Synthesis of Rapid Setting Repair Materials

Final Report
February 2022

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16. Abstract

Rapid setting materials are typically designed to achieve enough strength in a few hours to resist traffic loads. This is done to minimize the disruption to the traveling public while providing a durable repair.

The goal of this document is to provide a useful framework for department of transportation (DOT) or transportation agency staff to make decisions about which rapid setting materials to use for pavements, bridges, and other projects.

This document is organized into two parts. The first part is designed to summarize the process of choosing the needs or the constraints required for a rapid setting material. A decision table is included to guide agency staff on which rapid setting material is best for their needs. Also, a summary is provided of typical approval, acceptance, and construction practices used for materials.

Part 1 is designed to be a standalone guide to give agencies what they need to choose the correct materials for their applications.

Part 2 provides the technical background used to create Part 1. Part 2 discusses the hydration reactions, commonly used admixtures, durability performance, and some case studies where rapid setting materials have been used. Part 2 is designed to be a reference document so that more information can be learned about the recommendations in Part 1.

The appendix references a useful Excel spreadsheet that provides detailed information about different commercially available rapid setting products and is available as a standalone reference at https://intrans.iastate.edu/app/uploads/2022/02/rapid_setting_repair_material_listing_and_links.xlsx.

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SYNTHESIS OF RAPID SETTING REPAIR MATERIALS

Final Report
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The author wants to acknowledge the other significant work that is heavily referenced in this document, as outlined at the end of the Executive Summary.

EXECUTIVE SUMMARY

The goal of this document is to provide a useful framework for department of transportation (DOT) or transportation agency staff to make decisions about which rapid setting materials to use for pavements, bridges, and other projects.

Rapid setting materials are typically designed to achieve enough strength in a few hours to resist traffic loads. This is done to minimize the disruption to the traveling public while providing a durable repair.

This document does not cover diagnosing the distress or choosing the size or depth of the repair. Guidance is provided for commercially available products actively used in the United States based on a survey of the members of the National Concrete Consortium (NC^2). Further, the discussion is focused on rapid setting products with documented performance on transportation projects and published laboratory studies where relevant comparisons were made between several commercial products. This means that some emerging materials are only briefly discussed, and no guidance is given.

Readers should note that rapid setting materials are not used as widely as conventional portland cement mixtures. Because of this, the amount of published research on the material properties and durability performance of these materials is lacking. This highlights the need for more systematic documented usage in the field as well as laboratory studies that systematically compare several different materials.

Overview of this Document

This document is organized into two parts. The first part is designed to summarize the process of choosing the needs or the constraints required for a rapid setting material. A decision table is included to guide agency staff on which rapid setting material is best for their needs. Also, a summary is provided of typical approval, acceptance, and construction practices used for materials.

Part 1 is designed to be a standalone guide to give agencies what they need to choose the correct materials for their applications.

Part 2 provides the technical background used to create Part 1. Part 2 discusses the hydration reactions, commonly used admixtures, durability performance, and some case studies where rapid setting materials have been used. Part 2 is designed to be a reference document so that more information can be learned about the recommendations in Part 1.

The appendix references a useful Excel spreadsheet that provides detailed information about different commercially available rapid setting products and is available as a standalone reference here:

https://intrans.iastate.edu/app/uploads/2022/02/rapid_setting_repair_material_listing_and_links.xlsx.

This document was created from literature reviews and surveys of state DOT and material manufacturer staff. This effort focused on gathering and synthesizing specifications, field performance, and laboratory studies.

Other Significant Work Referenced

A large study that systematically compared the performance of many of the repair materials was sponsored by the FHWA under the Exploratory Advanced Research (EAR) program and led by Kimberly Kurtis at Georgia Tech University (Alapati et al. 2019). In addition, Texas DOT project 6723, Development of Rapid, Cement-Based Repair Materials for Transportation Structures (Dornak et al. 2015), led by Kevin Folliard, was an outstanding reference and greatly influenced this document.

These two research reports are heavily referenced because they completed a direct comparison of the material properties and major durability mechanisms within the same set of materials and in the laboratory. This is unique, and additional research is needed in the future with a wide range of repair materials being compared. This testing, when combined with the information from the DOTs and materials manufacturers, allows practical insights to be gained and shared in this document.

PART 1 OVERVIEW – CHOOSING AND CONSTRUCTING RAPID REPAIR MATERIALS

Making any engineering choice is a balance between the project needs and the available resources. This is true for rapid setting repair materials. Part 1 aims to guide department of transportation (DOT) staff through this process to ultimately make a choice of which materials to use or allow for any given application. This part provides a framework for deciding which materials and evaluation practices to use. This process starts by answering four basic questions.

1.1 Four Questions to Choose a Rapid Setting Material

While many things contribute to which rapid setting materials are chosen for a certain application, most of these choices can be guided by answering four fundamental questions:

- How soon do you need the patch to withstand traffic?
- What strength is needed?
- Is the reinforcing steel close to the surface?
- How long do you need the repair to last?

Each question is discussed along with several key areas to consider.

1.1.1 How Soon Do You Need the Patch to Withstand Traffic?

It is inconvenient and sometimes dangerous to delay opening a roadway to traffic until a repair reaches a certain strength. This can cause long wait times for the public and roadway delays that often cost more than the repairs themselves. Because of this, many repairs are made overnight to minimize impacts on traffic. This is done by closing the roadway in the evening and then opening it for traffic the next morning.

This approach can require the patch material to be mixed, placed, consolidated, and gain opening strength in less than 6 hrs. This is where cement with specific formulations and specialized admixtures must be used. These projects require tight schedules, put significant stress on contractors, and can, therefore, have a negative impact on workmanship.

Workmanship may suffer with the lack of time to correct errors. If these projects allow a few more hours, it can have significant improvements on the quality of the final product. This additional time allows contractors to take greater care and also to reduce rapid strength gain requirements. This additional time can also lower costs and greatly impact the smoothness, quality, and durability of the final product. This time can allow more flexibility to contractors and give them extra time to check their work. These few hours can minimize future repairs that may force dangerous detours for the traveling public and minimize repair work near live traffic.

While many applications do require overnight closure for driver safety, in cases with lower traffic volume, the cost, durability, and quality of the project can be vastly improved if the repair can remain closed to traffic for 24 hrs. This delay in opening time gives the repair material longer to gain strength and also allows curing to stay in place.

1.1.2 What Strength is Needed?

A critical input for the rapid setting repair material is the strength needed at the opening. A recent Moving Advancements into Practice (MAP) Brief, entitled Optimizing Concrete Pavement Opening to Traffic (Delatte 2021), is used, in part, along with a lengthier upcoming document on this subject, to guide the discussion in this section.

The focus is that the design strength of a patch should be chosen based on the depth of the patch and the type of traffic that the patch will see on opening. The lengthier upcoming document should be referenced for additional details and case studies when it becomes available. However, depth of repair and type of loading are also discussed here based on the information in that upcoming document and others.

1.1.2.1 Depth of Repair

When choosing the design strength, the depth of the patch is important because it impacts the structural behavior of the pavement or bridge deck. Full-depth repairs are often used when the deterioration impacts the majority of the depth of the section. Partial-depth or surface repairs are chosen in other cases.

If the depth of the patch is about 3 in. or less, it is considered a surface patch, and the repaired area can be opened with a flexural strength of 350 psi (Cavalline et al. 2020). Also, this material will continue to gain strength over time, so little damage is expected.

Once the depth of the patch reaches half or more of the depth of the section, the design strength becomes more important, because the repair material will experience more flexural stresses.

1.1.2.2 Type of Loading

To determine the stress level, the types of loads that are placed on the structure are needed. For example, is the patch exposed to construction traffic, light-duty vehicles, or heavy-duty trucks? Each of these can be treated differently.

Types of construction traffic may include haul trucks, skid steers, water trucks, and slipform pavers. While this equipment is heavy, the number of times that it will be passing over the patch will likely be limited. Also, if areas that are known to cause high stresses, such as loading on the edge of a pavement, these areas can be avoided until the patch has reached the desired strength.

Light-duty traffic such as cars and personal trucks do not create large stresses. Given the small stresses, concerns that these vehicles will cause damage are less.

Repairs that see a high volume of heavy-duty traffic on opening become more challenging. These repairs should be investigated in more detail to take into account the thickness, expected loads, and any support conditions, such as the subgrade or the span length for a bridge. It is important to select these patching materials to have enough strength so that regular loading does not cause significant internal cracking or damage. The full strength of a patch is often not required before it is open to traffic. However, keep in mind that most design is completed for the ultimate strength of a member or to accommodate the long-term fatigue performance and, so, requiring these same strengths are often not necessary for the repair materials.

A widely accepted recommendation is that a material can withstand infinite load cycles if the applied stresses are 40% of the ultimate strength of the material (Delatte 2014). This means if a partial-depth patch for a bridge requires 3,500 psi compressive strength for ultimate loading, the patch could be opened to traffic once it has reached 40% of this value or 1,400 psi with no concern for damage. This value is chosen because there is no expected fatigue damage at this level of stress. Also, the repair material is continually gaining strength, so this further reduces the chance for damage.

Many DOTs simplify all of this and just require a single strength on the opening of the repair. Based on a recent state survey, the compressive strength values are between 1,200 and 4,500 psi (Masten and Ley 2021). Several states allow opening at 2,000 psi, so this seems to be a practical value that has been successfully used with different materials and environments for both full-depth and partial-depth repairs.

1.1.3 Is the Steel Rebar Close to the Surface?

Because of the importance of reinforcing steel in the capacity of a structure, any repair that is protecting reinforcing steel that is within 3 in. of an exposed surface needs special attention. This typically occurs on a bridge repair and does not apply for reinforcement within a pavement or slab. This repair material should have low permeability and should also be resistant to carbonation.

The permeability of the concrete patch material will be the primary method of protecting the reinforcing steel and extending the life of the structure. Unfortunately, concrete that gains strength rapidly does not necessarily have low permeability. Furthermore, cement such as calcium sulfoaluminate (CSA), calcium aluminate (CAC), and alkali-activated (AA) often have impressive resistance to electrical flow as measured by resistivity and rapid chloride permeability testing (RCPT), but they do not necessarily show improved resistance to ion penetration. This often means that long-term ponding and field tests are needed to understand the performance of these materials. This is discussed in more detail in Part 2 of the document.

Another concern for repair materials that protect reinforcing steel is that these materials must resist carbonation. Carbonation is when carbon dioxide penetrates the concrete and reacts with calcium hydroxide to form calcium carbonate. This reaction lowers the pH of the pore solution of the material.

When the pH is reduced to about 9 to 10, the concrete no longer protects the reinforcing steel bar within the concrete, and the reinforcing will start to corrode without any external deicing salts. This is similar to rebar corrosion that occurs on the surface of the rebar when left exposed to the air. The primary concern with carbonation-based corrosion is that the corrosive products are expansive, and they cause the repair material to crack and either deteriorate or provide a direct path to the reinforcing for more damage to occur.

Carbonation is more damaging in environments where the relative humidity is between 40% and 70%. Also, if a surface is directly exposed to moisture, this will decrease the rate of carbonation because it raises the relative humidity of the sample.

Carbonation is not a common durability concern with OPC-based binders with a water to cementitious material (w/cm) ratio < 0.50, such as rapid strength gaining OPC or ultra-high performance concrete (UHPC). This is because of the high amount of calcium hydroxide produced when OPC hydrates.

A high volume of calcium hydroxide creates a high buffer capacity. This buffer capacity means that, not only is the pH high within the material, but there is a reserve of calcium hydroxide to help the pH to stay high. While most of the repair cement has a high pH when first placed, very few of these cements have a high buffer capacity or the ability to maintain this high pH over time. This means that carbonation can be a problem in non-portland cement-based repair materials that protect reinforcing steel.

The primary way to improve the resistance to carbonation is to lower the permeability of the repair material by using a low w/cm ratio (for example, a w/cm ratio < 0.35) and to include a polymer additive such as latex within the cement. The polymer may be included in the bagged product or added in the field to fill the pores formed within the concrete during hydration and help reduce the penetration of outside chemicals. This is commonly done with CSA cement and some OPC cement. It is important to verify that this polymer is contained in your products if you need long-term performance. Another strategy is to blend cement with low buffer capacity with OPC. While this improves the buffer capacity of the cement, it may compromise some other properties like early strength gain or shrinkage.

1.1.4 How Long Do You Need the Repair to Last?

The desired service life of a repair is an important parameter in determining which materials to choose. Based on a recent state survey of National Concrete Consortium (NC^2) members, it is common for repairs to last between 5 and 10 yrs with some lasting more than 20 yrs. This shows that, in certain circumstances, patches can have a long service life.

When choosing a patching material, it is critical to understand what durability mechanisms are most important for the environment and application of the patch. For example, if a patch is subjected to deicing salts and a freezing environment, it is important to use a low w/cm ratio, a proper air void system for the material, and possibly a polymer additive to reduce the permeability of the repair material. If the patch is near the ocean and needs to protect reinforcing steel, a low w/cm ratio and a polymer additive may be important. If the patch is being used for a dry environment, it is helpful to choose a material with reduced shrinkage to minimize cracking.

For partial-depth patches, materials must have sufficient bond strength. Laboratory bond testing from the National Transportation Product Evaluation Program (NTPEP) is available for many commercial repair materials. The concrete surface must be roughened and cleaned before the repair material is placed.

1.2 Current Practices and Recommendations

This section outlines the current agency practices used to approve, accept, and construct repair materials and recommendations based on field performance and the literature. The agency responses are based on a survey completed for the Spring 2021 NC^2 meeting with 35 states responding. All regions of the US are represented except for Alaska and Hawaii. The responding states have significant experience using repair materials as 90% of the respondents reported having completed at least five projects that use these materials.

The sections are broken into current practices and recommendations. These recommendations are based on the existing literature review of comparative testing between multiple repair products for durability performance, field performance, and interviews. As new studies are completed and more case studies are reported, this will allow improved recommendations.

1.2.1 Approval of Repair Materials for Usage

Repair materials are typically approved by a battery of laboratory tests. A summary of the most common tests is given in Table 1.

Table 1. Summary of tests required for approval of repair material

Required Laboratory Tests	Percent of Respondents
Compressive/Flexural Strength	74%
Shrinkage	63%
Freeze-Thaw	51%
Other	34%
None	20%

Source: Masten and Ley 2021, *NCC Spring 2021 State Reports on Fast Setting Patching Materials*

DOTs primarily use compressive or flexural strength, shrinkage, and freeze-thaw performance for the preapproval of a product. About one-third of the states also require additional testing such as bond tests, setting time, RCPT, or some other state-specific test. The survey showed that 20% of the DOTs did not require any testing for preapproval. About two-thirds of the DOTs reported completing the approval testing themselves, and 30% use NTPEP or a third-party testing agency. Only 6% of the states relied on manufacturer data to approve materials. More information can be found in the state report summary (Masten and Ley 2021).

Agencies should not require durability tests or physical properties that do not apply to the performance of the repair material for their application. For example, freeze-thaw testing should not be required when the concrete will not be exposed to continuous moisture and exposed to subsequent freeze-thaw cycles. One example is a bridge column or abutment that will not have continuous moisture in contact with the surface.

Also, some repair materials expand at early ages during curing, and this will not be captured by traditional ASTM C157 shrinkage testing. It would be better to take continuous measurements of these samples with an embedded strain gauge such as a vibrating wire gauge. This is discussed more in Part 2 of this document.

The current values for RCPT and resistivity were developed for OPC mixtures. This means that using these values to make decisions about rapid setting repair materials is not recommended until more testing has been completed. A correlation needs to be established between chloride diffusion testing and electrical methods for these repair materials. For this reason, it is suggested that a chloride ponding test (ASTM C1543) be used to pre-approve different repair materials, and electrical tests like RCPT and resistivity be used for information only until a relationship with the diffusion coefficient is established.

It is not recommended to require repair materials to be tested for alkali-silica reaction (ASR) unless the patch is expected to last more than 20 yrs. Testing for sulfate attack should only be a concern if the local project site necessitates that, and long life is required. This information should be available from soil borings and the local environment.

1.2.2 Acceptance of Repair Materials On Site

The acceptance of a repair material at a project is typically done with fresh property testing, hardened property testing, and some non-destructive testing. A summary of the acceptance methods used is shown in Table 2.

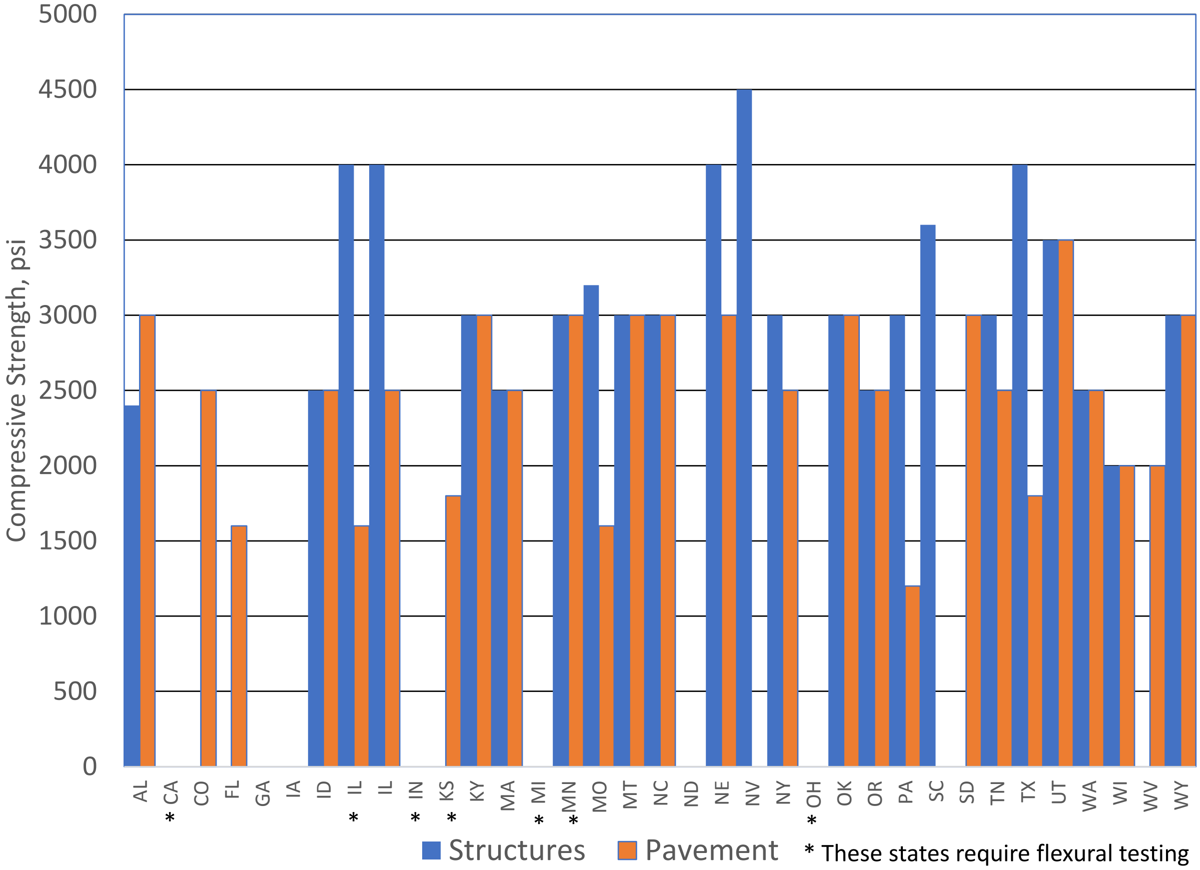
Table 2. Summary of tests required for acceptance of repair material

Required Field Tests	Percent of Respondents
Compressive Strength	66%
Air Content	40%
Slump	34%

Required Field Tests	Percent of Respondents
Flexural Strength	17%
Other	17%
None	23%

Source: Masten and Ley 2021, *NCC Spring 2021 State Reports on Fast Setting Patching Materials*

The most common way to accept repair materials in the field is to use compressive strength. This is done by two-thirds of the agencies that responded. A little under 20% of the states use flexural strength as a method of acceptance. This shows that the rate of strength gain is important for these materials and is a major point of focus. A summary of the compressive strength required for bridge and pavement repairs is given in Figure 1.



* States that require flexural testing; data source: Masten and Ley 2021

Figure 1. Summary of compressive strength requirements for traffic opening for structures and pavements

States with an asterisk require flexural testing. More detailed information can be found in the states survey report (Masten and Ley 2021).

The air content is measured by 40% of the survey respondents. One reason why this percentage may not be higher is the concern that repair materials cannot be tested given their rapid hardening. This did not seem to be a concern for about half of the respondents.

The slump test was required in the field by about one-third of respondents. It was not clear if this test is used for informational purposes or acceptance.

About 20% of the states had some other required test, such as the Minnesota DOT (MnDOT), which requires a visual inspection of all patches for cracking. If patches are cracked, they must be removed. They also require an inspector to check for debonding of the patch with a chain drag. If the chain drag indicates debonding, the patch is required to be removed.

Finally, about one in four agencies require no testing for acceptance. This means that whatever material is delivered to the job is used. The service life of these repair materials may be improved if more attention is paid to the property and construction of these materials.

For the acceptance of repair materials, it is recommended that some testing be required. Some verification must be done on these materials and the mixture to ensure the correct material is delivered. It is also recommended that slump testing be used for informational purposes only if required at all.

Air content should be measured if it is important for the long-term durability of the material. As previously discussed, the strength requirement for opening should not be a fixed value and should depend on the application. Furthermore, some states have much higher strength requirements than others.

It appears that many states are requiring the patching material to obtain the same strength as the material around it before opening. While this may appear conservative, it requires the patch to obtain this high strength in a few hours. This causes the material to use more binder and lower w/cm ratios than needed. This leads to increases in cracking and lower overall durability for the patch material. It can also shorten the life of the patch, which will cause additional repairs to be made. A national effort should be made to unify the requirements for patching materials.

1.2.3 Change to Construction Specification for Repair Materials

For construction, 50% of the agencies made no changes to their current specifications for repairs on bridges or pavements, and 34% required a modification to the curing practices. It was most common to use wet curing or cover the repair with plastic for as long as possible. This helps maintain moisture and temperature in the repair and helps ensure long-term performance.

One common change was to allow volumetric mixers to mix the repair materials onsite. This gives the contractor the longest working time possible with the materials. It also allows rapid setting materials to be placed with lower amounts of set-controlling admixtures. While many states have been concerned in the past about using volumetric mixers, this equipment has improved dramatically, and volumetric mixers are a useful tool as long as they are maintained and calibrated.

The survey showed that 75% of the agencies allow volumetric mixers to be used. However, because of the tight time constraints and fast setting materials, many contractors are not able to ensure a smooth surface is provided. Given that, half of the agencies reported requiring grinding after placing the repair materials.

The surface preparation of the repair is very important. For full-depth repairs, efforts should be made to not disturb the base materials during construction. It is recommended that agencies require all repair surfaces to be brought to saturated surface-dry (SSD) or require a bonding agent before placement of repair materials. All repair surfaces should be free of laitance and debris.

Curing practices should depend on the material and application. Use of wet burlap, blankets, and curing compounds should be used and remain in place as long as practical.

It is recommended to follow the manufacturer's recommendations in surface preparation and construction. Agencies should also require a localized smoothness measurement to determine if grinding is required. This will improve the smoothness of the roadway and will reduce the need for grinding, which may crack the young repair material. This will extend the life of the repair material and improve the driving experience for road users. It is recommended that more effort be made to inspect the quality of the repair after it has hardened. This can be done with a chain drag and visual inspection, as outlined by MnDOT.

It is a good practice to require a mock-up to be placed with the materials, equipment, and personnel that will be used on the project. This allows the owner to set any expectations for smoothness, cracking, and strength gain, and it allows the contractor to evaluate the working time, finishing, and curing practices. This helps ensure the success of the contractor in a low risk environment before completing work on the project. This can also provide strength-to-gain information from field materials and practices.

These mock-ups could also be cored and used to verify how in-place properties compare to expected values from the laboratory. These mock-ups should be required in the specifications and paid for accordingly.

Also, these mock-ups should be repeated until satisfactory performance is obtained. This could be done in an area away from the project on a right-of-way or could be done on a patch on the project with the least amount of risk. These mock-ups could also be left in place to compare their performance to the repairs in service. This has been done by Illinois DOT and has paid great dividends.

1.3 Common Repair Materials

Table 3 provides a list of common repair materials.

Table 3. Percentage of states that have approved different repair materials

Rapid Repair Material	% of States Where Materials are Approved	
	Pavement	Bridge
Accelerated Portland Cement Concrete	71%	63%
Non-Shrink or Shrinkage Compensating Cement (CSA)	69%	77%
Magnesium Phosphate Cement	23%	46%
Polyester Concrete	20%	54%
Calcium Aluminate Cement (CAC)	17%	17%
Ultra-High Performance Concrete (UHPC)	11%	29%
Alkali-Activated (AA) Cement	9%	9%
Other	29%	37%

Source: Masten and Ley 2021, *NCC Spring 2021 State Reports on Fast Setting Patching Materials*

The materials are organized by general categories and the percentage of agencies that approve them. The list is organized by the most approved material for pavements to the least approved material. More details can be found in the states survey report (Masten and Ley 2021).

This list shows that accelerated OPC and CSA cement materials are the two most popular repair materials for pavements and bridges. These materials have almost the same amount of usage in pavements, and the CSA cement has a slightly higher usage for bridges. The magnesium phosphate cement, polyester concrete, and CAC are next. Both the magnesium phosphate and polyester concrete see higher usage in bridges. Next, CAC, UHPC, and AA materials complete the list.

This document focuses on the most commonly used repair materials. Because of the lack of comparative studies with UHPC, this material is only briefly discussed in this document. Many DOTs are researching UHPC, so this material may see increased usage in the future.

1.4 Repair Material Usage Recommendations

Based on the documented field performance and comparative laboratory testing, Table 4 outlines the usage of repair materials for use in pavements and structures with and without exposure to freeze-thaw cycles, along with expected service life.

Table 4. Recommendations for repair materials in different applications

	Usage	Repair Materials
Pavement	No Freeze-Thaw	OPC, CSA-P, CAC, CSA, AA, Polyester
	Freeze-Thaw	OPC, CSA-P, CAC, Polyester
Structures	**No Freeze-Thaw**	
	< 15 yr service life	OPC, CSA-P, CAC, CSA, AA, Polyester
	≥ 15 yr service life	OPC, CSA-P, CAC, Polyester
	Freeze-Thaw	
	< 15 yr service life	OPC, CSA-P, CAC, Polyester
	≥ 15 yr service life	OPC, CSA-P, CAC, Polyester

15 year service life is based on failure from the carbonation and/or corrosion
Blended CAC cement can show good performance in corrosion but has not shown good performance in carbonation
Freeze-thaw recommendations are based on both bulk freeze-thaw and surface scaling results from the laboratory and field projects

The primary difference between these lists is that mixtures with CSA and AA were not shown to have satisfactory laboratory performance in either salt scaling or bulk freeze-thaw tests. This is discussed more in Part 2 of this document.

Structural members often contain reinforcing steel near the surface, so the repair materials must resist carbonation and corrosion. The only materials that have shown successful performance in resisting carbonation in a wide variety of environments in the field and also in laboratory testing are OPC, CSA cement modified with a polymer (CSA-P), and polyester concrete. Because of this satisfactory performance, these materials are expected to have a service life greater than 15 yrs. If carbonation and corrosion are not a concern, these recommendations may change.

1.5 Field Testing Research and Performance Analysis Needs for Rapid Setting Repair Materials

More comparative testing is needed to evaluate the durability and field performance of different rapid setting repair materials. A more systematic study is needed to provide more uniform material specifications and requirements.

DOTs would benefit from having a list of projects used in their state and key details such as the materials used, specifications required, notes during construction, and testing data from production. Also, these projects need to be regularly inspected to determine their performance. The visual inspection should look for cracking, scaling, and any other concerning behavior.

Cores could also be taken to measure the depth of carbonation in the local environment and depth of chloride penetration, and to evaluate the quality of the microstructure through a petrographic inspection.

All of this information will provide outstanding information about the field performance of these rapid setting repair materials.

PART 2 TECHNICAL BACKGROUND

Part 2 provides the technical background for the rapid setting materials.

2.1 Production and Hydration of Rapid Repair Materials

This section covers hydration chemistry, common admixtures, and the durability performance of rapid setting materials.

Rapid setting materials can seem overwhelming because they appear to be so different than OPC materials. These types of cement have different set times, strength gains, and durability. Furthermore, these materials are rarely discussed in coursework, training, or at conferences. These factors can make the use of rapid setting materials intimidating.

While rapid setting materials are different from OPC materials, many details are similar between the materials. For example, OPC, CSA cement, and CAC based cement are all produced with a similar procedure. Raw materials of different amounts are ground, mixed, and added to a kiln. The raw material is ground, and other components may be added to control the hydration reactions. Although the processes are similar to producing OPC, the amounts and types of raw materials and temperatures used in the kiln vary based on the cement that is being made.

AA, geopolymers, and magnesium phosphate cement (MPC) react by mixing a solid material, such as fly ash or slag, in the case of an AA or geopolymer, or magnesium oxide, in the case of an MPC, with an activator solution. The activator for an AA or geopolymer is typically basic or creates a high pH environment during the hydration reaction, and the activator for MPC is acidic or forms a low pH environment.

The composition and hydration reactions of the different rapid repair material systems are discussed below. References are also given where more information can be found. Cement chemistry shorthand is typically used in the discussion.

2.1.1 Ordinary Portland Cement (OPC)

The main phases present in anhydrous portland cement are tricalcium silicate or alite (C_3S), dicalcium silicate or belite (C_2S), tricalcium aluminate or aluminate (C_3A), tetracalcium aluminoferrite or ferrite (C_4AF), and anhydrite, or a form of gypsum ($C\overline{S}$). When water is added, the dissolution and reaction of these phases create calcium silicate hydrate, ettringite, monosulfate, and calcium hydroxide. The calcium silicate hydrates (C-S-H) are the main strength-giving components, and they reduce the penetration of outside chemicals. The calcium hydroxide (portlandite) and the sodium and potassium oxides are responsible for raising the pH. This keeps the alkalinity of the pore solution high and helps protect reinforcing steel. Also, the C-S-H, monosulfate (alumina, ferric oxide, monosulfate [AFm]) phases, and the C_3A, can bind chlorides. This can reduce the concentration of free chlorides within the concrete and further help protect the reinforcing steel bar surface.

To make OPC usable as a rapid setting repair material, it is common to use a range of admixtures and tools to increase the speed at which it gains strength. This can be done by using cement with a high fineness, like Type III cement. The materials in the mixture can also be heated to speed the chemical reaction. Thick curing blankets are commonly used to trap as much heat as possible in the concrete as it is hydrating, for example. These OPC mixtures often contain binder contents > 700 lbs/yd^3, a w/cm ratio < 0.35, and 5% to 8% silica fume, while often not containing slag or fly ash, given these supplementary cementitious materials (SCMs) can decrease early-age strength gain (Macadam et al. 1984).

Rapid setting mixtures contain high dosages of non-chloride accelerators, such as calcium nitrite and calcium nitrate, to decrease the set time and increase early-age strength gain. These mixtures also contain high dosages of polycarboxylate superplasticizers due to the low w/cm ratio and may contain an air entraining agent (AEA) for freezing environments and some shrinkage-reducing admixture to reducing cracking. This mix design makes rapid setting mixtures quite complex and sometimes challenging to troubleshoot. Some examples of typical mixture designs and admixture dosages used by the California DOT (Caltrans) have been reported (Urbanek et al. 2015).

2.1.2 Calcium Sulfoaluminate (CSA) Cement

Typical CSA cements contain $C\overline{S}$, C_2S, and $C_4A_3\overline{S}$ (ye'elimite) (Geng et al. 2014). The hydration reactions and products depend on the ratio of gypsum to ye'elimite in the cement. These reactions will also change if calcium hydroxide is present. The presence of calcium hydroxide causes the hydration products to be expansive, which can offset future shrinkage experienced by the repair material.

The primary hydration products from CSA cement are ettringite and aluminum hydroxides. These materials are responsible for the strength and durability of CSAs. An overview of the reactions is shown in Equation 1.

Equation 1

$$C_4A_3\overline{S} + 2C\overline{S} + 38H \rightarrow \text{Ettringite} + 4AH_3 \quad \text{(i)}$$
$$3CA + 3C\overline{S} + 38H \rightarrow \text{Ettringite} + 2AH_3 \quad \text{(ii)}$$
$$3C_4A_3\overline{S} + 18H \rightarrow \text{monosulfate} + 2AH_3 \quad \text{(iii)}$$
$$C_4A_3\overline{S} + 8C\overline{S} + 6CH + 90H \rightarrow 3\ \text{Ettringite} \quad \text{(iv)}$$

If sufficient gypsum is present in the cement, reactions (i) and (ii) in Equation 1 occur, forming ettringite as the main hydration product, as well as aluminum hydroxide. This is what forms immediately when water is added. The ettringite that forms are long crystals that are quite strong. If insufficient gypsum is present, reaction (iii) will be dominant. This will form monosulfate instead of ettringite, and this will not produce a material with the same strength or durability (Winnefeld and Barlag 2010, Glasser ad Zhang 2001). This will only occur after all the gypsum is reacted. This can be avoided if sufficient gypsum is added during grinding. However, care should be taken to not use too much gypsum in the cement, as this can cause expansion and macro cracking (Bizzozero et al. 2014).

If the CSA cement also contains C_2S or belite, a fourth reaction (iv) occurs. First, the belite reacts with water and forms C-S-H and calcium hydroxide. The C-S-H can increase the strength and reduce the porosity of the material. The calcium hydroxide that is formed combines with the ye'elimite and gypsum to form additional ettringite. Given that belite takes so long to hydrate, this reaction may occur over relatively long periods (past 28 days). This shows the great potential for CSA cements to continue to react after their first 28 days.

Ettringite and C-S-H (formed in CSA binders containing belite) are the main hydration products for CSA cements. With little to no C_3S present in typical CSA cements and, given the calcium hydroxide that is formed will further react to form more ettringite, the amount of calcium hydroxide is low in the mix compared to that of traditional OPC systems. Because of this, only the sodium and potassium within the cement will cause the pH to increase. This means that CSA cements typically have a low capacity to bind outside chemicals like chlorides or to form a passive layer to protect the reinforcing steel within the CSA cement. This can lead to reduced protection from corrosion and carbonation. One way to address this issue is to include polymer additives in the mix to resist the penetration of outside fluids.

Some CSA cement can expand during hydration to help offset shrinkage; however, not all cement behaves like this. The expansion is a function of the chemical composition, particle size, w/cm, ye'elimite, gypsum, and particle size (Chen et al. 2012). This suggests that traditional shrinkage tests may not be appropriate for these materials. It is recommended to use an embedded strain gauge to measure the expansion during hydration.

2.1.3 Calcium Aluminate Cement (CAC)

The main phases with CAC are CA, C_3A, and C_4AF. Some CACs may also contain C_2S and C_2AS. The nature of hydration products formed on reaction with water greatly depends on the temperature during hydration. With temperatures < 15° C, CAH_{10} forms [reaction (i) in Equation 2].

Equation 2

$6CA+60H \rightarrow CAH_{10}$ (i)
$6CA+60H \rightarrow 3C_2AH_8+3AH_3+27H$ (ii)
$6CA+60H \rightarrow 2C_3AH_6+4AH_3+36H$ (iii)

When the temperature is > 15° C, the reaction produces C_2AH_6 and C_3AH_6 [reactions (ii) and (iii) in Equation 2]. The reaction products produced in reactions (i) and (ii) convert to the product in reaction (iii). This conversion occurs at about 60 days and typically causes micro cracks that allow outside chemicals to penetrate the concrete along with a decrease in strength by as much as 50% (Scrivener et al. 1999, Chotard et al. 2003, Cong and Kirkpatrick 1993).

Like CSA cement, given relatively little C_3S or C_2S is present, a minimal amount of calcium hydroxide is produced during hydration. Because of the low amount of calcium hydroxide formed, this lowers the protection of reinforcing steel bar from corrosion and carbonation. The hydration products formed have the potential to bind outside chlorides; however, the binding may not be stable, and the chlorides can be released (Goñi and Guerrero 2003, Goñi et al. 1994, Goñi et al. 1991).

Because of the conversion and lack of resistance to carbonation, CAC is commonly used in combination with other binders like OPC. If these mix combinations are correctly designed, the conversion can be avoided, and the resistance to carbonation can be improved. This is why most commercial repair materials that contain CAC will be a blend of other materials. In this document, the acronym CACT is used for blends of CAC with other cements.

2.1.4 Blends of OPC, CSA, and CAC

Blends of OPC, CSA cement, and CAC are used in practice to try to improve mix properties and lower the cost. Theoretically, these blends should produce a microstructure that is a combination of these materials; however, secondary reactions occur that change the observed behaviors. This makes performance difficult to predict. Many proprietary products are a combination of these materials, and they are carefully formulated to meet specific performance goals. This highlights the need for agencies to require acceptance testing to meet the needs and criteria for their applications.

2.1.5 Activated Aluminosilicate (AA) Binders

The products formed in AA systems depend on the types of raw materials and the activator solution. For mixtures that use calcium-rich raw materials, such as slag and Class C fly ash, the main hydration products are C-S-H type materials with a modified structure.

For example, one material may have a higher aluminum content and form a hydration product known as C-A-S-H. Another hydration product has sodium instead of calcium, and this material is known as N-A-S-H.

The AA binder can also produce some C-S-H, ettringite, AFm phases, and stratlingite (Haha et al. 2011, Myers et al. 2013). AA systems can also be produced with low-calcium raw materials such as Class F fly ash. In these binders, the N-A-S-H is the dominant hydration product. Slag or blends of fly ash and slag can also be used to produce useful materials for reactions. Alkalies contained within the raw materials and activator can increase the pH of the pore solution, but do not typically provide a reserve or buffer to keep the pore solution pH high enough to form a passive layer around the reinforcing steel bar or to resist carbonation; however, additional work is needed in this area to understand the wide variety of possible combinations that can be used to produce AA.

2.1.6 Magnesium Phosphate Cement (MPC)

Typically, MPCs are made by combining powdered MgO with a water-soluble acid phosphate. An ammonium phosphate such as diammonium hydrogen phosphate or $(NH_4)_2HPO_4$ is the most studied activator in MPCs. The ammonium phosphate is typically added as a high concentration solution that is mixed with MgO powder. The consistency or workability of the mixture is sensitive to the ratio of the MgO powder to the concentration of the diammonium hydrogen phosphate. The reaction is summarized in Equation 3.

Equation 3

$$MgO + (NH_4)_2HPO_4 + 5H_2O \rightarrow NH_4MgPO_4 \times 6H_2O + NH_3$$

The products of the reaction are struvite ($NH_4MgPO_4\ 6H_2O + NH_3$) and ammonia gas. The ammonia gas can be decreased if alkali phosphates are used instead of the ammonium phosphates. Struvite is responsible for the hardening and strength gain of the material. Other undesirable products can be formed during the reaction if the water content in the mixture is low (Hall et al. 1998).

About 50% of the strength of the mixture is obtained within 4 hrs after hydration begins. Set-controlling retarders also increase the ultimate strength of the mixture. MPCs produce concrete with a low pH. They rely on their low permeability to resist chlorides and CO_2 from penetrating the concrete. The activator on some commercial products is reported to form a protective layer around the reinforcing steel (Phoscrete 2021); however, no long term field data have been found for these materials.

2.1.7 Ultra-High Performance Concrete (UHPC)

Ultra-high performance concrete (UHPC) has been historically known as densely packed cementitious materials or reactive powder concrete. This material combines OPC with a specially designed combination of powders that are finer and more coarse. These additional powders can be silica fume, silica flour, limestone, fly ash, bauxite, rutile, and slag. Other powders may be used if they contain the correct size distribution. The size distributions of the powders must be carefully controlled to minimize the voids within the powder so that minimal water content can be used in the mixture. This may require special processing or sources of the materials to be sure that they do not contain agglomerates or impurities.

Placement of these materials requires large dosages of superplasticizers and mixing times between 10 and 20 min with high energy mixers. This allows a w/cm ratio < 0.25 to be used in the field. This creates a very low permeability and very high-strength mixtures (typically 5 times higher than OPC). These mixtures often contain steel fibers and pea gravel aggregates. The steel fibers help arrest cracks and provide ductility, because the material is extremely brittle. The small aggregates reduce chemical shrinkage during hydration while minimizing the impact on strength. The properties of UHPC can be improved if heated > 80^{o} C during hydration; however, this is often not practical in the field. The hydration process produces a C-S-H material that is similar to that with OPC reactions. The ratio of the calcium to silica content of the C-S-H is reduced if silica fume is present in the mixture (Lu et al. 1993).

The low permeability and high strength of UHPC are created from the dense packing of particles that are cemented together with hydration products from OPC and some pozzolanic reaction products of the silica fume. Because of the low w/cm ratio, only about 50% of the cement and 10% of the silica fume has been found to react (Cheyrezy et al.1995, Zanni et al. 1996). These unreacted materials help improve the packing and the strength of the UHPC, but they are areas for future improvement of the material. In some UHPC mixtures, the unreacted silica fume has caused ASR-like cracking (St. John et al. 1996).

Because of the low permeability and decreased percentage of hydration products, UHPC seems to be more sensitive to fires than typical OPC mixtures. When UHPC is exposed to elevated temperatures, the hydration products decompose, and strength is lost at faster rates than what is typical for OPC mixtures. Also, explosive spalling has been observed when wet UHPC is exposed to high temperatures (Wise and Kevan 1989). This is similar to what is observed in high-performance concrete in a fire, but it is more common with UHPC. Many studies are ongoing to produce non-proprietary UHPC mixtures to be used as closure pours or repair materials with low permeability.

2.2 Admixtures for Rapid Repair Materials

This section provides insights into the most common admixtures used for rapid setting repair materials. A more comprehensive discussion is included in the provided references.

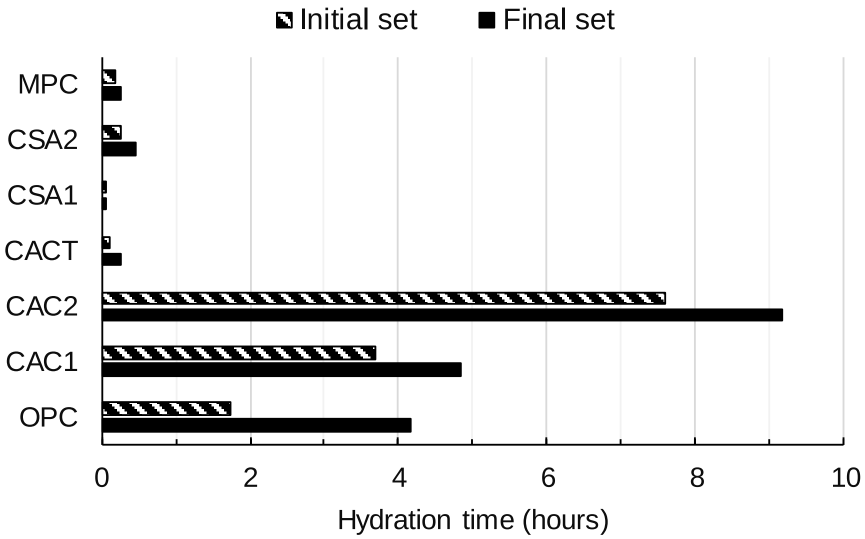
2.2.1 Polymer Additives

Polymers such as latex, or more specifically styrene butadiene rubber (SBR), are typically added to materials to reduce the porosity and the connectedness of the pores. These materials have been used on high-performance overlays for some time. Historically, these are used as liquid additives in high dosages. However, many repair products have developed powder additives that react when mixed with water.

These additives are an outstanding way to improve the durability of repair products. The effectiveness of the inorganic polymer seems to be dependent on the w/cm ratio of the mixture. Low w/cm ratio mixtures have fewer connected pores, because the grains are closer together when they react. When these grains are close enough to each other, the addition of the polymer seems to significantly decrease the permeability and therefore improve the durability against outside fluid penetration. This is discussed more in the durability performance section after this one on admixtures.

2.2.2 Set Control

Initial and final sets for paste mixes with various binders are shown in Figure 2.

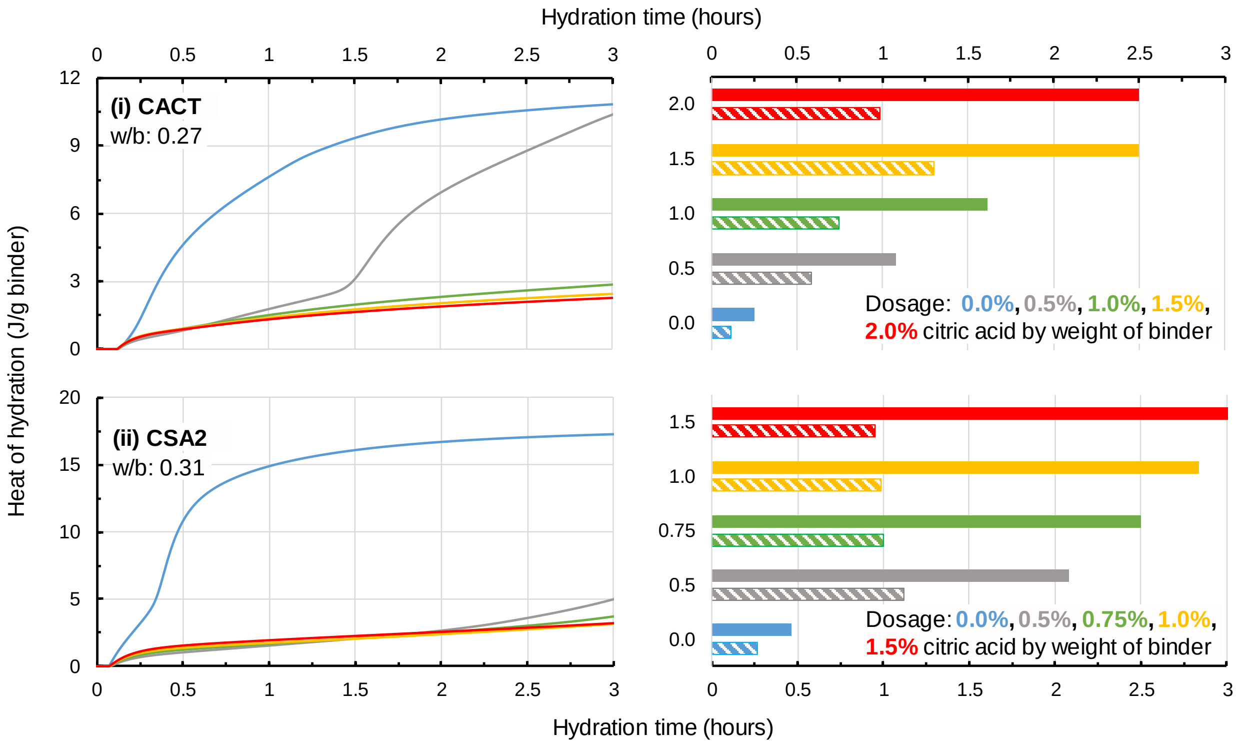


Alapati et al. 2019

Figure 2. Vicat setting times of cement pastes for a variety of repair materials

In this figure, both the CAC1 and CAC2 mixtures have higher initial and final set compared to OPC. Whereas CACT, CSA1, CSA2, CSA2P, and MPC have both initial and final setting times less than 60 minutes and are significantly lower times compared to that of the OPC. The CACT product was a blend of calcium aluminate and portland cement.

Because mixtures with CSA, blended CAC, or MPC typically show both initial and final setting times < 20 min after water is added to the mixture, it is important to be able to delay set to help ensure the mixture can be placed and consolidated. For CAC and CSA, extending the set time is typically done with citric acid. Figure 3 shows how different dosages of citric acid impact the heat of hydration, as well as the initial and final set of different mixtures for a CAC and CSA, with the paste at a constant consistency.



Alapati et al. 2019

Figure 3. Influence of citric acid dosage on early age heat of hydration from isothermal calorimetry (left) and Vicat setting times (right) of cement pastes made with CACT and with CSA2

When the citric acid dosage is > 0.5% by weight of the cement, the initial and final set is delayed. However, as the citric acid dosage is increased, the initial set or initial stiffening does not continue to increase. This means some loss in workability occurs with both of these cements after about 1 hr and that it cannot be delayed using an increased dosage of citric acid. However, the final set time can continue to be extended with increased dosages of citric acid. This shows that the set time of CAC and CSA can be extended with citric acid to obtain set times that are similar to OPC mixtures. For MPC, boric acid is used. Both of these additives seem to form a temporary coating on the cement that delays hydration, but additional research is needed to confirm this.

2.2.3 Water Reducers

Water reducers are used to improve the workability of concrete mixtures by spreading or dispersing the cement grains. This makes the materials easier to place and helps to obtain high strengths while still making workable mixtures.

Most commercial water reducers used in concrete can be used with CSA cement. The CAC cements commonly use a specialized water reducer that is formulated for high aluminate cement. Unfortunately, no known water reducers have been established for AA or MPC cement. These types of cement commonly use water to increase workability. The use of water as a dispersant decreases the strength of the mixture.

2.2.4 Air Entraining Agents (AEAs)

AEAs are used to protect concrete from damage when concrete is exposed to moisture and then freezes. This helps avoid damage from freeze-thaw cycles, as well as from surface scaling. Based on systematic testing, only synthetic AEAs or sodium oleates have been found to create stable air void systems with OPC, CSA, CAC, and AA binders (Alapati et al. 2019); however, other AEAs may provide satisfactory performance. Additional work is needed to understand how different admixtures and blends of materials impact the performance of AEAs.

2.3 Durability Performance of Rapid Setting Repair Materials

2.3.1 Volume Change

Given a repair is surrounded by existing concrete, the volume changes of the repair cause significant stresses, and this can lead to debonding or cracking. For this reason, the bond stress of the repair material is important for partial-depth patches. This means that proper material choices and construction practices are needed to provide clean surfaces for the repair.

If the volume changes are enough to cause cracks in the repair material, it is problematic because the cracks reduce the strength of the repair. The cracks also allow outside chemicals to penetrate. This can reduce the service life of the repair. For this reason, care should be paid to the volume change of different repair materials.

The volume changes discussed here are focused on shrinkage and temperature changes. Other changes, such as swelling from exposure to water, are not reported to be significant, but these may need to be checked if shown to be an issue in the field.

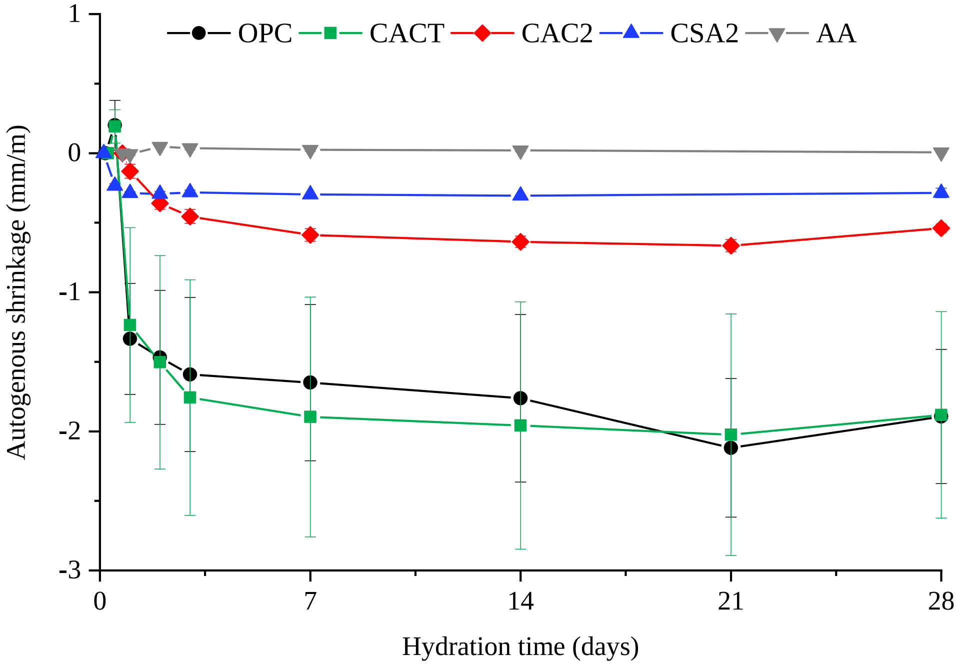
2.3.2 Shrinkage

Three types of shrinkage occur in cementitious systems: chemical, autogenous, and drying. Chemical shrinkage occurs within the first few hours of hydration before the concrete has significant stiffness. Chemical shrinkage occurs because the hydration products that form take up less volume or are denser than the original cement binder powder and fluid. This creates voids within the material that cause subsequent shrinkage. A portion of the chemical shrinkage occurs before the concrete is rigid, and, so, the strains do not typically lead to damaging stresses. Given this, a comparison of chemical shrinkage is not discussed, but additional details can be found in other documents (Burris et al. 2019, Alapati et al. 2019).

Autogenous shrinkage is the consumption of water from hydration within the pores. The water is first lost in the large pores, and, then, as more water is consumed, the smaller pores empty. As a pore empties, the surface tension of the water creates a suction or pressure on the concrete. This suction is larger in smaller pores than in larger pores. The majority of autogenous shrinkage occurs within the first week of hydration. Given the concrete has hardened, the shrinkage that occurs causes stresses and possible cracking. Both chemical and autogenous shrinkage is magnified as the w/cm ratio is decreased (Kovler and Zhutovsky 2006).

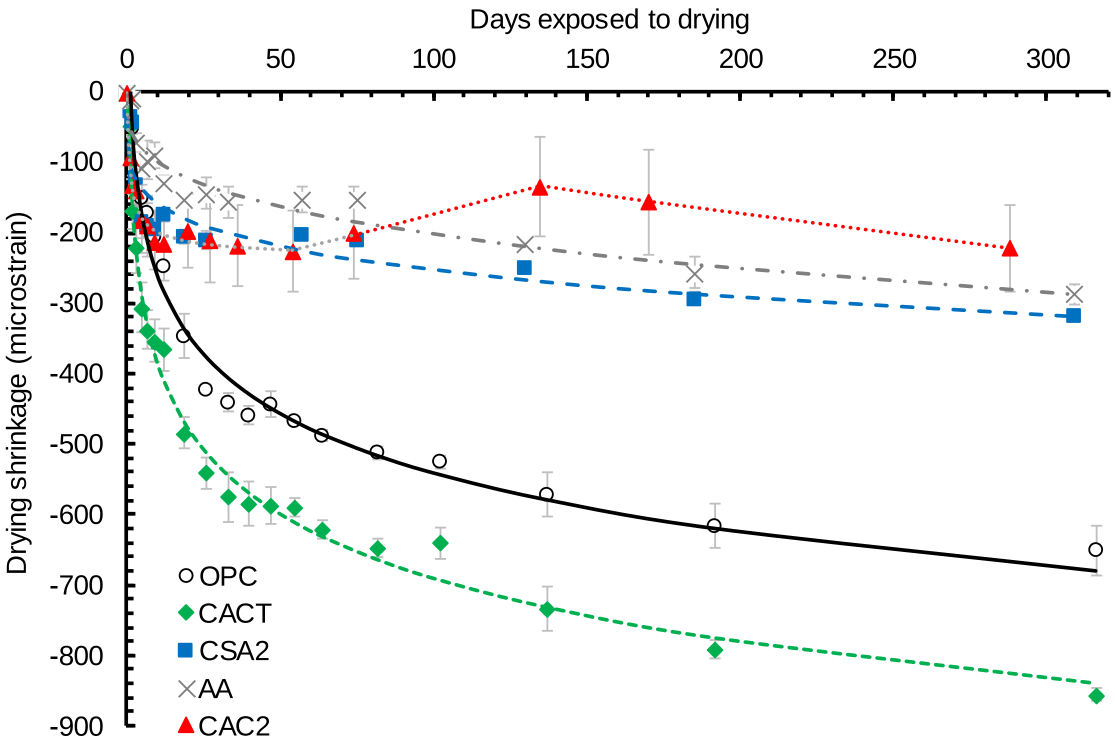
The last form of shrinkage is drying shrinkage. The mechanisms of drying shrinkage are the same as they are for autogenous shrinkage, but the water is lost to evaporation and not consumed by hydration products. Drying shrinkage is dependent on the environment in which the repair is placed, the surface-to-volume ratio of the repair, and which surfaces are available for drying.

Figures 4 and 5 show the autogenous and drying shrinkage for five different rapid setting repair products.



Burris et al. 2019, Alapati et al. 2019

Figure 4. Autogenous shrinkage of mortar samples with a 0.40 w/cm ratio over 28 days of hydration



Burris et al. 2019, Alapati et al. 2019

Figure 5. Drying shrinkage of concrete prisms with a 0.40 w/cm ratio when exposed to 50% relative humidity (RH) and 73° F

All of the mixtures used a 0.40 w/cm ratio and set-controlling admixtures to have a 1.5 hr working time. In all of the testing, the CACT and OPC showed similar and more than double the shrinkage of the other repair products (Alapati et al. 2019).

Other work confirms these findings by comparing the 28 days drying shrinkage of different repair products (Dornak et al. 2015). For example, three commercial CSA cements and a CSA cement with polymer additives all showed a decrease in shrinkage compared to that for rapid-strength OPC and three commercial CACs and a CAC with polymers. This study also showed that an AA product had three times more drying shrinkage than the rapid-strength OPC concrete. This much higher shrinkage is different from what was measured and shown in Figure 5. This shows the difference in performance that can occur with AA cement because of changes in binder type and activator chemistry.

Some field cracking studies have also been completed (Dornak et al. 2015). These were done by casting a highly restrained two-span elevated slab to simulate a bridge deck. Cracks were measured over 6 months, but the majority of the cracks appeared within the first 7 days. The CSA and rapid-strength-gain OPC showed the lowest percentage of cracks, and the CACs showed the highest percentage. The AA cement did not show significant cracking, but this material contained fibers that may have reduced the percentage of observed cracks.

This lower amount of shrinkage from CSA cement is a major advantage where cracking is a concern, such as repairs with a large surface-to-volume ratio like a thin overlay or inlay on a bridge or a pavement. This lower amount of shrinkage also shows the improved performance of CSA cements in environments with significant drying.

Typically, drying shrinkage measurements for OPC are not started until 7 to 28 days of curing. If this is used for rapid repair materials, important performance may be missed. For example, some rapid repair materials expand during the first few days, and others show excessive shrinkage from their low w/cm ratios. If drying shrinkage measurements are not started until after 7 days of curing, this will be missed.

For example, one study found that if shrinkage is compared after 7 days, there is little difference in the shrinkage of repair materials; however, if shrinkage is measured after 4 hrs, the difference is significant (Urbanek et al. 2015). One way to address this is to require a strain gauge such as a vibrating wire gauge to be embedded within the shrinkage beam when it is cast.

Previous research has shown that these gauges show good agreement with the typical measurement of the embedded pins (Burris et al. 2019, Alapati et al. 2019). These gauges can begin to measure strains immediately after casting and demolding. This information can be required during the approval of the rapid repair mixture when concerns about shrinkage exist.

2.3.3 Coefficient of Thermal Expansion

The coefficient of thermal expansion (CTE) describes the expansion or contraction of material as the temperature changes. If a repair material is bonded to or cast adjacent to existing concrete, the differential movement between the repair material and the existing concrete can cause the repair material to debond or to crack from the restraint of the surrounding concrete. This is especially a concern for repair materials that will see large temperature changes in service. This damage can be avoided by choosing repair materials with a similar CTE to that of the adjacent concrete or paying close attention to how the patch material is prepared and allowing for its expansion.

The repair materials with the largest difference in CTE are polyester concrete and any other binder that is predominately made of a polymer. These materials should be used with care because their CTE can be more than double that of other rapid repair materials.

This concern does not apply to rapid repair materials that are predominately cementitious binders and only use polymers as an admixture. The CTE of these materials is dominated by the hydration products and aggregates, because they take up the most volume in the mixture. Also, mixtures with high paste content have a higher CTE than concretes with higher aggregate content.

If a material is used with a higher CTE than the surrounding concrete, the sides of the patch should be roughened to have at least a 1/4 in. magnitude of deformation, and details need to be included that allow the repair material to freely move. For example, the material may need to be cast with a gap, or foam may be used on one side of the repair to allow expansion and contraction to occur. An example of this is shown in Figure 6.

Walt Peters, Oklahoma DOT

Figure 6. A repair material being cast with a formed joint that will be removed and replaced with joint sealant to allow for future movement

2.3.4 Freeze-Thaw Durability

Repair materials are commonly exposed to moisture and freezing temperatures. This can cause either bulk freeze-thaw damage or surface scaling of the concrete. The most common way to avoid this damage is to include air entrainment.

Alapati et al. (2019) conducted laboratory testing to investigate rapid repair materials in bulk freeze-thaw damage using ASTM C666 and surface scaling using ASTM C672. The bulk freeze-thaw testing required a durability factor of 70% or above to be satisfactory and the salt scaling damage was measured by collecting the mass lost from the sample (according to MTO LS-412) and comparing it to an acceptable threshold. This provided a quantitative way to compare the results. Most of the mixtures were prepared with a w/cm ratio of 0.40, but some were investigated at a w/cm ratio of 0.35.

Performance in both bulk freeze-thaw damage and surface salt scaling with OPC suggests that, as the entrained air content increases, the performance in both bulk freeze-thaw and salt scaling improves. This same trend was observed in bulk freeze-thaw performance for all of the repair materials. As the air content increased, so did the resistance to freeze-thaw damage. The minimum air content for satisfactory bulk freeze-thaw performance was 2% and 5% depending on the repair material. These results are summarized in Table 5.

Table 5. Recommended air content given to perform in bulk freeze-thaw (ASTM C666) and surface scaling (ASTM C672) specifications

Binder	w/cm Ratio	Recommended Air Content
CSA2	0.40	none
CSA2B	0.40	2% to 4%*
CSA2B	0.35	> 2%
CAC2	0.40	none
CACT	0.40	2.5% to 5.5%*
AA	0.40	none
OPC	0.40	> 4%

* Lower air content limit is set by bulk freeze-thaw damage (ASTM C666), and higher air content is set by salt scaling (ASTM C672)
None=no recommended air content was found that satisfied both ASTM C666 and ASTM C672
Source: Based on Alapati et al. 2019

While an increase in air volume improved performance in bulk freeze-thaw performance, this was not the case for the salt scaling performance of CAC, CSA cement, or AA cement. The binders showed unsatisfactory scaling performance above 5% air volume. This means that, for these cements, too much air causes salt scaling, and too little air causes bulk freeze-thaw damage. In summary, if the air content was too low, it failed in bulk freeze-thaw, and, if the air content was too high, it scaled. Some examples of this behavior are shown in Figure 7.

OPC – 6.4% AA – 8.4% CSA – 7.2%

Jacob Peery

Figure 7. Salt scaling results for three samples with varying air content

The results showed that, with AA and CSA samples, higher air content increased the susceptibility to scaling, while the OPC showed improved performance (Alapati et al. 2019).

For example, for CSA cements with a 0.40 w/cm ratio, no air content satisfied both bulk freeze-thaw durability and salt scaling. This means that this material should not be used in a freeze-thaw environment where extended life is needed. However, when polymer additives were included and a 0.35 w/cm ratio was used, there was no damage from bulk freeze-thaw or salt scaling regardless of the air content of the mixture. This means that this material showed satisfactory freeze-thaw resistance with only minimal entrained air in the mixture. Similar performance may occur in other rapid repair materials, but this has not been documented in the literature.

The previous Table 5 summarizes these findings by showing the range of air content for each type of rapid repair material.

The low air content was set based on the bulk freeze-thaw performance, and the high air content was based on the surface scaling limit. Based on the materials tested, air content within the range used should provide satisfactory performance.

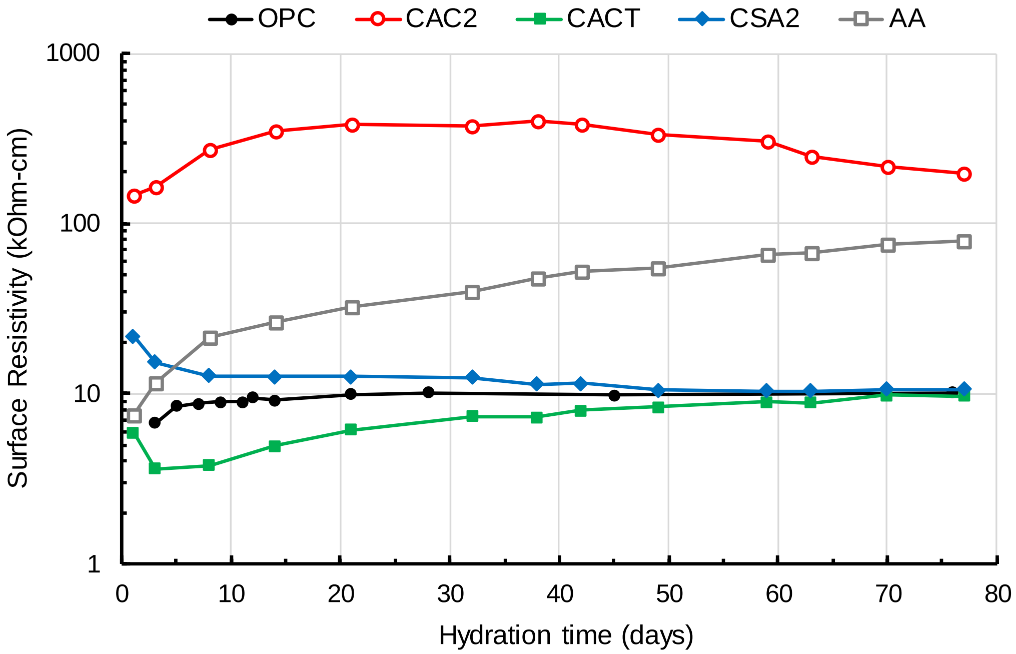
While air volume is a commonly specified parameter, the air void spacing as measured by the spacing factor from hardened air void analysis or indirectly using the Super Air Meter number (SAM number) has shown to be a better indicator of performance. Some limited spacing factors and SAM numbers have been compared to freeze-thaw durability for repair materials. The results show that the recommended limits for freeze-thaw durability may be different for repair materials than they are for OPC; however, there only a limited amount of data has been gathered (Alapati et al. 2019, Dornak et al. 2015). More data are needed to provide reliable recommendations.

2.3.5 Permeability

The rate at which outside fluids penetrate repair materials is important for all deterioration mechanisms. Special care is required in interpreting test results from sorption, resistivity, rapid chloride permeability, porosity, and salt ponding with repair materials. The tests and the timelines used to evaluate performance were developed for OPC. Because of the way that some of the non-OPCs hydrate, and because their chemistry and microstructures are so different, it's important to examine how these materials perform and when they should be tested.

Rapid test methods such as resistivity or RCPT are commonly used to estimate resistance to ion penetration or the permeability of OPC samples. These are indirect measurements that measure the electron mobility within the sample to gain an insight into the connectivity of the pore structure. When OPC mixtures have higher resistivity or RCPT values, it is expected that these materials will have a lower ion mobility permeability. However, the limits chosen for OPC may not be representative of what is needed for other types of rapid repair materials.

For example, Figure 8 shows the surface resistivity of concrete mixtures with comparable setting time and the w/cm ratios for CACT, CAC, CSA, OPC, and AA mixtures.



Surface resistivity on the vertical axis is expressed as a log scale so that all materials can be shown on the same plot
Alapati et al. 2019

Figure 8. Electrical resistivity of rapid repair material mixtures

The resistivity measurements show minimal change over the 80-day period shown on the plot. This would suggest minimal change to the pore structure during this time. Also, the results show that the CAC and AA cement have significantly higher resistivity values than those for the OPC, so it would be expected that they have a much higher resistance to outside chemical penetration.

Figure 9 shows the diffusion coefficient and porosity measured on paste samples with a 0.40 w/cm ratio over time.

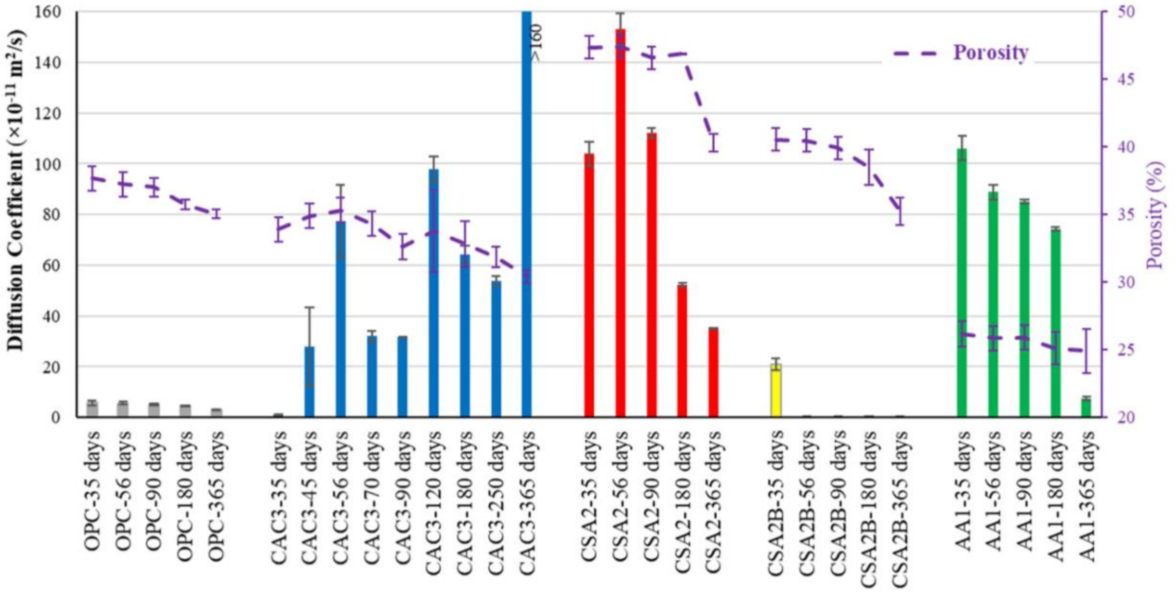


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Figure 9. Diffusion coefficient and porosity measurements of pastes made with different repair materials

The values in Figure 9 are a direct measurement of ion penetration, so they are a better indicator of what is occurring within the different mixtures than what is shown in Figure 8. These were the same binders tested for surface resistivity in Figure 8,so the results are comparable.

The diffusion coefficient measurements show a significant change in the connectivity of the microstructures between 35 days and 90 days that is not shown in the surface resistivity measurements. This is easiest to see with the CAC sample, as the diffusion coefficient increases by 2.5 times, while the resistivity only changed by 20%.

Other publications have also mentioned a lack of correlation between electrical methods and the actual pore structure of the concrete (Kang et al. 2020, Berke and Li 2007). This difference in performance between OPC and these other cements is caused by differences in pore solution chemistry and pore structure. It may be possible to overcome these issues by establishing a relationship between these electrical tests and the diffusion coefficient. This is an area for future work.

The direct measurements of the diffusion coefficient shown in Figure 9 are helpful to understand the change in the microstructures of the repair materials over time. For example, the diffusion coefficient of OPC is largely constant after 35 days of hydration, but the diffusion coefficient of CSA cement makes significant improvement at 90 days, and the diffusion coefficient for AA cement changes significantly at 180 days. Furthermore, the diffusion coefficient of the CSA cement with a polymer (CSA2B) changed by 18 times between 35 days and 56 days! This different behavior between the cements is caused because each cement has a different pore structure. This means that, at a key point during hydration or growth of the polymer, the pore structure is no longer interconnected, and this drastically reduces the diffusion coefficient or the penetration of outside ions.

It is also possible that the diffusion coefficient of the material will drastically decrease in performance over time. For example, the CAC in this study showed a 20 times increase in the diffusion coefficient from 35 days to 45 days. This substantial increase in the diffusion coefficient is likely caused by the conversion of the hydration products. (This was previously discussed in the background on CAC.) The diffusion coefficient of the CAC measured between 45 days and 250 days is quite variable. This high variability is attributed to the randomness of the cracking within the sample. Also note that these measurements were done with paste, and cracking may be reduced if aggregates are included.

All of this highlights how the performance of CAC, CSA cement, and AA cement is very different than that of OPC in microstructure and performance levels. This also means that different times may be appropriate for diffusion testing these materials. For example, the sample of a CSA cement with a polymer (CSA2B) at 56 days had a penetration depth that was 10 times smaller than that of the OPC. This was outstanding performance, and it never would have been realized if the two types of cement were compared at 35 days of hydration. The data shows that the diffusion coefficient after 90 days may be the most appropriate time to compare the diffusion coefficients of the rapid repair materials, and some AA cement samples continue to show significant improvements after 1 yr of hydration.

In summary, more direct measurements of fluid penetration, such as the diffusion coefficient, would be a better indicator of performance for repair materials. Also, these tests should be run after a significant amount of time to allow the reactions to occur and the microstructures to change. This time is found to be 90 days for these materials.

2.3.6 Chloride-Induced Corrosion

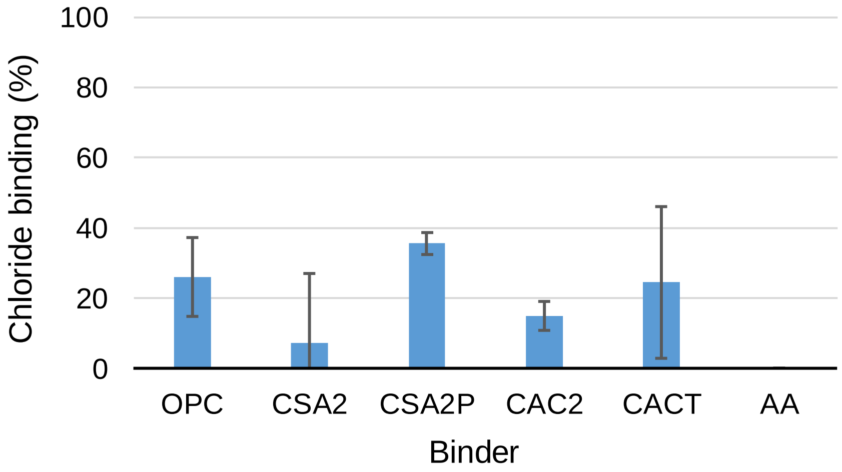
Chloride-induced corrosion is a complicated process because it depends on many different properties of the cement used in the mixture. First, chlorides penetrate to the level of the reinforcing steel and must be free in the pore solution and not bound within hydration products.

As chlorides penetrate the concrete, a portion of the chlorides can be bound or combined either physically or chemically with existing hydration products. This is called the binding capacity of the cement. Bound chloride remains within a hydration product and is not free to cause corrosion. This means a cement with a higher binding capacity will lower the penetration of chlorides and reduce the ions available for corrosion.

Next, a critical amount of chloride must be present at the surface of the reinforcement. This is known as the chloride threshold level. Finally, the electrons must transfer from the corrosion site through the concrete to other parts of the reinforcing bar for the reaction to proceed. This is controlled by the conductivity of the surrounding concrete.

After the ions have penetrated the concrete, the corrosion is controlled by the chloride binding capacity of the microstructure, the chloride threshold level at the surface of the reinforcement, and the conductivity of the surrounding concrete. These parameters can be used to compare the performance of rapid repair materials.

Figure 10 compares the chloride binding capacity of OPC, CAC2, CACT, CSA2, and AA mortar mixtures that were made with a 0.46 w/cm ratio and a 0.24 w/cm ratio for the AA mixture (Alapati et al. 2019).



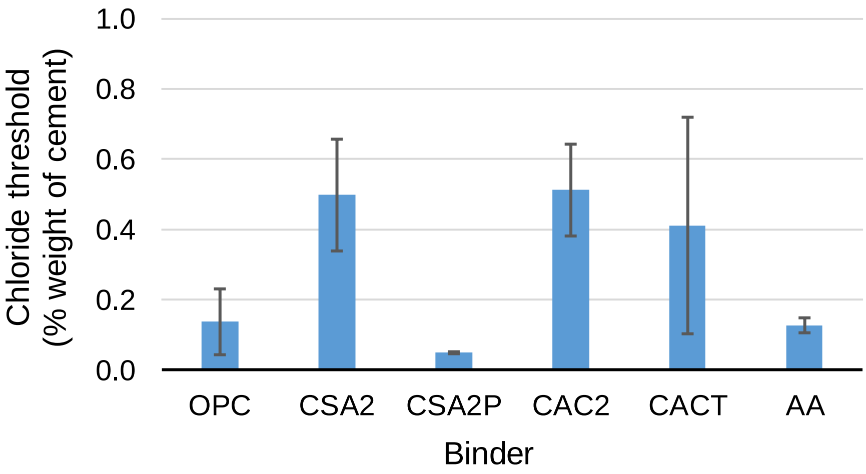
Alapati et al. 2019

Figure 10. Chloride binding capacity of typical repair mortars

The binding capacity was determined by using the ratio of the water-soluble chloride to the acid-soluble chloride ion concentration at the surface of the reinforcing bar once corrosion was initiated. The materials with the highest binding capacity were OPC, CSA2P, and CACT. All three of these had similar values.

The CSA2 and AA cements showed very low binding capacity, and the CAC2 cement was between the two groups. The low binding capacities of these cements could be due to the lower amounts of hydration products that are known to bind chlorides, such as C-S-H, AFm, and anhydrous calcium aluminates or ferrite phases. The higher binding capacity of the CSA2P cement was attributed to the low concentration of chloride ions due to the polymer additive. Given this cement had lower concentrations, the ions that were bound were a larger percentage of the available ions.

Next, the level of chlorides when corrosion is initiated was found from the same mortar samples. These results are shown in Figure 11.

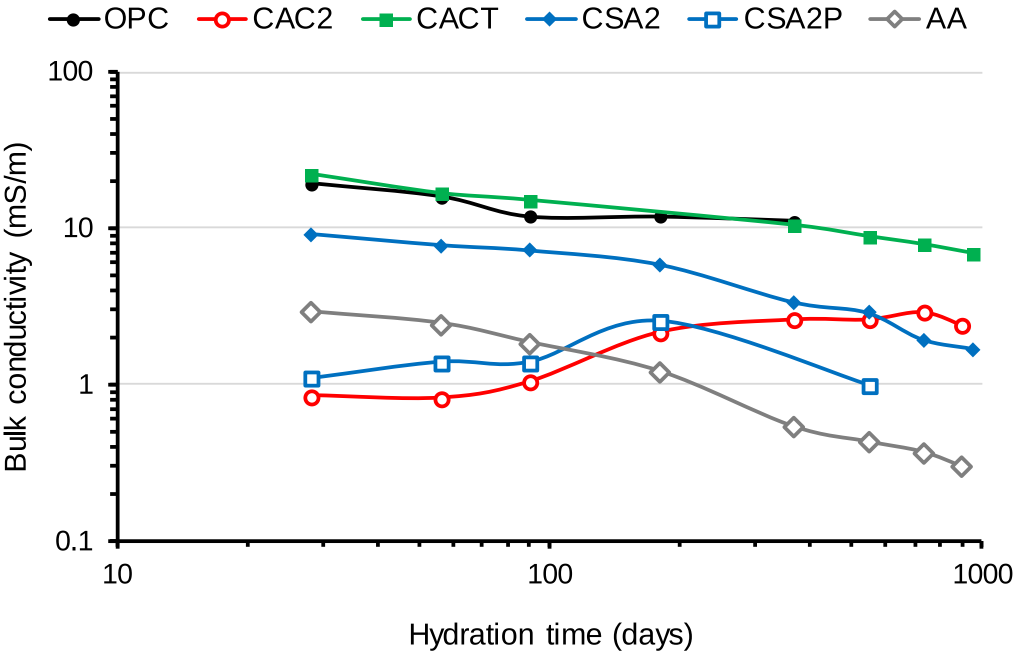


Alapati et al. 2019

Figure 11. Chloride threshold in ACM and OPC mortar mixtures

The CSA2, CAC2, and CACT mixtures had the highest chloride threshold levels, and the OPC, AA, and CSA2P mixtures had the lowest chloride threshold levels. This is another important parameter in the corrosion process, because it can be used to estimate the chloride concentration level when the corrosion process will begin. Note that care should be taken not to evaluate the corrosion performance only on this parameter.

Figure 12 shows the bulk conductivity for common repair materials.



Bulk conductivity on the vertical axis is expressed as a log scale so the results for all materials can be shown on the same graph
Alapati et al. 2019

Figure 12. Change in bulk conductivity of ACM and OPC mixtures over hydration time

The OPC, CACT, CSA2, and AA mixture samples showed a decrease in bulk conductivity with time. This means that it is more difficult to transfer electrons in these materials, and this will slow the corrosion process in concretes with these binders. The OPC and CACT mixtures had the highest conductivity, and the AA and CSA2P samples showed the lowest. The CAC2 mixture started with the lowest initial conductivity, but it increased over time. This increase in conductivity was likely caused by the increase in permeability due to the conversion of this cement and the subsequent formation of cracks. The CSA2P samples showed lower conductivity than the CSA2 sample. This decrease in conductivity was likely caused by polymer addition.

The OPC, CSA2P, and CACT mixtures showed good potential to resist corrosion in their concrete. The binders showed good combinations of binding potential, chloride threshold level, and bulk conductivity. Note that both the CSA2P and CACT mixtures showed superior performance to the OPC. While the CAC samples showed good potential, the conversion of their microstructures seemed to cause cracking as seen by their bulk conductivity measurements. This can impact the long-term performance of these materials. The AA samples showed good performance in bulk conductivity but poor performance in chloride binding and their chloride threshold levels. This means these materials may have issues in corrosion performance.

More detailed testing about active current during corrosion tests with these materials can be found in other publications (Alapati et al. 2019). These tests measure the transfer of electrons in a cracked beam specimen, and detailed evaluation of reinforcing steel has been examined. This testing confirms the observations summarized in this document.

2.3.7 Carbonation

Carbonation is the reaction of carbon dioxide from the atmosphere with hydroxide ions or calcium hydroxide to form calcium carbonate. This process lowers the pH of the concrete and allows the internal reinforcing to corrode. The corrosion product causes the concrete to crack and eventually spall. This damage weakens the repair materials and allows outside chemicals to penetrate the concrete.

Carbonation becomes a significant concern when the concrete surrounding steel reinforcing no longer has a high pH. This typically happens when the reinforcing bar is within 3 in. of a surface such as a bridge structure. Carbonation most readily occurs when the average relative humidity is between 70% and 40% and is accelerated with an increase in temperature (Drouet et al. 2019). Carbonation is also decreased by direct exposure to water. This means that the concern for carbonation can be complicated and is only limited to certain environments and structures. Additional work is needed to better understand which environments are the most severe, but field studies show that this is a concern for certain mixtures (Dornak et al. 2015).

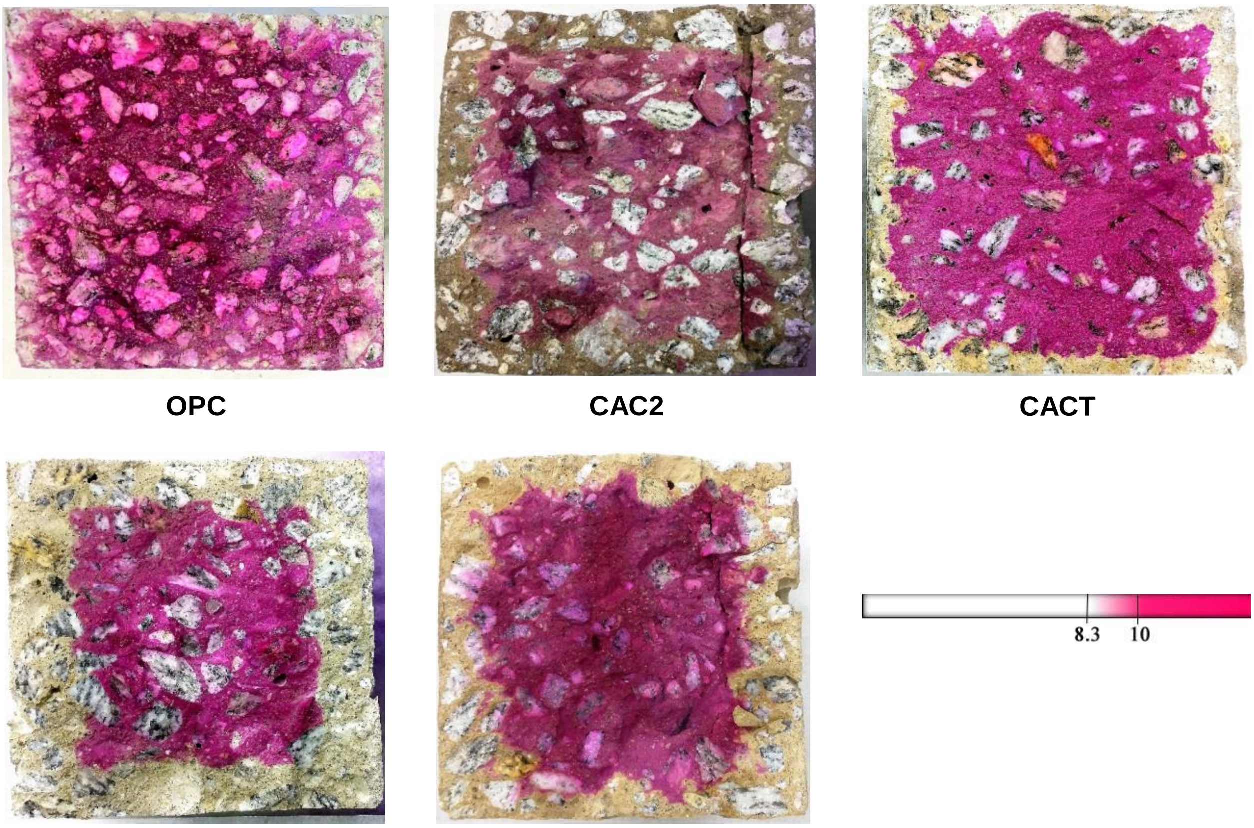
Carbonation is not a concern with OPC-based concrete with moderate to no SCMs and a w/cm ratio < 0.50. This is because of the high amount of calcium hydroxide that forms when OPC hydrates. Unfortunately, other repair materials do not create a significant amount of hydration products that can maintain a high pH such as calcium hydroxide. This means that carbonation can be a concern for these repair materials when they are used in bridge structures or any other structure where the reinforcing steel bar is within a few inches from the surface.

One way to reduce carbonation in non-OPC repair material is to decrease the penetration of the CO_2. This can be done by reducing the w/cm ratio and also treating the non-OPC repair material with a polymer that blocks the pores and reduces steel the penetration of outside fluids. An impermeable membrane can also be used on the surface of the repair material; however, these membranes deteriorate or are worn away from surface friction. It may be possible to mix OPC with other repair materials to raise the amount of calcium hydroxide or the buffer capacity against carbonation. Additional work is needed to understand how effective this is.

Very few laboratory studies have been conducted on carbonation because it is not a significant issue with concrete that uses a reasonable w/cm ratio. Carbonation is measured by breaking concrete open and spraying the surface with a pH indicator, like phenolphthalein or a rainbow pH indicator. These indicators change color based on the pH of the pore solution.

Phenolphaline is the most common indicator, and it highlights areas in pink with a pH above 10. It is clear when the pH is below 8.3. Although phenolphthalein is only an indirect indicator of pH, any region that is not pink would show a concern for carbonation.

Figure 13 shows samples for a variety of repair materials with a 0.45 w/cm ratio.



OPC **CAC2** **CACT**

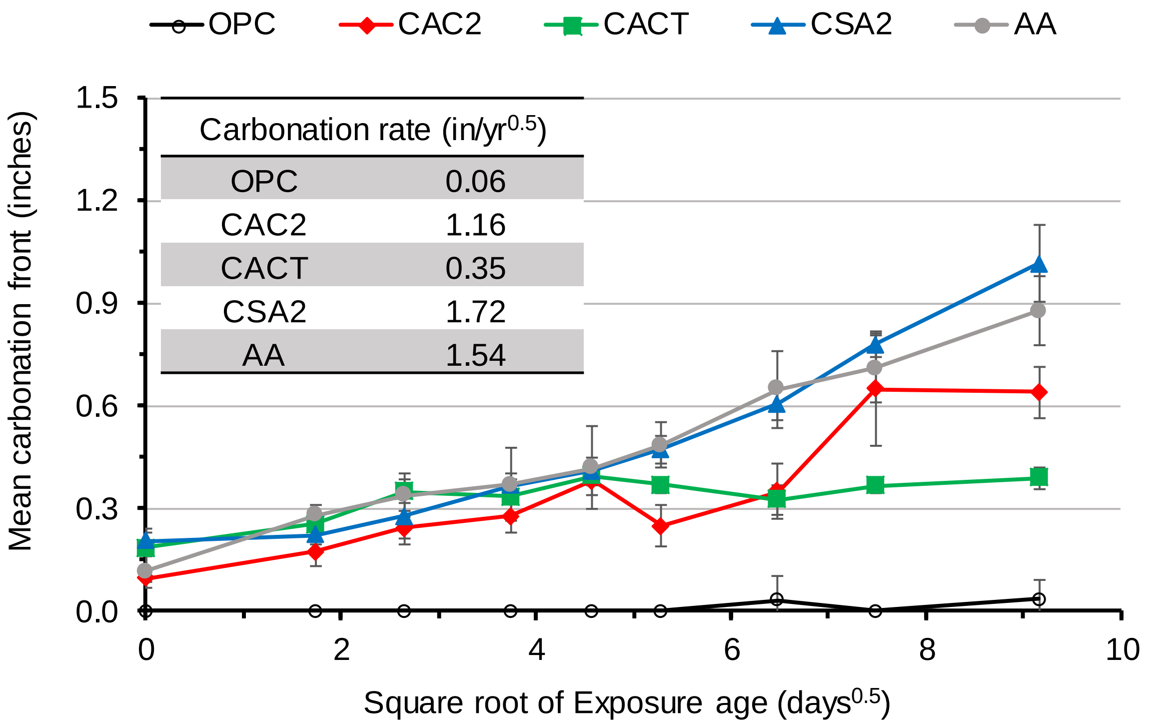
CSA2 **AA**

Alapati et al. 2019

Figure 23. Concrete samples after exposure to 7% CO_2 for 84 days and sprayed with phenolphthalein indicator

These samples were cured for 28 days and then exposed to 7% CO_2 gas for 84 days. This CO_2 concentration is 175 times higher than what is in the atmosphere. This is done to accelerate carbonation so that results can be obtained in a reasonable timeframe. While the OPC mixture shows minimal carbonation, the CSA, CAC, and AA mixtures all show carbonation over 0.75 in. The CACT material was a blend that contained OPC, and this material showed a decrease in the rate of carbonation, but the amount of OPC used was not high enough to stop carbonation.

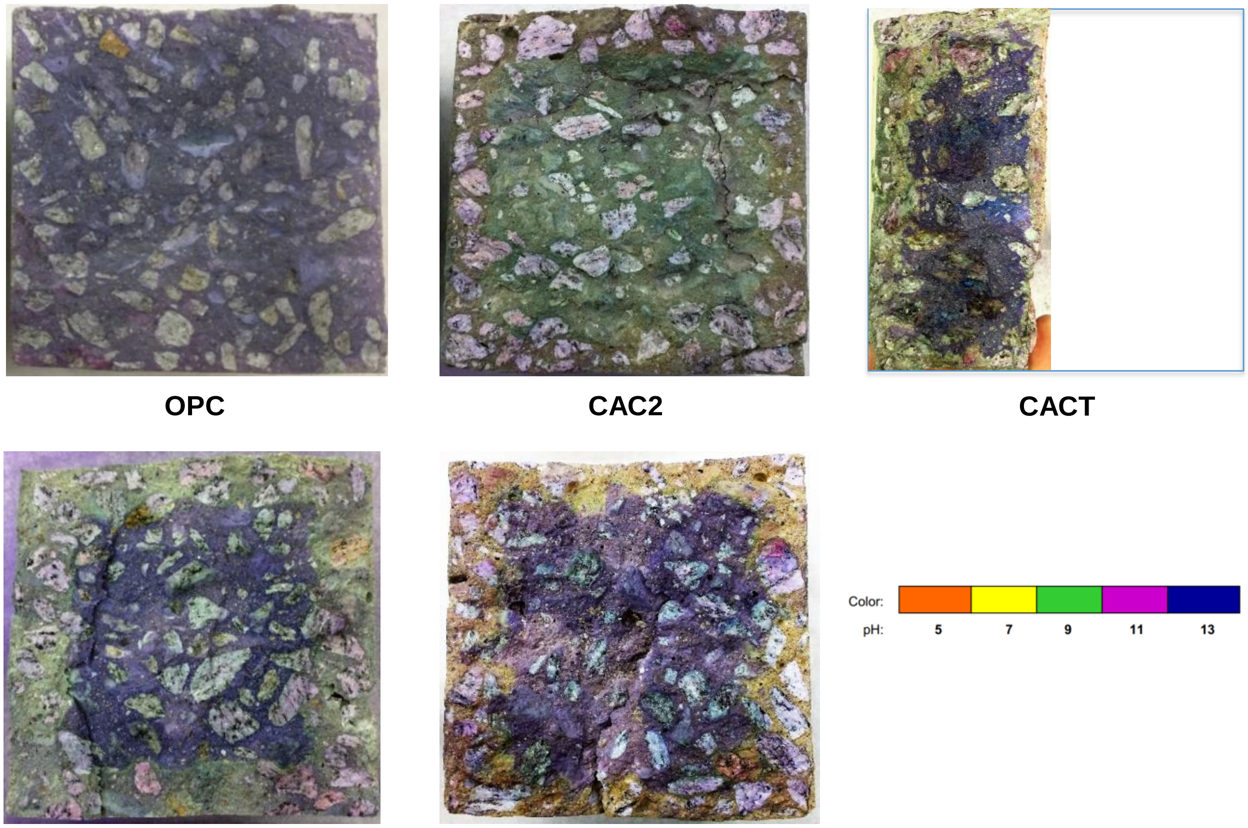
A summary of the depth of penetration over time for these five samples is shown in Figure 14.



Alapati et al. 2019

Figure 14. The mean carbonation front of concrete samples made with OPC and ACMs, exposed to 7% CO_2, at different exposure ages

To gain more insight into the observed performance, a rainbow indicator was used on the surface of the same concretes exposed to 7% CO_2 for 84 days. These results are shown in Figure 15.



OPC **CAC2** **CACT**

CSA2 **AA**

Alapati et al. 2019

Figure 15. Concrete samples after exposure to 7% CO_2 for 84 days and sprayed with a rainbow indicator

This figure shows additional details about the pH that was reached for the different materials at different depths. This can be helpful, as phenolphthalein provides only limited information about the pH. For example, the CAC sample showed a lower pH in the center of the sample that is not carbonated. The AA samples showed a high pH in the center but dropped to about 5 very quickly. The CSA sample showed a higher pH in the center, but this decreased to about 9 in the outer regions, and this pH is low enough to cause carbonation.

Only limited carbonation studies have been done on field samples. One important study compared OPC, CSA cement, two CACs, and an AA cement. This work consisted of casting 4 in. × 4 in. × 17 in. concrete prisms, placing the prisms outside in Austin, Texas, and measuring the depth of carbonation at 6 months and 11 months. The w/cm ratio and paste content changed slightly between the mixes so that they reached a strength of 3,000 psi at a few hours.

The prisms were stored either directly exposed to the weather or in a container that allowed airflow but did not allow sun or rain exposure. The difference in storage helped quantify how direct exposure to water changes the rate of carbonation. The two exposure conditions simulated the surface of the concrete that is directly exposed to water, such as the surface of a bridge deck, and an area that is not directly exposed to moisture, like the underside of a bridge deck, or in a substructure element, like a column that is under a roadway. The samples were cut; then the carbonation depth was measured using phenolphthalein. The results are summarized in Table 6.

Table 6. Carbonation depth for repair materials in field conditions for 11 months

Repair Material	Carbonation after 11 Months Exposure	
	Exposed	Covered
Rapid Strength OPC	0.01 in.	0.05 in.
CAC -3	0.13 in.	0.25 in.
CAC -2	0.12 in.	0.14 in.
AA	0.17 in.	0.29 in.
CSA	0.14 in.	0.34 in.

Source: Dornak et al. 2015

The findings showed that the two CACs, the AA cement, and the CSA cement all had carbonation depths 12 to 17 times higher than that of the OPC in the exposed samples and nearly 3 to 7 times higher than the OPC in the covered samples. All but one of the covered samples (CAC -2) showed close to or more than 2 times more carbonation than their exposed samples. The greatest depth of carbonation observed was 0.34 in. for the covered CSA sample. If carbonation continues at the same rate over time, this means a sample with reinforcing bar at 1.5 in. of cover would start carbonating in 5 yrs if it was not exposed to weather and 10 yrs if it was exposed to the weather.

This illustrates the concern with using these repair materials to protect reinforcing steel at < 3 in. with cover, such as that for a bridge. And, the increase in the carbonation rate of field samples confirms the carbonation concerns expressed through previous laboratory studies.

This is why polymer additives are so useful for CSA repair materials. However, additional research is needed to better understand how polymer additives change the depth of carbonation.

2.3.8 ASR

Very limited work has been done with repair materials to resist ASR. One reason for this is that ASR typically occurs after 20 yrs or more of service, and a patch material may not have time to show damage from ASR before being damaged from some other deterioration mechanism, or the repair may be removed from service. However, the work that has been done shows that these materials show great potential to lower the damage caused by ASR.

ASR occurs when a high pH pore solution breaks down aggregates within the concrete and creates a gel that absorbs water and then swells. For the same reason that many of these repair materials have challenges with carbonation, these materials show improved performance with ASR. Given these materials do not have as much calcium hydroxide as OPC, they do not cause the aggregate to dissolve at the same rate. Also, ASR gel requires a certain amount of free calcium that is absorbed into the gel and then released. This process may be modified by these different types of cement.

Of the repair materials investigated in rapid mortar testing (using ASTM C1260) and concrete prism tests (using ASTM C1293), AA cement showed the best resistance to ASR (Alapati et al. 2019). The performance of Alapati et al.'s CAC2, CSA2P cement, and CSA2 cement all showed similar results. The CACT and OPC had similar performance (Alapati et al. 2019). This may have been because the CACT was a blended material that contained OPC.

Additional studies of these materials are needed given some of them could serve as an additive to help reduce ASR expansion. Other repair materials, such as MPC and polymer-based cement, should not have ASR issues because they do not have a high pH.

2.3.9 Chemical Sulfate Attack

Sulfates in the soils or from some other source can cause a chemical attack of OPC. This causes the material to chemically degrade and to lose strength and crack, allowing more deterioration. This occurs because the sulfate ions attack the monosulfoaluminate, a hydration product created by tricalcium aluminate (C_3A) hydration. This can be controlled in OPC by using an ASTM C150 Type II or V cement and by using slag or class F fly ash.

Because repair materials do not form monosulfoaluminate, they are less susceptible to chemical sulfate attack. Results with CSA cement, CAC, and AA binders show that they can be used in high sulfate exposure environments. However, it should be noted that the tests to evaluate performance were designed for OPC, and more basic research to learn how these types of cements are impacted by sulfates is needed.

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APPENDIX: LISTING OF COMMONLY USED RAPID SETTING MATERIALS AND LINKS TO THEIR PRODUCT SHEETS

The standalone Excel spreadsheet for this appendix provides a listing of commonly used rapid setting repair materials and links to product sheets in which more information can be found. This is not an exhaustive list, but these are most of the common commercially available materials. https://intrans.iastate.edu/app/uploads/2022/02/rapid_setting_repair_material_listing_and_links.xlsx.

The classification of the material is a label used to help in understanding what the primary binder is within the material. This label does not include all of the additives, supplementary cementitious materials, or admixtures used in these materials, but it does provide general guidance that can be correlated to the tables and figures in this document.

Summary of abbreviations used in the materials spreadsheet

Abbreviation	Description
OPC	Ordinary portland cement
CSA	Calcium sulfoaluminate cement
CAC	Calcium aluminate cement
AA	Alkali activated
MgP	Magnesium phosphate
Unclear	Cannot be determined based on the information provided
P	A polymer additive is included to help reduce the permeability

It is recommended that the material data sheets be used to further understand the individual materials and their performance before using them. All of the links in the spreadsheet were valid in December 2021, but these may change over time. It is recommended to search for the product name or to contact the company to find the latest information on each product.

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