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INDIANA DEPARTMENT OF TRANSPORTATION
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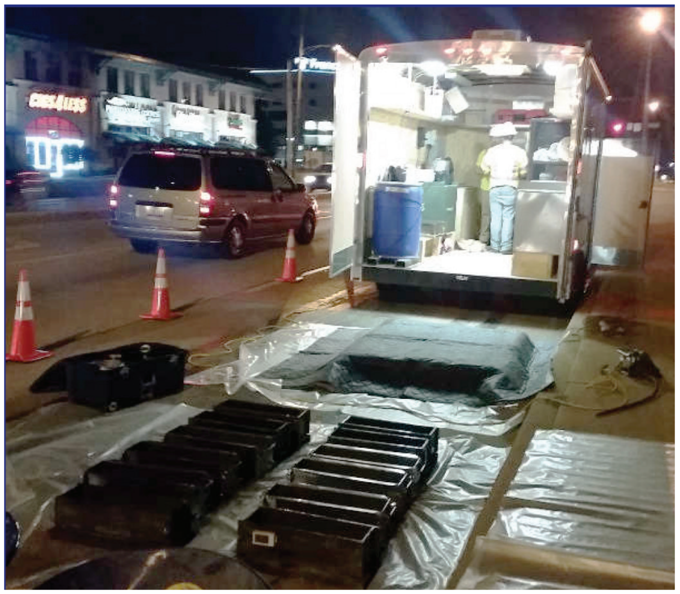
Concrete Patching Materials and Techniques and Guidelines for Hot Weather Concreting



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16. Abstract

High early strength (HES) concrete is becoming increasingly used to repair damaged concrete pavement sections. The use of HES concrete enables the repaired pavement to be opened to traffic within hours of placing the concrete. Rapid repair of concrete pavement is an attractive solution since the traveling public is not delayed by the repair of the pavement in addition to a decrease in the amount of exposure to traffic by construction personnel; however, there are challenges due to strict requirements for opening strength and severe penalties for not achieving the target strength. This project examined failure to obtain long term strength in the construction practices of long patches in concrete pavements. The work examined issues associated with temperature on sulfate balance, flexural strength prediction (maturity methods) considering the influence of moisture (effects of self-desiccation), shrinkage mitigation techniques (internal curing), and improving the overall durability of HES concrete patching materials.

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EXECUTIVE SUMMARY

CONCRETE PATCHING MATERIALS AND TECHNIQUES AND GUIDELINES FOR HOT WEATHER CONCRETING

Introduction

High early strength (HES) concrete is increasingly being used to repair damaged concrete pavement sections. Its use enables repaired pavement to be opened within hours of placing the concrete, reducing both delays for the traveling public and exposure to traffic for construction personnel. However, the use of HES concrete also presents challenges due to strict requirements for opening strength and severe penalties for not achieving the target strength. This project examined failure to obtain long-term strength in long patches in concrete pavements.

Findings

When the temperature of HES concrete patches is expected to be elevated and accelerating admixtures are used, the balance of sulfates need to be considered. While the experiments showed that additional sulfate can improve the effectiveness of accelerating admixture, this is likely not practical for field use. Rather, experiments to determine whether the sulfate balance is attained at high temperatures with admixtures may be useful for suppliers.

Since these mixtures are mixed at a low water-to-cement ratio, they are prone to self-desiccation that leads to shrinkage and causes hydration and strength development to cease. Internal curing can be used to supply additional curing water to HES mixtures, thus improving durability, hydration, and strength development (i.e., mechanical properties). Modified maturity methods that account for self-desiccation can be used to increase the accuracy of target strength predications. This would consist of adding a term to standard current practices to account for self-desiccation.

Implementation

This project examined why INDOT patching mixtures were not obtaining the strength predicted by standard testing methods. It was determined that the use of admixtures at a high temperature resulted in challenges with the balance of sulfates that interfered with the hydration process. These findings were presented to the study advisory committee, at Purdue Road School, and at the annual meeting of the American Concrete Paving Association. Furthermore, self-desiccation limits strength development, and this research report outlines a procedure that incorporates a term to be added to the maturity method to account for how strength development can be limited by self-desiccation.

CONTENTS

LIST OF FIGURES

1. INTRODUCTION

Billions of dollars are being spent by federal, state, and local agencies each year in an effort to improve the aging roadway infrastructure of the United States (American Society of Civil Engineers, 2013; U.S. Department of Transportation Federal Highway Administration, 2010, 2015). In an effort to reduce disruption to the travelling public, these agencies have also begun shortening construction times by utilizing weekend only and nighttime construction more and more to rehabilitate interstates, highways, etc. (Bryden & Mace, 2002; Cottrell, 1999; Shane, Kandil, & Schexnayder, 2012).

Overnight concrete pavement patching is a method of rapid roadway rehabilitation utilized by the Indiana Department of Transportation (INDOT) and other transportation agencies. High early strength (HES) concrete patching materials are used to repair damaged pavement sections thereby enabling the repaired pavement to be opened to traffic at an early age. A common approach for rapid repair consist of closing a pavement section after evening rush hour traffic, removing the existing pavement, preparing the patch area, placing a HES concrete repair material, and opening the repaired pavement to traffic loads the following morning (Todd, 2015; Wilson et al., 2016). In this repair methodology, the HES concrete is expected to have gained the target strength over-night so that it can be opened to traffic early the following morning. As a result, traffic delays during day-time hours are kept to a minimum. The rapid repair of concrete pavement is attractive because the traveling public is not delayed by the repair of the pavement and costs associated with traffic delays are kept to a minimum.

Although rapid repair of concrete pavement is attractive, inherently it has challenges. Contractors recognize that there is a high risk for not achieving the target strength in the allotted time, thus incurring penalties. Because of this, bid price is adjusted to account for the costs of the penalties, requiring higher average bid prices for these types of projects (Ellis & Kumar, 1993; Hinze & Carlisle, 1990-2; Minchin, Thurn, Ellis, & Lewis, n.d.). In addition, these type of projects have strict requirements for opening, requiring simultaneous construction tasks including site specific traffic control.

The challenges associated with successfully completing a HES concrete repair job safely, on time, and at or above target strength frequently result in the contractor modifying the mixture design and curing procedures. These modifications can have a negative impact on durability properties of the concrete. Modifications include use of the following:

1. admixtures such as accelerators (which have been observed to alter the sulfate balance and alter strength gain (Paulini, 1990; Roberts & Taylor, 2007; Todd, 2015; Wilson et al., 2016);
2. high cement contents (and often a lack of supplementary cementitious contents which have been observed to increase the potential for deicing salt damage (Monical, Villani, Farnam, Unal, & Weiss, 2016);
3. heated blankets for high temperature curing (which may result in an increased potential for thermal cracking, especially when combined with high cement contents (Bagade & Puttaswamy, 2009; Deo, 2016; Gajda, 2008); and
4. low water-to-cement ratios (w/c) that are susceptible to the consequences of self-desiccation.

While not immediately obvious, self-desiccation is important in these materials because consequences can include excessive shrinkage, shrinkage cracking, and a reduced rate of strength gain.

This report aims to help INDOT improve the performance and predictability of patching materials with high early strength and long-term durability. By improving the predictability and performance of these materials, INDOT can reduce costs associated with traffic control and the risks associated with liquidated damages; thereby reducing the overall cost of construction.

Chapter 2 of this report discusses the main findings of the literature review regarding HES concrete patching materials for the rapid repair of concrete pavements.

Chapter 3 discusses the main findings of the project, and a brief summary list is listed below.

1. Site visits for rapid repair using HES concrete (3.1)
2. Temperature of field-produced concrete (3.2)
3. Flexural strength under variable curing conditions (3.3)
4. Use of nondestructive testing (NDT) methods for strength determination (Windsor Pin) (3.4)
5. Effects of self-desiccation on HES concrete (role of water) (3.5)
6. Accelerator dosage variations at ambient and elevated temperatures (optimum sulfate levels) (3.6)
7. Activation energy determination (3.7)
8. Durability and fracture mechanics of materials containing accelerating admixtures cured at ambient and elevated temperatures (3.8)
9. Shrinkage and stress reduction (3.9)

Chapter 4 describes the main conclusions for improving the performance, predictability, and durability of HES concrete patching materials for the rapid repair of concrete pavements.

Chapter 5 lists two master's theses that provide more detail on the findings of this report.

2. MAIN FINDINGS OF THE LITERATURE REVIEW

Transportation infrastructure in the United States is aging. With the U.S. Interstate System nearing its 60th Anniversary (U.S. Department of Transportation Federal Highway Administration, 2015) and many of the in-service pavements running on decades of service, the problem of maintaining infrastructure has become a priority (American Society of Civil Engineers, 2013). Maintenance and rehabilitation have led/can lead to traffic delays and back-ups. The queuing of vehicles has been shown to increase crash frequency, and ultimately is viewed negatively by citizens, taxpayers and state governments (Transportation Research Board, 2003). Data from 2010 shows a crash in a one lane closure on a two lane interstate system increases travel time from about 8 min to over 75 min when traffic levels go above the construction zones capacity of 1500 cars/hr/lane (Haseman, Wasson, & Bullock, 2010). Others (U.S. Department of Transportation Federal Highway Administration, 2005) have shown that lane closures during peak travel times cause queuing and therefore lead to crash events and reduced travel times. This leads to significant cost impacts on businesses, state agencies, and consumers utilizing the roadways within a state.

As recently as 2014, the Indiana Department of Transportation (INDOT) and other transportation agencies are transitioning to overnight lane closures for roadway construction to attempt to take advantage of significant reductions in traffic volumes. Traffic volumes usually peak around 8–9 a.m. and again around 5–6 p.m.; in contrast the traffic volumes are at a minimum from about 9 p.m. to 6 p.m. (Haseman et al., 2010). Agencies seek to take advantage of traffic level reductions with nighttime lane closures (INDOT, 2013, 2014b), attempting to minimize the impact to the traveling public. Typically, for roads with speeds below 45 mph, the queue distance can be used as a quantification to the delay that a member of traveling public might encounter. Recent data from the Joint Transportation Research Program (JTRP) at Purdue University shows that in the state of Indiana a traveler can expect at least a 10-mile queue at midnight of speeds less than 25 mph on Interstate-65 (I-65) (Haseman et al., 2010), one of the major interstates that traverses the state of Indiana. One example, on June 12, 2015, during a period of nighttime closure, an 18-mile queue on I-65 was observed around 1 a.m. While these statistics show vehicle queuing even during nighttime construction, it is significantly reduced compared to the delays that would be associated with daytime operations.

In addition to reducing congestion, nighttime roadway construction attempts to increase safety. A strong correlation has been established between queuing and traffic delays leading to higher crash numbers (Haseman et al., 2010). As such, the construction and maintenance during low traffic times helps to reduce events and increase construction employee and driver safety.

While helpful in achieving reductions in travel times, queuing, and crashes, overnight construction has caused an increase in contract prices for similar sized projects occurring during normal business hours (Ellis, Herbsman, & Chheda, 1992; Hinze & Carlisle, 1990-2; Minchin et al., n.d.). Nighttime lane closures force contractors to work quickly under a tight time constraint to allow adequate strength development on concrete pavements before the roadway must reopen to traffic (INDOT, 2014c). For example, current specifications in Indiana for patches less than 15 feet in length have been recently changed to flexural strengths of 300 psi at 24 hours (Antico, De la Varga, Esmaeeli, Nantung, Zavattieri, & Weiss, 2015; INDOT, 2014c). Agencies might also typically include penalties or liquidated damages for contractors who are not able to achieve acceptable strength in time to open the roads before the general public hits its morning high traffic levels, and are often looking at obtaining opening times of about six hours from placement (INDOT, 2014a). For the project discussed herein, liquidated damages can be assessed to the contractor for failing to open the roadway to traffic at the end of the lane closure period (INDOT, 2014a). This tight schedule leads to contractors increasing their bids in order to account for risk on these types of projects.

This project investigated approaches to improving the mix design and specification and construction practices of patches in concrete pavements. Further, this project examined methods to predict opening times with increased accuracy and reduced risk. Specifically, it examined issues associated with temperature fluctuations and flexural strength prediction.

3. SUMMARY OF THE MAIN FINDINGS OF THIS PROJECT

3.1 Site Visits for Rapid Repair, HES Concrete Projects (Utilizing MIMTL from SPR-3858)

Site visits were investigated as a part of INDOT SPR-3905 and occurred at an ongoing pavement rehabilitation project on US Highway 30 in northwest Indiana. A combination of short (<15 feet) and long (15 feet and greater), full-depth high early strength concrete patches were constructed under INDOT Project No. R-35341. The project site consisted of two lanes in each direction, from the Illinois border through the city of Dyer, IN, and briefly beyond Calumet Avenue. Two initial site visits were performed in mid-August 2014 to evaluate the project setting and obtain preliminary data. Three more site visits occurring in September and early October 2014 supplied the bulk of the presented data. All site visits were overnight construction sequences, with the exception of the last visit in early October, which was a daytime visit.

An example of the typical process followed by a contractor was recorded for HES concrete repair on US 30 in northern Indiana and is described in the following paragraph (Todd, 2015; Wilson et al., 2016). For this project, lane closure began at approximately 6 p.m. when the contractor initiated a traffic control plan to divert vehicles into a single lane of traffic in each direction. From 6 p.m. to 7 p.m., the concrete pavement was saw cut to enable the damaged concrete to be removed. The demolition and removal crew began to remove the damaged concrete between 7 p.m. and 9 p.m. A jackhammer or drop hammer was used to crush the damaged concrete, and it was removed with a track hoe or other machine. The base, subbase, dowels, and tie bars were prepared from 9 p.m. to 10 p.m. Specifically for partial depth patches, the patch area was sandblasted clean, and a bonding agent was applied to horizontal and vertical surfaces. For full depth patches, coarse aggregate was added to the subbase and leveled, with the purpose of establishing drainage. A receptive pocket for the tie bars was drilled into the existing pavement, and the bars were placed. From 10 p.m. to 11:30 p.m., the HES repair concrete was cast into the patch area. Hydration retarder was added at the batch plant, and accelerating admixture was added on site, just prior to discharge of the concrete. The concrete was finished immediately, and from 11:30 p.m. to 12:30 a.m., the patches were covered with plastic and thermal blankets while the quality assurance/quality control samples were collected. The concrete strength was periodically tested, and the repaired section was opened to traffic between 5 a.m. and 6 a.m. (provided the specified opening strength was achieved). If the required strength was not achieved and the repaired pavement was not opened to traffic by 6 a.m., penalties would be applied. In this repair methodology, the HES concrete is expected to have gained the target strength over-night so that it can be opened to traffic early the following morning.

3.2 Temperature of Field-Produced Concrete

The temperature profiles from two site visits at the INDOT HWY 30 repair project are shown in Figure 3.1. The results for temperatures shown were measured in a repair patch in the pavement, in a field cast concrete beam, and of the air temperature near the samples. The temperature in the concrete patches read in excess of 50°C and 60°C for cool and warm nights respectively. This points out that the concrete pavements are reaching a substantially higher temperature and a substantially higher equivalent age than flexural beams after as little as six hours (in real time).

3.3 Flexural Strength under Variable Curing Conditions

A testing plan was developed to investigate the influence of temperature on the rate of strength development and the resulting long-term strength, which utilized a temperature matched curing (TMC) procedure. TMC enabled concrete beam specimens to be subjected to temperatures experienced in the field. TMC was achieved using heating blankets layered around the concrete beam test specimens. Using heating blankets, construction blankets, and plastic on both the bottom and top sides of the specimens, high temperature conditions similar to those experienced in patches were achieved. Figure 3.2 shows the temperature matched curing beam configuration on a project site.

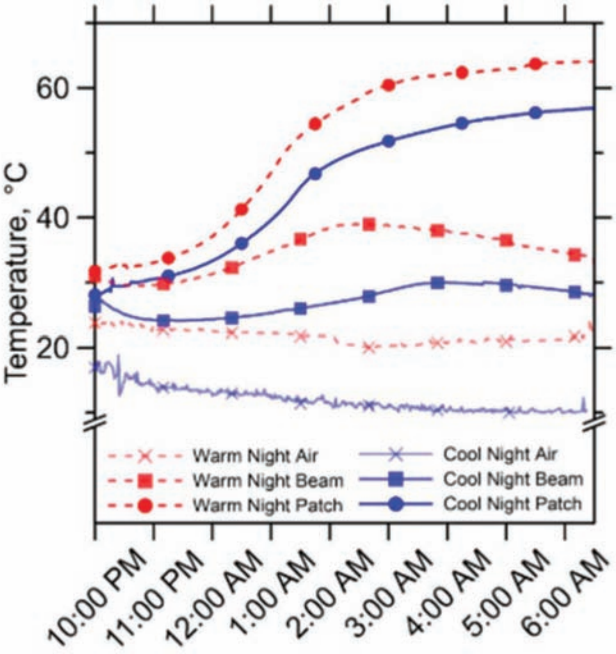


Figure 3.1 Temperature profile of warm and cool nights for different concrete geometries at US Highway 30 INDOT repair project.

A common trend began to reveal itself as temperature matched curing was carried out on several field visits. The beams subjected to elevated temperatures, or the ones being heated in the temperature matched curing condition, typically have a large, initial strength gain at early ages, up to 4–6 hours for this mixture. Thereafter, TMC beams develop strength at a minimal rate. Traditional views suggest higher temperatures lead to an accelerated reaction or higher degrees of hydration at earlier ages and therefore higher flexural strengths (ACI Committee 308, 2001; Eren, 2002; Kim, Moon, & Eo, 1998). Compared to temperature match cured beams, air cured beams experienced a more constant strength development for both early and late ages. The beams cured at higher temperatures had a lower long-term strength. This is problematic since while it is good to open the pavement quickly, problems can arise in long-term durability, strength and fatigue performance due to the lower strengths.

For the HES mixture in this project, a crossover in flexural strength between air cured and TMC beams was observed at ages between four and eight hours. The air cured beams flexural strength surpassed that of the temperature matched curing beams beyond this crossover. In addition, the air cured beams continued to gain strength at a greater rate than that of the TMC beams. This repeatable observation is being called a crossover strength and has been seen consistently in the field. An example of this is shown in Figure 3.3 for the Site Visit 2. It can be seen that the TMC beams show a higher strength before 6 hours than the air cured beams, then the rate of strength gain decreased dramatically, resulting in lower rates of strength gain at later ages. This project examined two potential causes for this phenomena: sulfate imbalance and self-desiccation. As such, this was examined in greater detail.

3.4 Using a Nondestructive Testing (NDT) Method for Strength Determination (Windsor Pin)

Nondestructive testing (NDT) has become a popular method of estimating the strength of in-place concrete structures in recent times. This section investigates the penetration resistance (Windsor Pin test) (IAEA, 2002; Malhotra & Carino, 2004). The research team was asked to evaluate whether a new device would be able to help provide an indication of when sufficient strength was reached. This new device is a Windsor pin, manufactured by NDT James Instruments Inc.


(a)

(b)

Figure 3.2 Field images of (a) temperature matched curing beams at a trial batch and (b) temperature matched curing beams and air cured on a site visit.

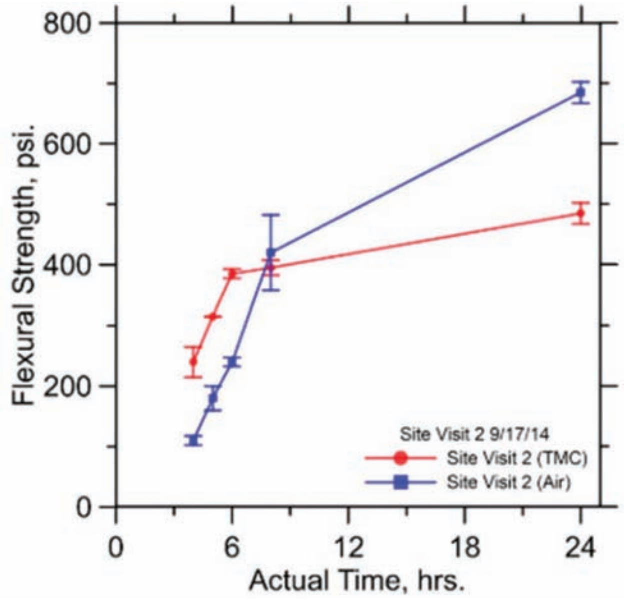


Figure 3.3 Flexural strength results for Site Visit 2 on 09/17/2014.

The Windsor Pin System is "a unique instrument for measuring the strength of new or existing construction materials in situ utilizing the established principle of resistance to penetration" (NDT Supply, n.d.). Simplified, the spring-loaded device shoots a steel pin into the surface of a concrete system, and the depth of penetration is then measured using the needle micrometer. This penetration is then correlated to a compressive strength of the concrete being measured.

The Windsor Pin was utilized during a trial batch in late September 2014 at an Irving Materials Inc. ready-mix plant in West Lafayette, IN. The goal of this site visit was to compare actual measured flexural strength results to that of those provided by the Windsor Pin. The testing was to evaluate the possibility of implementing this nondestructive test method as a means of predicting pavement strengths for opening to traffic. At ages of 4, 6, 8, and 12 hours, three flexural beam samples were tested to determine their flexural strength. At the same ages, each beam was "shot" with the Windsor Pin system ten times to provide an estimate of the concrete's compressive strength. For the comparative purposes for this study, the compressive strength was converted to a flexural strength using the ACI definition of modulus of rupture of concrete (ACI 318-14, 2014).

Results from the Windsor Pin testing showed extremely high variability with statistical ranges of 150 psi or more, even considering that ten measurements were recorded to produce a larger sample set for a better statistical average. Figure 3.4 illustrates the data at each age of the calculated flexural strength from the Windsor

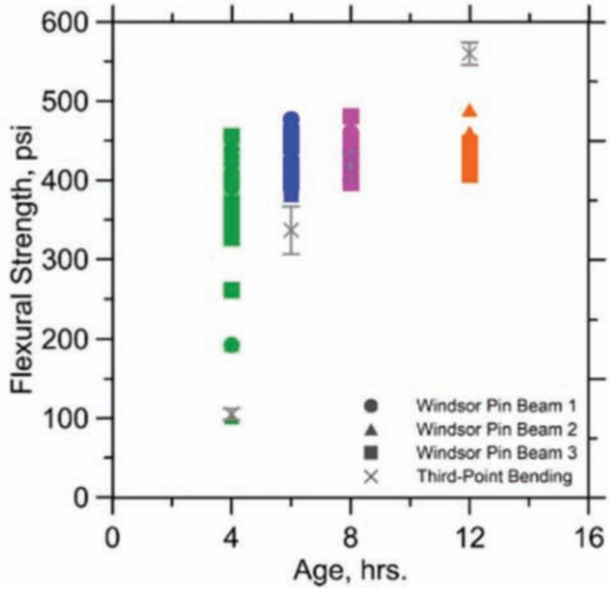


Figure 3.4 Calculated flexural strength of Windsor Pin and actual third-point bending results.

Pin. At ages 4 and 6 hours, Windsor Pin values overestimate the flexural strength; at 8 hours, they are a good representation; and at 12 hours, they underestimate the measured flexural strength values. High inaccuracy in the Windsor Pin results puts into doubt the ability of its implementation as a reliable means of nondestructive testing, specifically to be used as a tool for estimating traffic opening of pavements or patches. As a result, this approach is not recommended for opening to traffic.

3.5 Effects of Self-Desiccation on HES Concrete (Role of Water)

First, it should be noted that self-desiccation occurs in every concrete mixture. Self-desiccation occurs when the reaction of cement and water results in a volume reduction known as chemical shrinkage (i.e., the volume of reacted products is smaller than the original constituent materials (cement and water) (Radlińska & Weiss, 2011; Fu, 2011). When the system is fluid (at very early ages), the volume of the material simply reduces. However, once the material has set (i.e., solidified gaining a rigid structure) this volume reduction results in the expansion of vapor filled spaces in the matrix (Sant, 2007). These vapor filled spaces occupy the largest of the pores. In high w/c mixtures, this has little impact on the hydration process as the vapor filled spaces occur in very large pores and have little impact on the remaining pore fluid (i.e., the water activity remains high). In contrast, low w/c mixtures have a finer pore structure and a decreased amount of water, thus vapor filled spaces occur in smaller pores, thereby reducing the activity of the water (reducing the measured relative humidity (RH) of these mixtures (Barrett, Miller, & Weiss, 2015). This can reduce the rate of hydration to such an extent that the hydration eventually stops (Persson, Bentz, & Nilsson, 2005). This can also increase the capillary pressure, thus increasing the shrinkage of these mixtures, making them more susceptible to cracking (Montanari, 2017). Considering that HES concrete typically contains a low w/c, the effects of sufficient self-desiccation can negatively impact the system.

In order to demonstrate the effects of self-desiccation, cement pastes with a w/c of 0.42 and 0.28 were cast in a sealed condition (no extra curing water) and a saturated curing condition (extra curing water was added). The cumulative heat released from isothermal calorimetry for sealed and saturated samples, the internal relative humidity (RH), β_H (which is the rate of hydration of the sealed system with respect to the rate of hydration in the saturated system), and the flexural strength of sealed and saturated samples (as determined from Ball-on-3-Ball testing experiments) were measured and shown in Figure 3.5.

The impact of sufficient self-desiccation on hydration, RH, β_H, and strength is shown in Figure 3.5 with mixtures with a w/c of 0.28 and 0.42. For the mixtures with a w/c of 0.28, the cumulative hydration of the sealed system deviated from the saturated system at around 1 day, and this occurred when the RH in the sealed system was approximately 92%. The corresponding β_H value was nearly 0.8 at 1 day, which implies that rate of hydration was already reduced by 20%. This indicates that the impact of sufficient self-desiccation starts at early ages when a mixture's w/c is low. As such, the corresponding strength of the sealed and saturated system began to deviate at one day. For the mixture with a w/c of 0.28, the rate of hydration (and strength gain) began to slow to the point of nearly ceasing when the RH reached 92% and β_H=0.8.

Figure 3.5 shows the mixture with a w/c of 0.42. The hydration of the sealed system did not deviate from the saturated system as there was initially sufficient water for continued hydration. This agrees with the Power's Model (Jafari Azad, Suraneni, Isgor, & Weiss, 2017) where the entire volume of cement can be hydrated by the initial mixing water. The calculated value for β_H remained at 1.0 through the 7-day testing duration because the rate of hydration of the sealed system was never exceeded by that of the saturated system. There is little benefit in terms of hydration when additional water is supplied to a mixture with a w/c of 0.42 during the first 7 days provided evaporation is negligible. The RH of the system with w/c of 0.42 never fell below 96% by 7 days. As such, the strength of the sealed system was similar to that of the saturated system because sufficient self-desiccation was not taking place. For HES concrete mixtures, with a low w/c, the effects of self-desiccation can negatively impact the hydration and strength development.

In addition, maturity methods that are used to predict the target strength of concrete can be modified to account for self-desiccation, thus increasing the accuracy of strength predictions as concrete mixtures with a low w/c run out of water (and sufficient self-desiccation

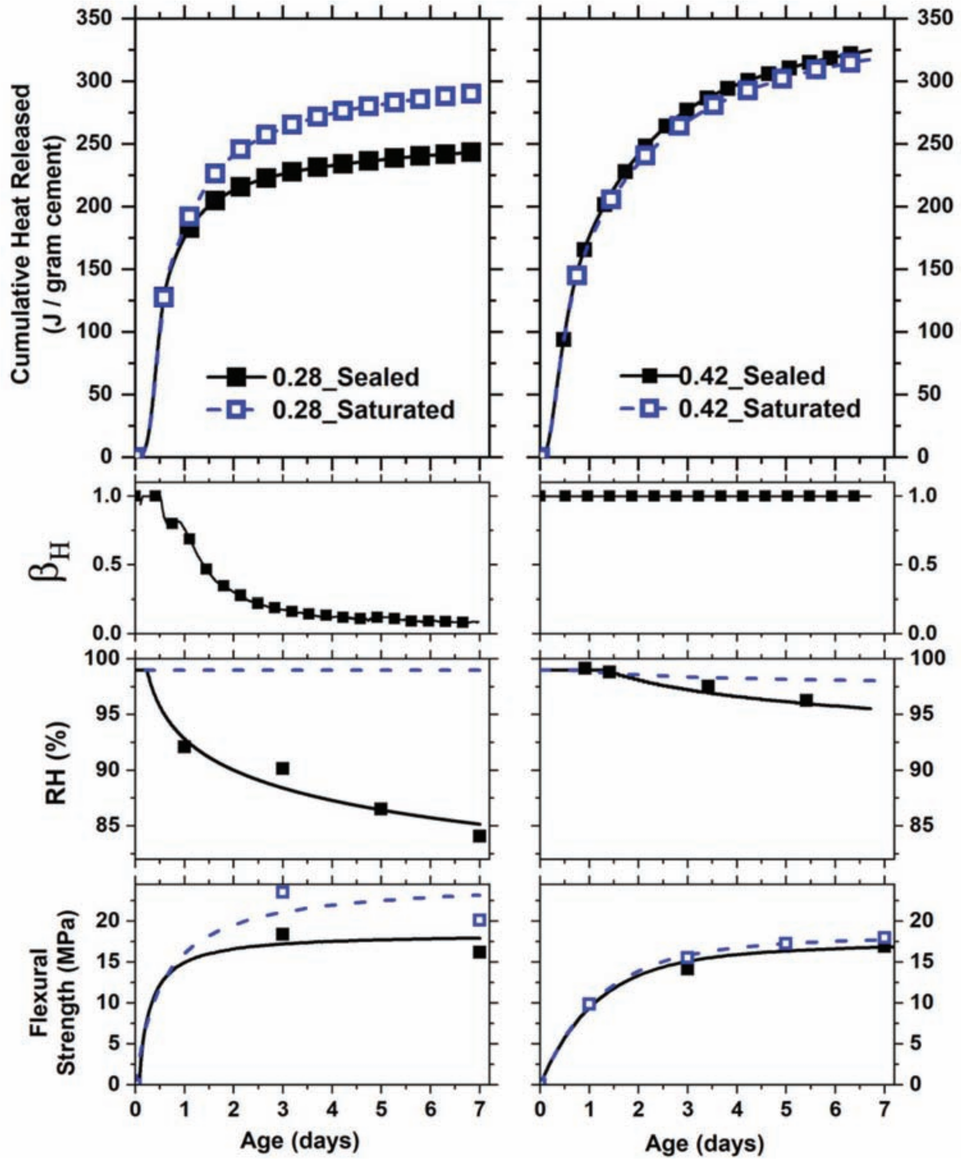


Figure 3.5 Cumulative heat released, β_H, RH, and flexural strength for pastes with a w/c of 0.28 and 0.42. Sealed and saturated cured data are presented.

occurs leading to a decrease in the rate of strength gain). The β_H parameter can be used in the modified methods along with the measured internal RH of the concrete. More on this topic can be found in the publications that resulted from the work done in this project listed in Chapter 5.

3.6 Accelerator Dosage Variations at Ambient and Elevated Temperatures (Optimum Sulfate Levels)

Temperatures tested for the laboratory program included 10°C, 23°C, 37.5°C, and 50°C to evaluate the HES mixture over a wide range. Evaluating higher temperature provides comparison to standard temperatures. This provides insight into performance that may be expected in the field.

The US Highway 30 project utilized accelerator dosages ranging from 0 to 60 ounces per one hundred pounds of cement (oz/cwt). Therefore, increments of 0, 20, 40, and 60 oz/cwt were implemented in the testing matrix. The most common dosage seen in the field was at 40 oz/cwt. Thus, dosages above and below were evaluated and compared. It was of interest to test variable ranges to determine the accelerators role on high early strength mixtures performance, especially at higher temperatures.

As expected, at ambient temperatures (i.e., 23°C) as the accelerator dosage was increased, the hydration reaction (determined from isothermal calorimetry) was accelerated as shown in Figure 3.6.

As the temperature was increased (as in the 50°C experiment), the accelerating properties of the admixture

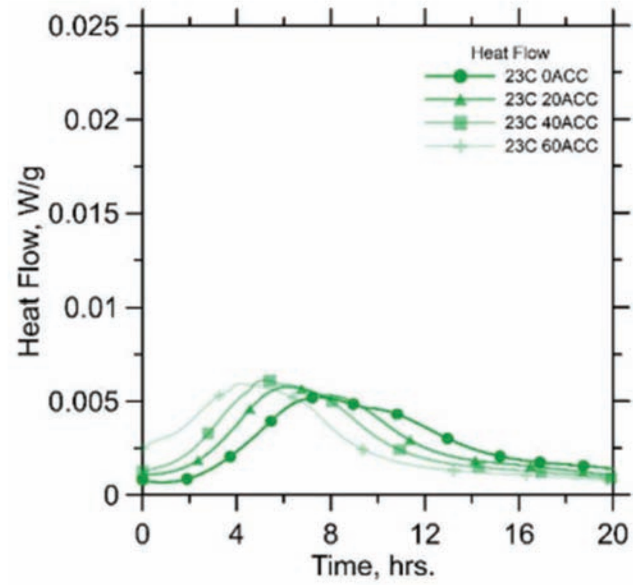


Figure 3.6 Rate of hydration from isothermal calorimetry at 23°C at various accelerator dosages.

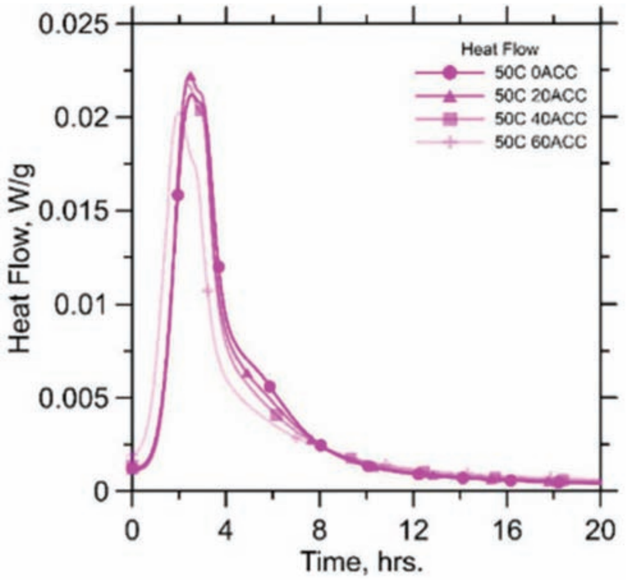


Figure 3.7 Rate of hydration from isothermal calorimetry at 50°C at various accelerator dosages.

decreased as shown in Figure 3.7. It can be seen that at 50°C the accelerating admixture was proven to be ineffective at accelerating the hydration reaction.

Another major finding from the isothermal calorimetry is that higher temperatures and accelerator dosages are related to the sulfate level or balance. At higher temperatures and accelerator dosages, it appears that the peak consistent with the hydration of the calcium aluminate has shifted which may suggest an imbalance in the optimum sulfate levels under these conditions. It appears the sulfate optimization has been lost when the HES mixture is exposed to high accelerator dosages and high temperatures.

Research has illustrated cement exposed to calcium nitrite based accelerating admixtures, such as the accelerating admixture used in this study Daraset 400 (W. R. Grace Inc., 2007, 2010), may lead to changes in the aluminate- sulfate balance and excessive retardation of the Alite reaction (Lerch, 1946; Roberts & Taylor, 2007; Sandberg & Roberts, 2003, 2005). If insufficient soluble sulfate is present, the aluminate–sulfate reaction may be altered (Pourchet, Regnaud, Perez, & Nonat, 2009; Sandberg & Roberts, 2003, 2005). Sandberg and Roberts discussed that because calcium nitrite has an ability to stabilize iron hydroxide, this may result in not enough soluble sulfate to keep the iron soluble, therefore causing retardation of the Alite hydration. Consequentially a sensitivity to low soluble sulfate levels causes damage to the aluminate-sulfate balance (Sandberg & Roberts, 2005). The observed sulfate imbalance may be a consequence of the interaction of the calcium nitrite accelerator in the system.

This could also help to explain the reasoning for a crossover strength discussed previously in Chapter 2, which is observed in beams exposed to temperature matched curing. Further discussion of the interaction between calcium nitrite in the cement system may be a cause of strength deterioration. If the Alite hydration is retarded due to a change in the available sulfate from solubility issues, this could potentially be the cause of the observed crossover (Roberts & Taylor, 2007; Sandberg & Roberts, 2003, 2005). The Alite reaction is what provides early strengths to cement hydration. Work by Niemuth and others has presented data illustrating isothermal calorimetry as a method for optimizing sulfate contents in cementitious systems (Niemuth, De la Varga, Barcelo, & Weiss, 2012; Niemuth, 2012; Sandberg & Roberts, 2003).

As a result of the heat release data evaluated at four temperatures and four accelerator dosages, two main conclusions were drawn. First, at higher temperatures, the accelerating admixture does not provide an accelerating effect to the hydration reaction for this mixture. This finding places in doubt the need for accelerating admixture in the application of HES concrete mixtures if adding it will not accelerate the reaction. Second, the sulfate content of these mixtures appears to be imbalanced at higher temperatures and accelerator dosages. An imbalance in the sulfate level could be the cause behind the observed crossover strength and a reasoning for deterioration in long-term flexural strength development for HES mixtures. Concrete pavements that do not reach adequate strengths will likely fail prematurely under traffic roads. Continual replacement of concrete patches due to premature failure would be extremely costly to agencies.

Although at ambient temperatures (23°C) the mixture appeared to be properly sulfated (allowing the accelerating admixture to accelerate the reaction), further work investigated how much additional sulfate should be added to the system in systems with elevated temperatures in order for the accelerating admixtures to be effective in accelerating the hydration reaction. It was decided that a blend of 50% industrial gypsum and 50% casting plaster would be used in combination to represent commercial gypsum in order to provide sulfate to the mixture. A 1% and 2% addition of sulfate was added to systems with varying amount of accelerating admixture, and the rate of heat released through isothermal calorimetry was measured. Figure 3.8 shows results for the 50°C experiment with a 1% sulfate addition. As the dosage of accelerating admixture is increased from 0, to 20, 40, and 60 oz/cwt., a transformation in the curves can be seen towards the left, indicating the acceleration of the hydration reaction. In addition, the sulfate levels are illustrated to be in balance, based on observation of the sulfate depletion peak to the right of the main hydration peak (Niemuth et al., 2012), as compared to data presented not including added sulfate. With a 1% addition of sulfate, the accelerating admixture was able to accelerate the hydration reaction at higher temperatures as the admixture dosage was increased.

Conclusions from experimental evaluation of added sulfate to HES mixtures led to interest in finding how this value added method extends to field applications. Therefore, concrete beams were cast with and without sulfate additions and the flexural strength was determined. TMC cured beams and ambient air cured beams were tested. A hypothesis was generated following conclusions of the role of additional sulfate, which believed that added sulfate will help the HES mixture to continue to gain strength when exposed to high temperatures. This is in stark contrast to the inability of the mixture to gain strength after the crossover at its particular state.

The hypothesis was validated by the results, which are presented in Figure 3.9. At six hours, the crossover is occurring which was observed repeatedly in the field. Most importantly however, it can be observed that air cured beams continue to generate strength at an appreciable rate. Similar to observations found in field investigations, TMC beams without additional sulfate showed a decrease in the rate at which flexural strength is generated. However, evaluating TMC beams with 1% additional sulfate illustrates a change in behavior. An improvement has been made in the mixtures ability to continue to gain strength when exposed to extreme temperatures. While not matching the results of air cured beams, a drastic improvement is made in comparison to the current mixtures performance. The ability to continue to generate strength is indicative of an improved long-term durability for HES mixtures.

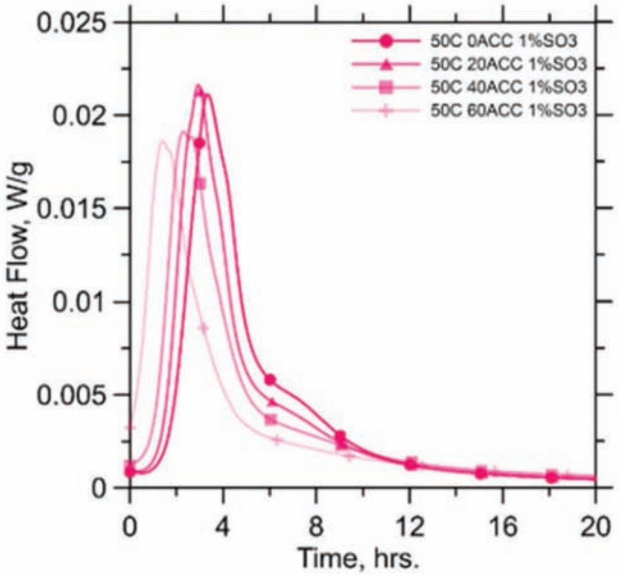


Figure 3.8 Rate of hydration from isothermal calorimetry at 50°C and 1% SO3 replacement at various accelerator dosages.

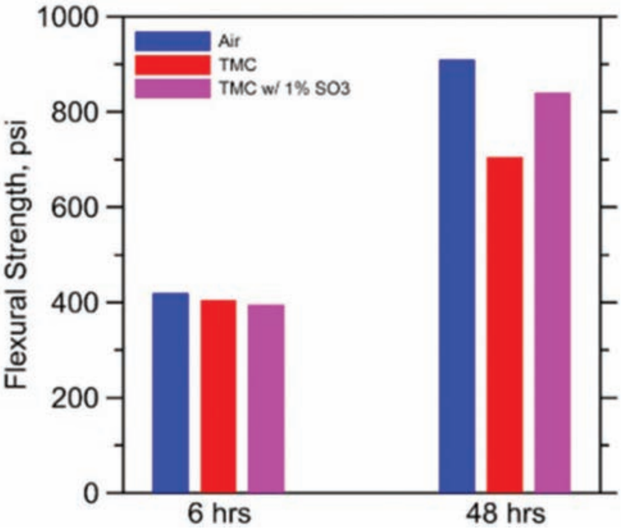


Figure 3.9 Flexural strength (psi) measured at 6 and 48 hours of laboratory cast air cured beams, temperature match cured beams, and temperature match cured with 1% additional sulfate beams.

3.7 Activation Energy Determination

Data obtained from isothermal calorimetry facilitated the computation of the activation energy of this HES mixture. The activation energy was calculated for mixtures without accelerator at temperatures of 10°C, 37.5°C, and 50°C in reference to standard temperature 23°C. Results of activation energy calculations are plotted in Figure 3.10 versus degree of hydration for each of the three mentioned temperatures. The average values are similar to expected, ranging from about 350 kJ/mol to 450 kJ/mol (Malhotra & Carino, 2004; Sant, 2007).

It can be observed from the plot that as the temperature increases, the activation energy decreases, a typical trend. However, the continued decrease from 37.5°C to 50°C is not expected considering work by Freiesleben Hansen which suggested that above 20°C, the activation energy of cement mixtures should remain constant (Carino & Lew, 2001; Freiesleben Hansen & Pedersen, 1977). Their work suggests that up to 20°C the activation energy decreases linearly, however,

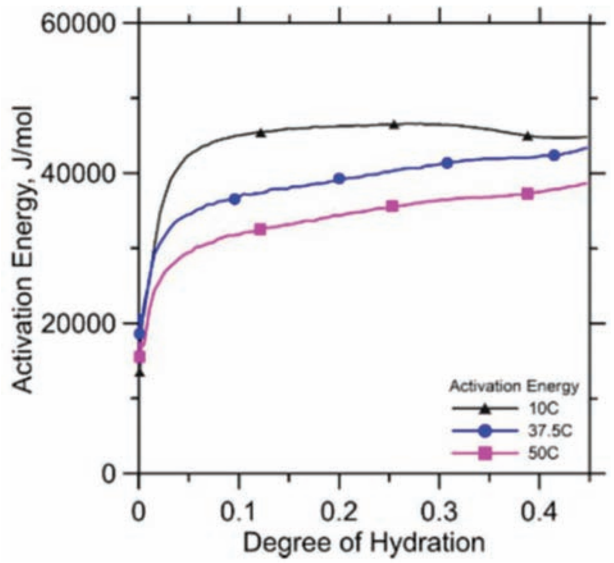


Figure 3.10 Activation energy (J/mol) versus degree of hydration for high early strength mixture without accelerating admixture at different testing temperatures.

beyond that temperature, it is a constant multiplied by the gas constant. Considering that the activation energy is used in the maturity approach to predict the strength of HES concrete, caution should be exercised when choosing an activation energy value (especially when elevated temperatures are expected).

3.8 Durability and Fracture Mechanics of Materials Containing Accelerating Admixtures Cured at Ambient and Elevated Temperatures

Mechanical testing of mortar samples was performed to examine fracture properties of elastic modulus, fracture toughness (K_{IC}), fracture energy (G_{IC}), and critical crack tip opening displacement (CTODc) of the HES mixture. The observed crossover strength provided questions to the potential of a change in fracture properties with and without accelerator at an array of temperatures, most notably high temperatures. Therefore, temperatures of 23°C, 35°C, and 50°C and accelerator dosages of 0 and 40 oz/cwt were inputs for a testing matrix of fracture properties. Note that 35 rather than 37.5°C was used for these studies due to available laboratory space.

Figure 3.11, displays the results for fracture testing at various temperatures and an equivalent age of 28 days. Raw data was analyzed using a simplified analysis procedure of the Jenq-Shah Two Parameter Fracture Model proposed by Jansen, Weiss, and Schleuchardt (Bažant, 2002; Jenq & Shah, 1985; Jensen & Hansen, 2001; Shah, 1990).

The figure displays the results of (a) elastic modulus, E (b) fracture toughness, K_{IC}, (c) fracture energy, G_{IC}, and (d) critical crack tip opening displacement, CTODc. In Figure 3.11(a), the data for elastic modulus is presented for each temperature and accelerator dosage. The results indicate that as temperature increases, the elastic modulus of samples without accelerator decreases. At room temperature, the sample with and without accelerating admixture have drastically different elastic moduli. However, as the temperature increases, the gap lessens, as the influence of accelerator on the HES mixtures elastic modulus becomes less apparent. From Figure 3.11(b), K_{IC} appears to slightly decrease as the testing temperature is increased, for the mixtures not containing accelerator. Once accelerating admixture is added however, the K_{IC} of this mixture remains constant with varying temperature.

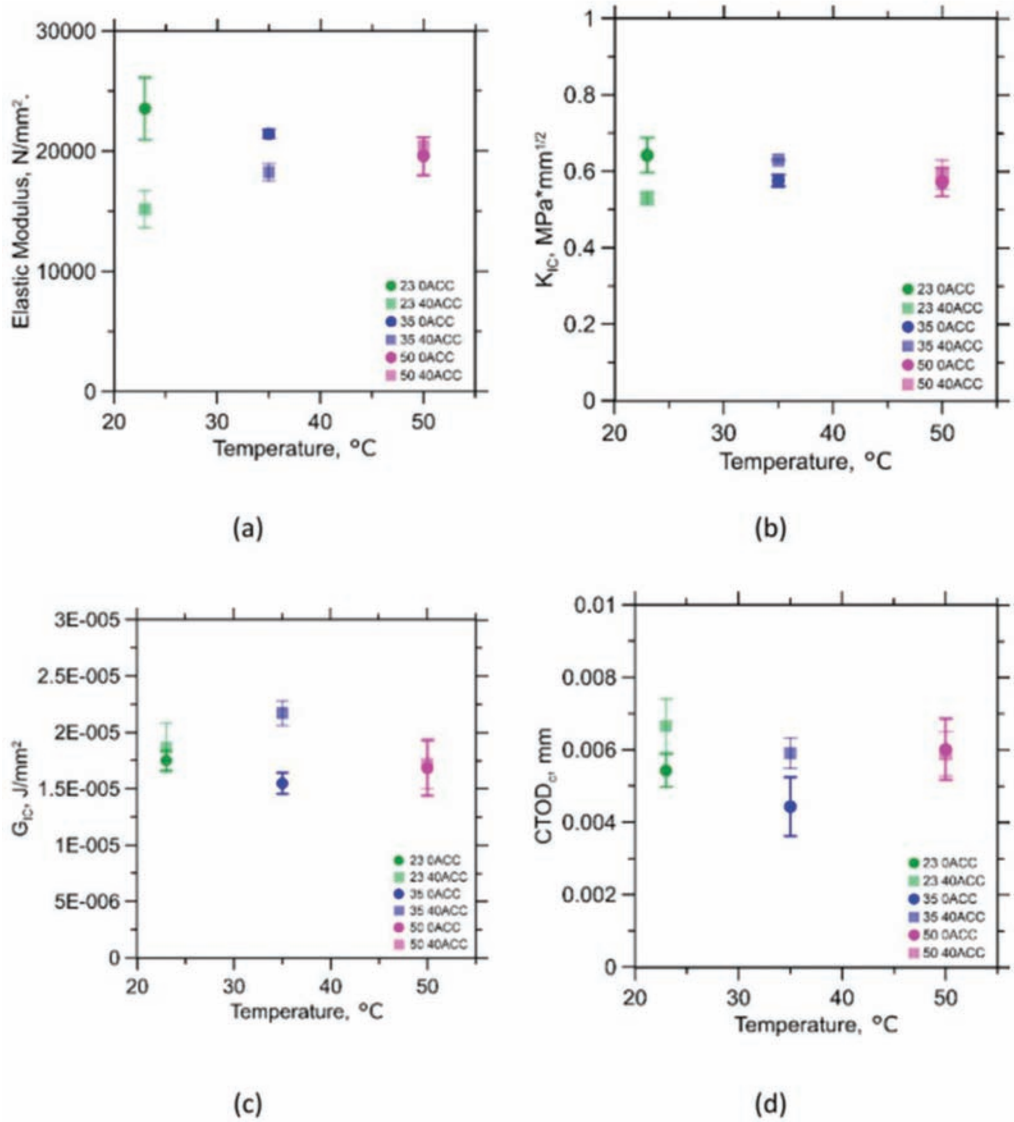
The remaining two figures in Figure 3.11, (c) and (d), do not provide further insight into potential reasoning behind the observed crossover strength. G_{IC} and CTODc, related to fracture and critical crack width opening, look as if to be relatively constant at each temperature and accelerator dosage. The bulk of the data from fracture property evaluation was not conclusive in providing a definite answer to the possible correlation between fracture and the observed crossover strength. The result of this work leads the authors to believe that the crossover strength is not directly related to a fracture property of the mixture.

3.9 Shrinkage and Stress Reduction

Much of this work has illustrated a need to improve the performance of HES concrete mixtures. Data has shown internal curing as a cost effective, value added methodology that reduces cracking and improves the durability and service life of concrete mixtures (Barrett, 2015; Barrett, Miller, & Weiss, 2014; Bentz & Snyder, 1999; Bentz & Weiss, 2011; De la Varga et al., 2014; Miller, Barrett, Zander, & Weiss, 2014; Schlitter, 2010; Schlitter, Senter, Bentz, Nantung, & Weiss, 2010).

Internal curing has been shown to be a method that can increase the RH and reduce autogenous shrinkage in mixtures with low w/c's (Barrett, De la Varga, Schlitter, & Weiss, 2011; Barrett et al., 2014; Barrett et al., 2015; Bentz & Weiss, 2011; Castro, Peled, & Weiss, 2016; Golias, Castro, & Weiss, 2012; Schlitter, Bentz, & Weiss, 2013; Yildirim, Meyer, & Herfellner, 2015). The addition internal curing water also benefit mechanical and durability properties (Castro et al., 2016; Golias et al., 2012). Figure 3.12 shows measured autogenous shrinkage for a plain and internally cured mortar mixture with a w/c of 0.28. The inclusion of prewetted lightweight aggregate (LWA) reduced the free autogenous shrinkage by nearly 50%.

Figure 3.13 shows the stress that developed when the shrinkage was restrained for both a plain and internally cured mortar with a w/c of 0.28. The temperature was decreased at 7 days, and the plain system developed 450 psi of tensile stress and a cracked when the stress reached 550 psi (a 100-psi remaining stress capacity), while the internally cured system had only 300 psi of tensile stress and cracked at 650 psi (350 remaining



(a) (b)

(c) (d)

Figure 3.11 Fracture testing results of (a) elastic modulus, N/mm2, (b) K_{IC}, MPa*mm1/2, (c) G_{IC}, J/mm2, and (d) CTODc, mm versus temperature, °C.

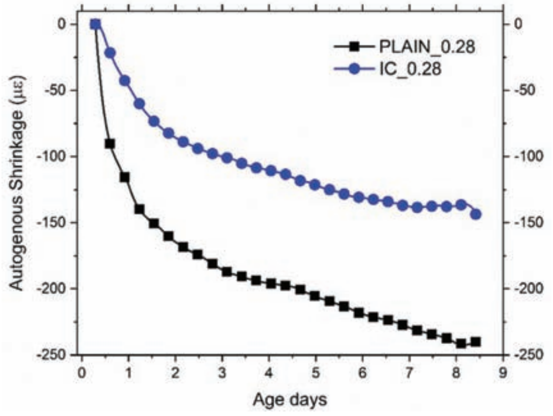


Figure 3.12 Autogenous shrinkage of pastes with a w/c of 0.28 (corrugated tube method).

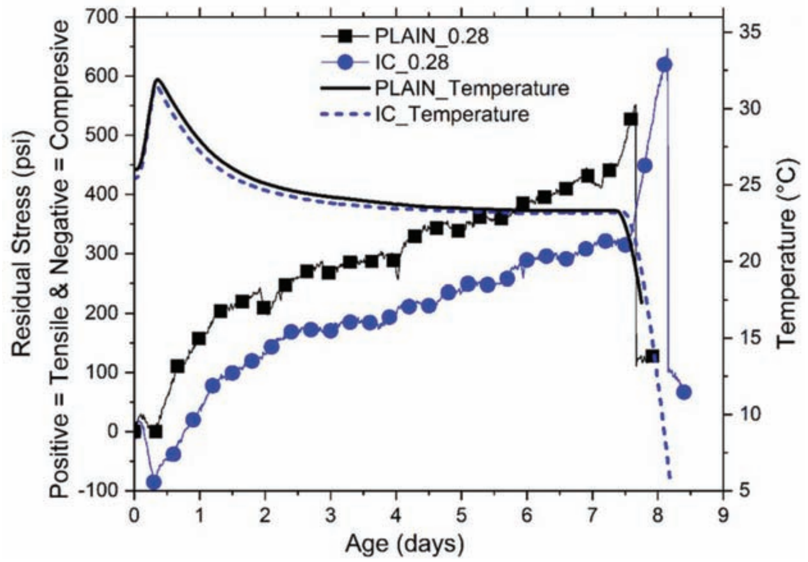


Figure 3.13 Restrained shrinkage of pastes with a w/c of 0.28 (dual ring test).

stress capacity). The internally cured system developed less stress by 7 days than the plain system while having more remaining stress capacity during the temperature decrease. In addition to the stresses occurring, the plain system required a temperature decrease of nearly 4°C to crack while the internally cured system required a temperature decrease 17°C to crack, implying that the internally cured system is more robust to thermal cracking. HES concrete mixtures (typically containing low w/c's) can benefit from additional water through internal curing.

4. FINAL CONCLUSIONS AND RECOMMENDATIONS

This work has illustrated some primary issues that can limit strength development and decrease the accuracy of strength predictions in HES concrete mixtures. First, internal curing can be used to supply additional curing water to HES mixtures, thus improving durability, hydration, and strength development (i.e., mechanical properties). Second, when the temperature of HES concrete patches is expected to be elevated, the balance of sulfates need to be considered. While the experiments showed that additional sulfate can improve the effectiveness of accelerating admixture, this is likely not practical for field use. Rather, experiments to determine if the sulfate balance is not attained at high temperatures with admixtures appears to be in order. Third, modified maturity methods that account for self-desiccation can be used to increase the accuracy of target strength predications. This would consist of adding a term (β_H) to account for self-desiccation to standard current practices. It appears that patches may benefit from internal curing which will enable hydration to occur while reducing shrinkage. Finally, excessive cement contents should be restricted.

5. ADDITIONAL INFORMATION

The findings of this report can be found in more detail in the following master's theses:

Todd, N. T. (2015). *Assessing risk reduction of high early strength concrete mixtures* (Master's thesis). Retrieved from http://docs.lib.purdue.edu/dissertations/AAI10062227

Wilson, C. A. (2018). *Improving the performance of high early strength concrete by controlling self-desiccation and mitigating shrinkage* (Master's thesis). Oregon State University. Retrieved from https://ir.library.oregonstate.edu/concern/parent/w95055483/file_sets/ht24wq61g

REFERENCES

ACI 318-14. (2014). *Building code requirements for structural concrete*. Farmington Hills, MI: American Concrete Institute.

ACI Committee 308. (2001). *Guide to curing concrete*. Farmington Hills, MI: American Concrete Institute.

American Society of Civil Engineers. (2013). 2013 Report card for America's infrastructure findings: Roads [Web page]. Retrieved from http://2013.infrastructurereportcard.org/

Antico, F. C., De la Varga, I., Esmaeeli, H. S., Nantung, T. E., Zavattieri, P. D., & Weiss, W. J. (2015). Using accelerated pavement testing to examine traffic opening criteria for concrete pavements. *Construction and Building Materials*, *96*, 86–95. https://doi.org/10.1016/j.conbuildmat.2015.07.177

Bagade, S., & Puttaswamy, N. (March 2009). *Early high strength concrete advantages and challenges* [Web page]. Retrieved from https://www.nbmcw.com/tech-articles/concrete/1333-early-high-strength-concrete-advantages-and-challenges.html

Barrett, T. J. (2015). *Improving service life of concrete structures through the use of internal curing: Impact on Practice* (Doctoral thesis). Retrieved from ProQuest Dissertations and Thesis database. https://search.proquest.com/docview/1735490777

Barrett, T. J., De la Varga, I., Schlitter, J., & Weiss, W. J. (2011). Reducing the risk of cracking in high volume fly ash concrete by using internal curing. *World of Coal Ash (WOCA) Conference*, (Ic), 2268–2278. Retrieved from http://www.flyash.info/2011/131-DelaVarga-2011.pdf

Barrett, T., Miller, A., & Weiss, W. (2014). Reducing shrinkage cracking with internal curing: From theory to practice. *Indian Concrete Journal*, *88*, 61–71.

Barrett, T. J., Miller, A. E., & Weiss, W. J. (2015). *Documentation of the INDOT experience and construction of the bridge decks containing internal curing in 2013* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2015/10). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284315532

Bažant, Z. P. (2002). Concrete fracture models: Testing and practice. *Engineering Fracture Mechanics*, *69*(2), 165–205. https://doi.org/10.1016/S0013-7944(01)00084-4

Bentz, D. P., & Weiss, W. J. (2011). *Internal curing: A 2010 state-of-the-art review* (NISTIR 7765). Gaithersburg, MD: National Institute of Standards and Technology, U.S. Department of Commerce. https://doi.org/10.6028/NIST.IR.7765

Bentz, D. P., & Snyder, K. A. (1999). Protected paste volume in concrete: Extension to internal curing using saturated lightweight fine aggregate. *Cement and Concrete Research*, *29*(11), 1863–1867. https://doi.org/10.1016/S0008-8846(99)00178-7

Bryden, J. E., & Mace, D. J. (2002). *A procedure for assessing and planning nighttime highway construction and maintenance* (NCHRP Report No. 475). Washington, DC: National Cooperative Highway Research Program. Retrieved from http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_475.pdf

Carino, N. J., & Lew, H. S. (2001). The maturity method: From theory to application. In *Proceedings of the 2001 Structures Congress & Exposition*. Washington, DC: ASCE. Retrieved from https://ascelibrary.org/doi/pdf/10.1061/40558%282001%2917

Castro, J., Peled, A., & Weiss, J. (2016). Full and partial internal curing in mortar in terms of internal relative humidity, hydration and performance. In *Eleventh International Society of Concrete Pavements* (pp. 1–20). San Antonio, TX.

Cottrell, B. H., Jr. (1999). *Improving night work zone traffic control*. Charlottesville, VA: Virginia Transportation Research Council. Retrieved from http://virginiadot.org/vtrc/main/online_reports/pdf/00-r8.pdf

De la Varga, I., Spragg, R. P., Di Bella, C., Castro, J., Bentz, D. P., & Weiss, J. (2014). Fluid transport in high volume fly ash mixtures with and without internal curing. *Cement and Concrete Composites*, *45*(2014), 102–110. https://doi.org/10.1016/j.cemconcomp.2013.09.017

Deo, S. V. (2016). Problems review and suggestions for early high-strength, high-volume, low-lime fly ash concrete. *European Journal of Environmental and Civil Engineering*, *20*(5), 611–624. https://doi.org/10.1080/19648189.2015.1053153

Ellis, R. D., Jr., & Kumar, A. (1993). The influence of nighttime operations on construction cost and productivity. *Transportation Research Record*, *1389*, 31–37. Retrieved from http://onlinepubs.trb.org/Onlinepubs/trr/1993/1389/1389-005.pdf

Ellis, R. D., Herbsman, Z. J., Chheda, P. N., Epstein, W. C., & Kumar, A. (1992). *Developing procedures for night operations*. Washington, DC: Transportation Research Board.

Eren, Ö. (2002). Strength development of concretes with ordinary Portland cement, slag or fly ash cured at different temperatures. *Materials and Structures*, *35*(9), 536–540. https://doi.org/10.1007/BF02483121

Freiesleben Hansen, P., & Pedersen, E. J. (1977). Maturity computer for controlled curing and hardening of concrete. *Nordisk Concreteg Stockholm*, *1*, 19–34.

Fu, T. (2011). *Autogenous deformation and chemical shrinkage of high performance cementitious systems* (Master's thesis). Retrieved from https://ir.library.oregonstate.edu/downloads/8w32r756r?locale=en

Gajda, J. (2008). Thermal issues in high performance concrete. *Concrete Bridge Views*, *47*(Jan/Feb). Retrieved from http://www.concretebridgeviews.com/i47/Article1.php

Golias, M., Castro, J., & Weiss, J. (2012). The influence of the initial moisture content of lightweight aggregate on internal curing. *Construction and Building Materials*, *35*(2012), 52–62. https://doi.org/10.1016/j.conbuildmat.2012.02.074

Haseman, R. J., Wasson, J. S., & Bullock, D. M. (2010). Real-time measurement of travel time delay in work zones and evaluation metrics using bluetooth probe tracking. *Transportation Research Record: Journal of the Transportation Research Board*, *2169*(1), 40–53. https://doi.org/10.3141/2169-05

Hinze, J. W., & Carlisle, D. (1990-2). *An evaluation of important variables in nighttime construction* (TNW90-05 Final Rpt). Seattle, WA: TransNow.

IAEA. (2002). *Guidebook on non-destructive testing of concrete structures* (Training Course Service No. 17). Vienna, Austria: International Atomic Energy Agency. Retrieved from http://www-pub.iaea.org/MTCD/Publications/PDF/TCS-17_web.pdf

INDOT. (2013). *Work zone traffic control guidelines*. Indianapolis, IN: Indiana Department of Transportation. Retrieved from https://www.in.gov/indot/files/WorkZoneTCH.pdf

INDOT. (2014a). *Indiana Department of Transportation Contract R-35341*. Indianapolis, IN: Indiana Department of Transportation.

INDOT. (2014b). *Indiana Department of Transportation interstate highways congestion policy*. Indianapolis, IN: Indiana Department of Transportation. Retrieved from https://secure.in.gov/indot/files/Safety_InterstateHighwaysCongestionPolicy_2014.pdf

INDOT. (2014c). *INDOT standard specifications*. Indianapolis, IN: Indiana Department of Transportation. Retrieved from https://www.in.gov/dot/div/contracts/standards/book/sep13/2014Master.pdf

Jafari Azad, V., Suraneni, P., Isgor, O. B., & Weiss, W. J. (2017). Interpreting the pore structure of hydrating cement phases through a synergistic use of the Powers-Brownyard model, hydration kinetics, and thermodynamic calculations. *Advances in Civil Engineering Materials*, *6*(1), 1–16. https://doi.org/10.1520/ACEM20160038

Jenq, Y., & Shah, S. P. (1985). Two parameter fracture model for concrete. *Journal of Engineering Mechanics*, *111*(10), 1227–1241. https://doi.org/10.1061/(ASCE)0733-9399(1985)111:10(1227)

Jensen, O. M., & Hansen, P. F. (2001). Water-entrained cement-based materials: I. Principles and theoretical background. *Cement and Concrete Research*, *31*(4), 647–654. https://doi.org/10.1016/S0008-8846(01)00463-X

Kim, J.-K., Moon, Y.-H., & Eo, S.-H. (1998). Compressive strength development of concrete with different curing time and temperature. *Cement and Concrete Research*, *28*(12), 1761–1773. https://doi.org/10.1016/S0008-8846(98)00164-1

Lerch, W. (1946). The influence of gypsum on the hydration and properties of Portland cement pastes. In *Proceedings of the American Society for Testing Materials* (Vol 46, pp. 1252–1291). Farmington Hills, MI: American Concrete Institute.

Malhotra, V. M., & Carino, N. J. (2004). *Handbook on non destructive testing of concrete* (2nd ed.). West Conshohocken, PA: ASTM International. Retrieved from https://www.researchgate.net/publication/243776217_CRC_Handbook_on_Nondestructive_Testing_of_Concrete

Miller, A. E., Barrett, T. J., Zander, A. R., & Weiss, W. J. (2014). Using a centrifuge to determine moisture properties of lightweight fine aggregate for use in internal curing. *Advances in Civil Engineering Materials*, *3*(1), 142–157. https://doi.org/10.1520/ACEM20130111

Minchin, R. E., Jr., Thurn, S. B., Ellis, R. D., Jr., & Lewis, D. W. (n.d.). *Using contractor bid amounts to estimate the impact of night construction on productivity for highway and bridge construction*. Retrieved from https://www.essie.ufl.edu/~dwlewis/ap/Nightwork_JCME_1.pdf

Monical, J., Villani, C., Farnam, Y., Unal, E., & Weiss, W. (2016). Using low temperature differential scanning calorimetry to quantify calcium oxychloride formation for cementitious materials in the presence of calcium chloride. *Advances in Civil Engineering Materials*, *5*(2), 142–156. https://doi.org/10.1520/ACEM20150024

Montanari, L. (2017). *Toward a mixture design methodology for internally cured concrete that considers filling specific pore sizes caused by self-desiccation* (Master's thesis, Oregon State University). Retrieved from https://ir.library.oregonstate.edu/downloads/1c18dm12k?locale=en

Niemuth, M. D. (2012). *Effect of fly ash on the optimum sulfate of Portland cement* (Doctoral dissertation, Purdue University). Retrieved from https://docs.lib.purdue.edu/dissertations/AAI3556556/

Niemuth, M., De la Varga, I., Barcelo, L., & Weiss, W. J. (2012). Considering robustness in the selection of sulfate contents for Portland cements. *Construction Materials*.

NTD Supply. (n.d.). (2010). James Instruments, Inc., Windsor Pin (product description). Retrieved from https://ndtsupply.com/james-instruments-inc-windsor-pin.html

Paulini, P. (1990). Reaction mechanisms of concrete admixtures. *Cement and Concrete Research*, *20*(6), 910–918. https://doi.org/10.1016/0008-8846(90)90053-Z

Persson, B., Bentz, D., & Nilsson, L.-O. (Eds.). (2005). *Self-desiccation and its importance in concrete technology* (Report TVBM-3126). Lund, Sweden: Lund Institute of Technology. Retrieved from https://ciks.cbt.nist.gov/~bentz/Lund2005/TVBM-3126hp1.pdf

Pourchet, S., Regnaud, L., Perez, J. P., & Nonat, A. (2009). Early C_3A hydration in the presence of different kinds of calcium sulfate. *Cement Concrete Research*, *39*(11), 989–996. https://doi.org/10.1016/j.cemconres.2009.07.019

Radlińska, A., & Weiss, J. (2011). Toward the development of a performance-related specification for concrete shrinkage. *Journal of Materials in Civil Engineering*, *24*(1). https://doi.org/10.1061/(ASCE)MT.1943-5533.0000364

Roberts, L. R., & Taylor, P. C. (2007). Understanding cement-SCM-admixture interaction issues. *Concrete International*, *29*(1), 33–41.

Sandberg, P., & Roberts, L. R. (2003). Studies of cement-admixture interactions related to aluminate hydration control by isothermal calorimetry. In Malhotra V. M. (ed.), *Seventh CANMET/ACI Int Conference on Superplasticizers and Other Chemical Admixtures Concrete*, *217*, 529–542.

Sandberg, P., & Roberts, L. (2005). Cement-admixture interactions related to aluminate control. *Journal of ASTM International*, *2*(6), 1–14. https://doi.org/10.1520/JAI12296

Sant, G. (2007). *Examining volume changes, stress development, and cracking in cement based systems* (Master's thesis). Purdue University, West Lafayette, IN.

Schlitter, J. L. (2010). New methods to quantify the cracking performance of cementitous systems made with internal curing (Master's thesis, Purdue University). Retrieved from https://docs.lib.purdue.edu/dissertations/AAI1490692/

Schlitter, J. L., Bentz, D. P., & Weiss, W. J. (2013). Quantifying stress development and remaining stress capacity in restrained, internally cured mortars. *ACI Materials Journal*, *110*(1), 3–12. https://doi.org/10.14359/51684361

Schlitter, J. L., Senter, A. H., Bentz, D. P., Nantung, T., & Weiss, W. J. (2010). A dual concentric ring test for evaluating residual stress development due to restrained volume change. *Journal of ASTM International*, *7*(9), 1–13. https://doi.org/10.1520/JAI103118

Shah, S. P. (1990). Determination of fracture parameters (K_{Ic}^{s} and $CTOD_c$) of plain concrete using three-point bend tests on notched beams. *Materials and Structures*, *23*(6), 457–460. https://doi.org/10.1007/BF02472029

Shane, J. S., Kandil, A., & Schexnayder, C. J. (2012). *A guidebook for nighttime construction: Impacts on safety, quality, and productivity* (NCHRP Report No. 726). Washington, DC: National Cooperative Highway Research Program. https://doi.org/10.17226/22723

Todd, N. T. (2015). *Assessing risk reduction of high early strength concrete mixtures* (Master's thesis, Purdue University). Retrieved from https://docs.lib.purdue.edu/dissertations/AAI10062227/

Transportation Research Board. (2003). *Providing a highway system with reliable travel times: Study 3—Reliability*. Washington, DC: Transportation Research Board.

U.S. Department of Transportation Federal Highway Administration. (2005). *Traffic congestion and reliability: Trends and advanced strategies for congestion mitigation*. Retrieved from https://ops.fhwa.dot.gov/congestion_report/congestion_report_05.pdf

U.S. Department of Transportation Federal Highway Administration. (2010). *Highlights: Highways and Bridges The Nation's Road Network is Extensive: Condition and Performance*. Retrieved from https://www.fhwa.dot.gov/policy/2010cpr/highlights.cfm

U.S. Department of Transportation Federal Highway Administration. (2015). History of the interstate highway system [Web page]. Retrieved March 8, 2015, from https://www.fhwa.dot.gov/interstate/history.cfm

W. R. Grace Inc. (2007). Daraset 400 material safety data sheet. Retrieved from http://portlandcleanair.org/files/merge/msds/DARASET_400.PDF

W. R. Grace Inc. (2010). Daraset 400 set-accelerating admixture data sheet.

Wilson, C., Todd, N., Barrett, T. J., Coyle, A., Spragg, R., Montoya, M. A., …Weiss, W. J. (2016). *A mobile concrete laboratory to support quality concrete, technology transfer, and training* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2016/18). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284316341

Yildirim, S. T., Meyer, C., & Herfellner, S. (2015). Effects of internal curing on the strength, drying shrinkage and freeze-thaw resistance of concrete containing recycled concrete aggregates. *Construction and Building Materials*, *91*, 288–296. https://doi.org/10.1016/j.conbuildmat.2015.05.045

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

Further information about JTRP and its current research program is available at:
http://www.purdue.edu/jtrp

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