify existing experimental setups to ensure that repeatable results can be obtained in a laboratory setting. For each unique overlay material, seven specimens should be cast and prepared for direct tensile pull off testing according to ASTM C1583. For each specimen, three pull off strength values can be obtained. These results will be evaluated according to ASTM C1583.

4.2 Substrate Preparation

The first step is to create a substrate consisting of concrete of 3 ± 1 in. slump and with air entrainment of 7 ± 1 % to ensure that the substrate does not fail prematurely during freeze-thaw cycles. The goal of this study is to investigate rapid repair overlay systems at a consistent depth of 1.5 in while modifying substrate preparation methods. The substrate itself represents half of the overlay specimen, and is cast in 3 x 4 x 16 in. stainless steel freeze-thaw molds with wooden spacers to create a specimen that is 1.5 x 4 x 16 in. Figure 4.1 illustrates the use of wooden spacers to obtain these substrate specimens.

(a)



(b)



Figure 4.1 (a) & (b): Substrate casting setup

Once a substrate is cast, it is cured for 24 hours before being placed in a saturated lime bath at 23 °C until 28 days of curing is achieved. This ensures that the concrete has gained adequate strength and prevents substrate failures from occurring during pull-off testing. At this point, the specimen can be prepared for the casting of an overlay. Different surface preparation methods can be studied. For example, concrete scarification involves abrading the concrete surface with a rotating drum consisting of cutters. For laboratory studies, an electric handheld scarifier can be used. The use of a scarifier creates a rough surface with a high bonding potential. Figure 4.2 (a) shows a hand scarifier and Figure 4.2 (b) illustrates a concrete surface prepared by scarifying. Once the surface has been scarified, it will be cleaned with a power washer prior to casting of the repair layer.

(a)



(b)



Figure 4.2: Substrate preparation

4.3 Overlay Placement and Testing

Once the substrate has been prepared, an overlay is cast by placing the substrates in freeze-thaw molds and placing a rapid repair layer on top. The repair layer should be cured for 1 day before the first set of pull of tests are performed on the control specimen for which no freeze-thaw cycles are performed. The rest of the specimens are then placed in a freeze-thaw chamber pictured below in Figure 4.3.



Figure 4.3: Freeze-thaw chamber

4.4 Recommended Conditioning Intervals

For each repair material, 6 of 7 specimens should undergo freeze-thaw cycles after being cured for 24 hours. One specimen should undergo pull-off strength testing after 24 hours with no conditioning. For each cycle, the temperature of the specimens should be alternately lowered from 4 to -18 °C and raised from -18 to 4 °C in not less than 2 nor more than 5 hours, according to ASTM C666 [44]. Control prisms outfitted with thermocouples are used to monitor the average internal temperature of the prisms in various locations within the chamber. Dummy specimens are used to keep the temperature changes consistent and to ensure that uniform temperature and time conditions are achieved.

Concrete is generally considered resistant to freeze-thaw when the relative strength loss, ΔR , is equal to or less than 20% after 150 cycles [46]. In this study, substrates exhibiting high air entrainment of around 7-8% ensure that freeze-thaw damage to the substrate does not control the failure mode observed during pull off testing done in accordance with ASTM C1583. In order to examine the effects of successive degradation to the bond zone between the substrate and repair, specimens undergo successively increasing levels of freeze-thaw cycling until 300 cycles is achieved for the final specimen. This enables a wide range of durability to be examined across various rapid repair materials.

The interval chosen between pull off strength testing is 50 cycles. Each of six specimens undergo various levels of freeze-thaw cycling. The first specimen is tested for pull off strength at 50 freeze cycles, the next will undergo testing at 100 cycles, and so on. For each specimen, three pull off strength values are obtained. For each unique overlay, 21 pull off strengths are obtained. Figure 4.4 illustrates the process that specimens go through from placement in the freeze-thaw chamber to determination of pull-off strength and interpretation of failure mode.

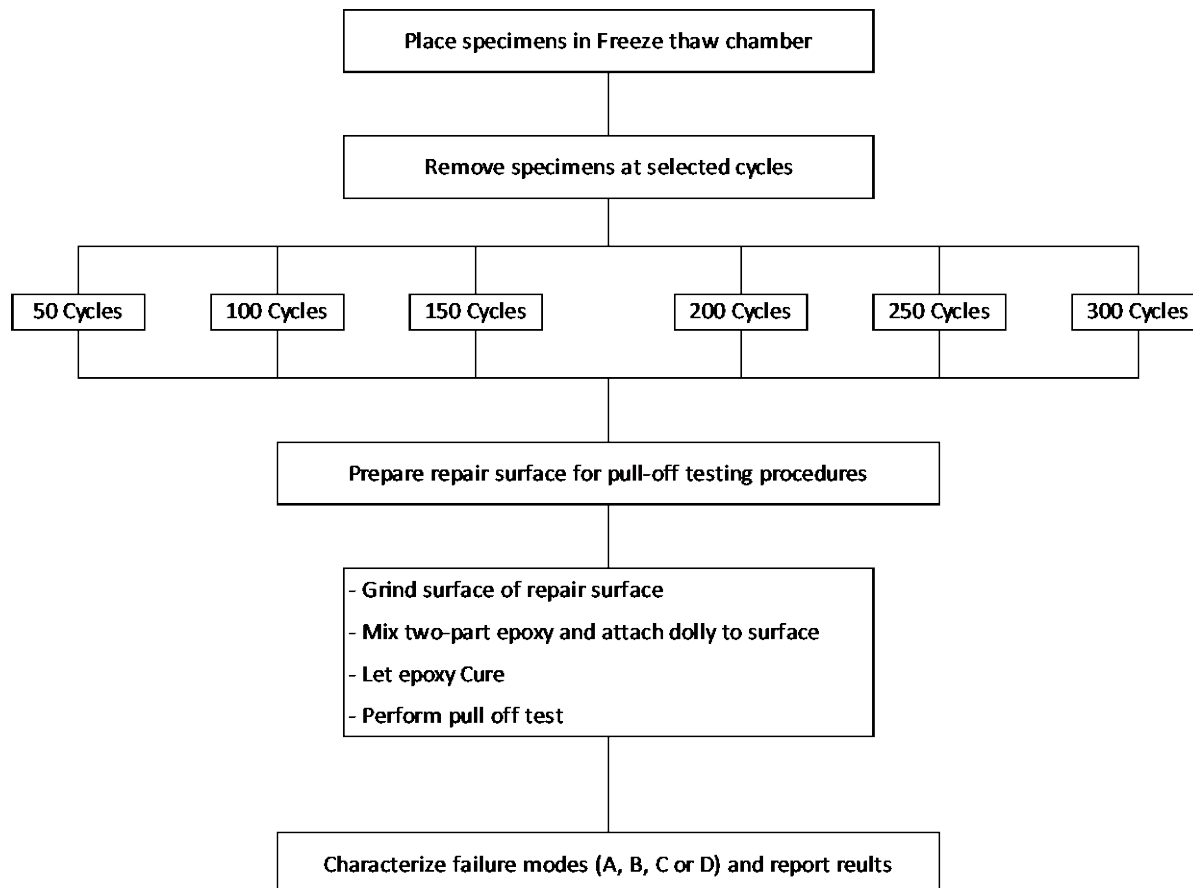


Figure 4.4: Freeze-thaw specimen procedure

4.5 Preparation for ASTM C1583

Overlay specimens must be grinded and core drilled in preparation for dolly placement. ASTM C1583 requires that the concrete surface is grinded to ensure an adequate bond between the test dolly and the contact surface. This prevents failure occurring in the epoxy layer between the test dolly and the contact surface. Once the surface of a specimen is grinded, 3 cores are then made, ensuring that the substrate layer is sufficiently drilled into. Figure 4.5 shows the core drill as well as a specimen being prepared for ASTM C1583 by attaching a steel dolly to the surface with an epoxy compound.



Figure 4.5: Preparation of a specimen for ASTM C1583 by core drilling

Overlay specimens must then be prepared for pull-off testing according to ASTM C1583. Due to the unique geometry of the freeze-thaw specimens, most available pull off test apparatus are not suitable to be placed directly on top of the specimen. For this reason, a steel plate with a hole slightly larger than the outside diameter of a dolly will be used to ensure that the feet of the pull-off tester will be stable. A diagram of the test setup is shown in Figure 4.6.

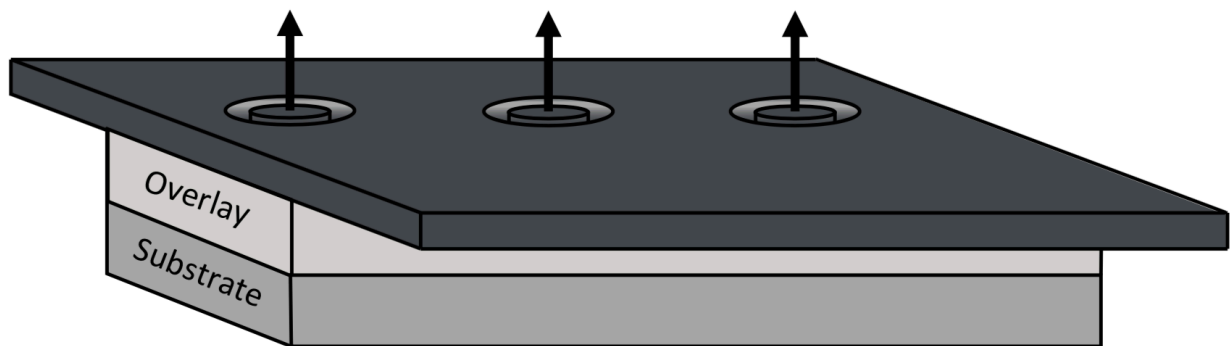


Figure 4.6: Pull-off test modification for ASTM C666 specimens

4.6 Pull-off strength testing and interpretation of results

Once the specimen is prepared, the dolly is attached to the load cell and the test is performed. Figure 4.7 shows the pull-off tester used in the study. This instrument is designed to be used in a field environment. In the current study, a steel plate is used to account for the unique geometry of the specimens for which ASTM C1583 is run. Results from specimens tested according to ASTM C1583 must be interpreted based on where the failure occurs. According to ASTM C1583, there are four failure modes, indicated in Figure 4.8. Specimens failing due to failure at the bond zone between the epoxy/overlay interface are to be discarded [45].



Figure 4.7: Controls Group™ pull-off strength load cell

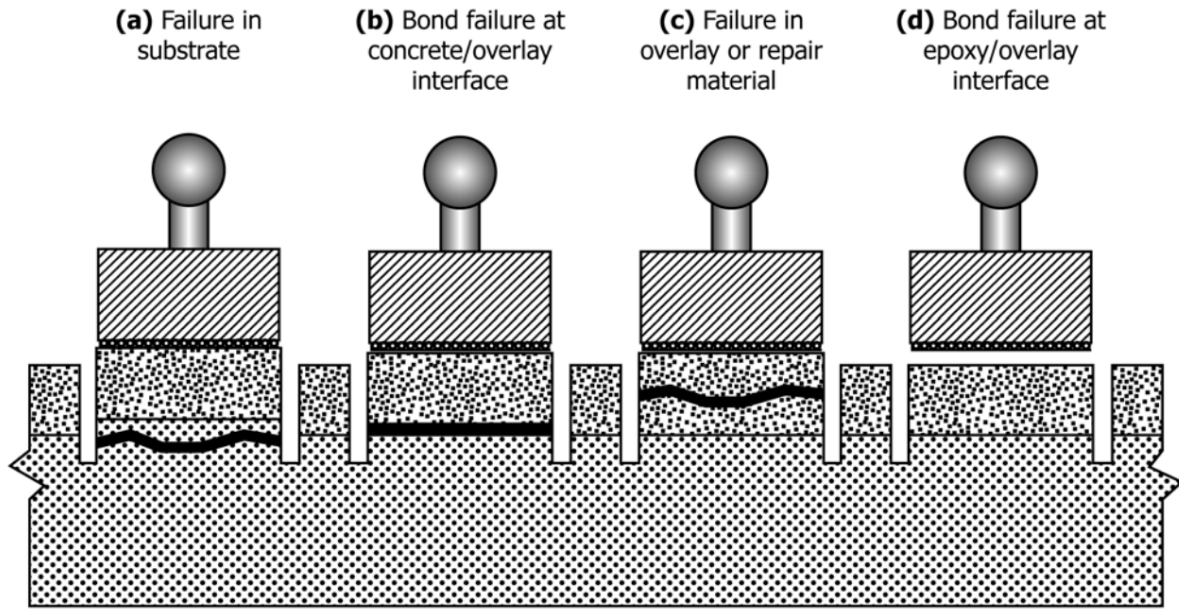


Figure 4.8: Failure modes of specimens tested according to ASTM C1583 [45]

Chapter 5

Summary, Conclusions, and Recommendations

5.1 Summary and Conclusions

This document reviewed the chemistry and properties of several different rapid repair cement systems including calcium aluminate cements, calcium sulfoaluminate cements, and accelerated portland cement systems. From this review, it is clear that while these systems are often used in similar applications, they do not behave similarly. As such, it is important to test their use in certain applications prior to using them in the field. These rapid repair systems are often used in overlay situations or in partial depth pavement repairs. For these situations, the bond of the repair material to the substrate is a paramount property.

The bond of the rapid repair materials to the substrate is generally quite good as long as the surface preparation is done correctly and the systems are used according to manufacturer directions. However, what isn't well understood is how the different systems' bond may behave over the long-term, particularly under freeze-thaw loading. In order for agencies to determine the appropriate materials to use in their particular regions, new testing methodology was developed as a part of this work for agencies to determine the long-term bond zone and repair material performance under freeze-thaw loading.

The guideline provided can be implemented within agency laboratories such that each material can be tested appropriately and approved. The guideline provides a detailed testing methodology to study the performance of overlay and repair materials under freeze-thaw cycling. This guideline uses modified standard testing procedures that can be easily implemented using standard equipment. It is recommended that transportation agencies implement these into their material approval testing programs.

5.2 Recommendations for Future Research

This project focused on disseminating knowledge on rapid-repair materials through a workshop and developing a protocol to physically test repair materials under various freeze-thaw conditions to benchmark their performance over time. Through the knowledge gained in these activities, the researchers recommend the following topics be considered as topics to expand upon this research:

Recommendation 1. Develop a survey and solicit feedback from federal, state, and local transportation agencies on the most commonly used rapid-repair systems used in their agencies and those that are specifically targeted in freeze-thaw environments.

- Recommendation 2. Using the proposed methodology to assess performance described in Chapter 4, compare the bond-zone strength under freeze-thaw conditioning of rapid repair systems currently in use by transportation agencies where freeze-thaw is an important design consideration.
- Recommendation 3. After completing the testing in Recommendation 2, qualitatively investigate failure surface behavior through microscopic analysis of different rapid-repair systems to better understand how their chemical properties influence their freeze-thaw bond-zone behavior
- Recommendation 4. Using the results from Recommendation 2 and 3, develop a list of materials that perform best in freeze-thaw environments for transportation agencies to deploy in partial depth repair environments.

References

- [1] USDOT, "FHWA Concrete pavement preservation guide."
- [2] D. Harrington and G. Fick, "Guide to Concrete Overlays: Sustainable Solutions for Resurfacing and Rehabilitating Existing Pavements." American Concrete Pavement Association, 2014.
- [3] K. Behfarnia, "Studying the Effect of Freeze and Thaw Cycles on Bond Strength of Concrete Repair Materials," *Asian J. Civ. Eng.*, vol. 11, no. 2, pp. 165–172, 2010.
- [4] H. Cai and X. Liu, "Freeze-Thaw Durability of Concrete: Ice Formation Process in Pores," *Cem. Concr. Res.*, vol. 28, no. 9, p. 7, 1998.
- [5] G. Hinds, "The electrochemistry of corrosion," 2012.
- [6] J. P. Broomfield, *Corrosion of Steel in Concrete*. 1997.
- [7] P. R. Roberge, "Corrosion Engineering-Principles & Practice," 2008.
- [8] K. Amini, "Laboratory Testing of High Performance Repair Materials for Pavements and Bridge Decks," Cleveland State University, 2015.
- [9] M. Dornak, J. Zuniga, A. Garcia, T. Drimalas, and K. J. Folliard, "Development of Rapid, Cement-based Repair Materials for Transportation Structures," *Texas Dep. Transp.*, p. 191, 2015.
- [10] Y. Guan, Y. Gao, R. Sun, M. C. Won, and Z. Ge, "Experimental study and field application of calcium sulfoaluminate cement for rapid repair of concrete pavements," *Front. Struct. Civ. Eng.*, vol. 11, no. 3, pp. 338–345.
- [11] D. P. Frentress and D. S. Harrington, "Partial Depth Repair of Concrete Pavements," Iowa State University Institute for Transportation, 2012.
- [12] G. Weisbrod, D. Vary, and G. Treyz, "Economic Implications of Congestion," National Cooperative Highway Research Program, 2001.
- [13] G. Weisbrod, D. Vary, and G. Treyz, "Measuring Economic Costs of Urban Traffic Congestion to Business," *Transp. Res. Rec.*, vol. 1839, pp. 98–106.
- [14] D.-H. Chen, H.-H. Lin, and R. Sun, "Field performance evaluations of partial-depth repairs," *Constr. Build. Mater.*, vol. 25, no. 3, pp. 1369–1378, 2011.
- [15] W. G. Smoak, T. B. Husbands, and J. E. McDonald, "Results of Laboratory Tests on Materials for Thin Repair of Concrete Surfaces," US Army Corps of Engineers, Repair, Evaluation, Maintenance, and Rehabilitation Research Program, 1997.
- [16] C. Gosselin, "Microstructural Development of Calcium Aluminate Cement Based Systems with and without Supplementary Cementitious Materials," Ecole Polytechnique Federale De Lausanne, Lausanne, Switzerland, 2009.
- [17] K. L. Scrivener, J.-L. Cabiron, and R. Letourneux, "High-performance concretes from calcium aluminate cements," *Cem. Concr. Res.*, vol. 29, pp. 1215–1223, 1999.
- [18] E. G. Moffatt, "Durability of Rapid-Set (Ettringite-Based) Concrete," University of New Brunswick, 2011.
- [19] O. Kirca, O. Yaman, and M. Tokyay, "Compressive strength development of calcium aluminate cement–GGBFS blends," *Cem. Concr. Compos.*, vol. 35, p. 8, 2013.
- [20] F. Winnefeld and B. Lothenbach, "Hydration of calcium sulfoaluminate cements — Experimental findings and thermodynamic modelling," *Cem. Concr. Res.*, vol. 40, no. 8, pp. 1239–1247, 2010.
- [21] E. Gartner, F. Quillin, and K. Quillin, "Low-CO2 Cements based on Calcium

- Sulfoaluminates," 2007.
- [22] J. Péra and J. Ambroise, "New applications of calcium sulfoaluminate cement," *Cem. Concr. Res.*, vol. 34, no. 4, pp. 671–676.
 - [23] D. Gastaldi, F. Canonico, and A. Telesca, "Hydraulic Behaviour of Calcium Sulfoaluminate Cement Alone and in Mixture with Portland Cement," 2011.
 - [24] F. P. Glasser and L. Zhang, "High-performance cement matrices based on calcium sulfoaluminate–belite compositions," *Cem. Concr. Res.*, vol. 31, pp. 1881–1886, 2001.
 - [25] J. H. Ideker and C. Gosselin, "An alternative repair material," *Concr. Int.*, 2013.
 - [26] E. N. B. S. Júlio, F. A. B. Branco, and V. D. Silva, "Concrete-to-concrete bond strength. Influence of the roughness of the substrate surface," *Constr. Build. Mater.*, vol. 18, no. 9, pp. 675–681.
 - [27] P. M. D. Santos and E. N. B. S. Júlio, "Factors Affecting Bond between New and Old Concrete," *ACI Mater. J.*, vol. 108, no. 449–456, p. 449, 2011.
 - [28] C. Talbot, M. Pigeon, D. Beaupré, and D. R. Morgan, "Influence of Surface Preparation on Long-Term Bonding of Shotcrete," *ACI Mater. J.*, vol. 91, no. 6, pp. 560–566.
 - [29] P. M. D. Santos and E. N. B. S. Júlio, "A state-of-the-art review on roughness quantification methods for concrete surfaces," *Constr. Build. Mater.*, vol. 38, pp. 912–923, 2013.
 - [30] T. Guo, Y. Xie, and X. Weng, "Evaluation of the bond strength of a novel concrete for rapid patch repair of pavements," *Constr. Build. Mater.*, vol. 186, pp. 790–800.
 - [31] J. Weiss, M. D. Cohen, A. Barde, S. Parameswaran, and T. Chariton, "Evaluation of Rapid Setting Cement-Based Materials for Patching and Repair," 2006.
 - [32] M. P. Adams and J. H. Ideker, "Volume Stability of Calcium Aluminate Cement and Calcium Sulfoaluminate Cement Systems," 2014.
 - [33] Z. Yang, J. Weiss, and J. Olek, "Water Transport in Concrete Damaged by Tensile Loading and Freeze–Thaw Cycling," *J. Mater. Civ. Eng.*, vol. 18, p. 11.
 - [34] W. Li, M. Pour-Ghaz, J. Castro, and J. Weiss, "Water Absorption and Critical Degree of Saturation Relating to Freeze-Thaw Damage in Concrete Pavement Joints," *J. Mater. Civ. Eng.*, vol. 24, p. 9, 2012.
 - [35] Z. Ma, F. Zhu, and G. Ba, "Effects of freeze-thaw damage on the bond behavior of concrete and enhancing measures," *Constr. Build. Mater.*, vol. 196, pp. 375–385, 2019.
 - [36] Y. Lo and H. M. Lee, "Curing effects on carbonation of concrete using a phenolphthalein indicator and Fourier-transform infrared spectroscopy," *Build. Environ.*, vol. 37, p. 8.
 - [37] B. Johannesson and P. Utgenannt, "Microstructural changes caused by carbonation of cement mortar.pdf," 2001, vol. 31, p. 7.
 - [38] E. Rozière, A. Loukili, and F. Cussigh, "A performance based approach for durability of concrete exposed to carbonation," *Constr. Build. Mater.*, vol. 23, no. 1, pp. 190–199.
 - [39] V. T. Ngala and C. L. Page, "Effects of Carbonation on Pore Structure and Diffusional Properties of Hydrated Cement Pastes," *Cem. Concr. Res.*, vol. 27, no. 7, pp. 995–1007, 1997.
 - [40] B. Reddy, G. K. Glass, P. J. Lim, and N. R. Buenfeld, "On the corrosion risk presented by chloride bound in concrete," *Cem. Concr. Compos.*, vol. 24, pp. 1–5, 2002.
 - [41] S. Lamberet, "Durability of Ternary Binders Based on Portland Cement, Calcium Aluminate Cement and Calcium Sulfate," 2005.
 - [42] H. Zibara, "Binding of External Chlorides by Cement Paste," University of Toronto,

- 2001.
- [43] H. Hirao, K. Yamada, H. Takahashi, and H. Zibara, "Chloride Binding of Cement Estimated by Binding Isotherms of Hydrates," *J. Adv. Concr. Technol.*, vol. 3, no. 1, p. 8, 2015.
 - [44] ASTM C666/C666M, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing." ASTM International, West Conshohocken, PA, 2015, 2015.
 - [45] ASTM C1583/C1583M, "Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method)," *ASTM International, West Conshohocken, PA, 2015.* 2015.
 - [46] J. Wawrzeńczyk and A. Molendowska, "Evaluation of Concrete Resistance to Freeze-thaw Based on Probabilistic Analysis of Damage," in *Procedia Engineering*, 2017, pp. 35–41.