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Development of Rapid PCC Pavement Repair Materials

Participating Consortium Member:
Southern University and A&M College

Authors:
Alex Hak-Chul Shin
Denita Walker

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16. Abstract

Being that pavement repair and construction represents a significant percentage of federal and state funding, new materials are being investigated to reduce cost and generate a more resilient material. The goal of the project is to develop cost-effective, high performance concrete materials for rapid pavement repair minimizing environmental impact. Experimental study was conducted to investigate sustainable concrete with recycled concrete aggregate (RCA), lightweight aggregate (LWA), and other materials to be used in rapid full-depth repair. To minimize cracking at early age, internal curing (IC) was adapted with RCA and LWA.

RCA and LWA is a viable and practical way of producing rapid repair concrete with less drying shrinkage. 10% replacement of silica fume was found to improve performance as necessary as introducing pre-soaked aggregates increases moisture affecting hydration of concrete specimen and decrease drying shrinkage. Further investigation on the materials and techniques together by conducting test trials consisting of fully and partially adding wet and non-wet RCA and LWA, is studied to satisfy the sustainable aspect of the research as a viable method for today's standards.

The Vibration-free concrete (VFC) mixtures provided by Dr. Feys in Missouri University S&T were modified to study the applicability in rapid pavement repair. The modified mixtures were used to study the effects of four different curing conditions (ambient, heat blanket, heat fan, and oven) and the results are presented. The study shows that heating can expedite the strength gain in early age, and oven curing was the best among the curing conditions. The blanket with higher hearing capacity is further studied since it is considered as the practical application in rapid pavement repair in the field. The bond strength between old concrete and VFC modified concrete shows pretty promising results to apply in the bonded concrete overlay, though more extensive measurement of bond strength should be followed. The elastic modulus of VFC modified concrete was measured at early age and the value was smaller than typical elastic modulus of concrete.

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Development of Rapid Pavement Repair Materials

PREPARED FOR THE

RE-CAST UNIVERSITY TRANSPORTATION CENTER

IN COOPERATION WITH THE

Southern University and A&M Collage

Prepared by:

Alex Hak-Chul Shin[1]

Denita Walker[2]

[1] Professor and Interim Chair, Department of Civil and Environmental Engineering, Southern University and A&M Collage, Baton Rouge, LA 70813, USA (PI)

[2] Former Graduate Research Assistant, Department of Civil and Environmental Engineering, Southern University and A&M Collage, Baton Rouge, LA 70813, USA

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Being that pavement repair and construction represents a significant percentage of federal and state funding, new materials are being investigated to reduce cost and generate a more resilient material. The goal of the project is to develop cost-effective, high performance concrete materials for rapid pavement repair minimizing environmental impact. Experimental study was conducted to investigate sustainable concrete with recycled concrete aggregate (RCA), lightweight aggregate (LWA), and other materials to be used in rapid full-depth repair. To minimize cracking at early age, internal curing (IC) was adapted with RCA and LWA.

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The authors would like to acknowledge Dr. Tyson Rupnow in LTRC for his assistance in identifying contractors and material supplies to understand filed practice and acquire mixing materials.

IMPLEMENTATION STATEMENT

This study was conducted to explore cost-effective rapid repair concrete materials to be used in rapid full-depth repair. Recycled concrete aggregate (RCA), light weight concrete (LWA) was used to implement internal curing of the repair concrete mixtures. Type III cement and silica fume was used to expedite early strength of the mixtures. The four-hour compressive strength was not satisfied for the requirement, but the use of internal curing shows a promising way to decrease drying shrinkage and further enhance long term strength. The variation of aggregate moisture, mixing consistency, and compression tests in early age should be further studied. Once the mixture satisfied the strength and other requirements, field test should be carried out to confirm field performance of the mixture.

The bond test results showed promise, but a better mixture should be found which has a strong 4-hour bond strength in case the roadway is opened earlier than expected. If this mixture is chosen for the roadway, the air-dry curing method would not work because the road will crack very quickly which is not in the best interest of the engineers or the drivers.

An efficient curing method should be found because the oven was not practical and the fan did not heat the concrete enough in the allotted time. The blanket would be a good option, but the financial resources would have to be put in place to purchase for the different parts of the road.

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INTRODUCTION

According to the 2017 Infrastructure Report Card of American Society of Civil Engineering (ASCE), America's infrastructure scores a "D+" in sixteen different areas. To enhance the America's infrastructure in good condition, \$3.9 trillion is estimated to invest in various areas of infrastructure including highway pavements. With over 4 million miles of roadways in the U.S., pavement maintenance and construction represents a significant portion of federal and state funding for infrastructure. Compounding these financial burdens are the significant indirect costs to users during construction. Louisiana has over 60,000 miles of highway and local roads according to the Louisiana Department of Transportation and Development (DOTD). Many portions of the highway systems suffer various deterioration problems due to high traffic volume, delay of rehabilitation, and lack of repair. Continuous rehabilitation and repair of damaged section of the pavements are essential to keep the condition of the roadways in good and safe driving condition.

Portland cement concrete (PCC) pavement had been constructed in interstate and major highway systems with its high stiffness and longer service life. The PCC pavement is characterized with the presence of joints and reinforcing bar in the pavement section. Typical jointed plain concrete pavement (JPCP) has a joint spacing less than 20 feet and no reinforcing bar in the pavement. Due to the presence of joints in JPCP, however the pavement type is sometimes suffered from faulting and loss of support due to erosion of base/subbase materials. Those deterioration eventually cause joint cracking and failure of the PCCP as shown in Figure 1.

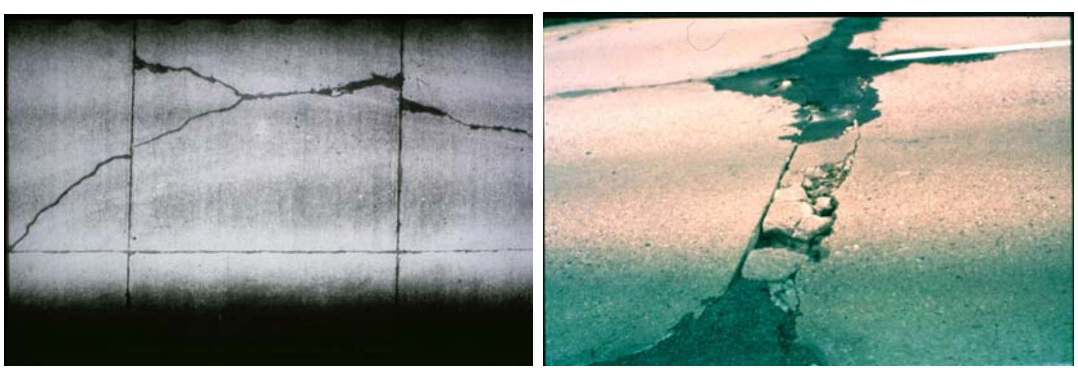

Figure 1. Cracking and joint failure in PCC pavements

To repair damaged pavement section and joint, accelerated pavement repair is performed over night to minimize traffic closure and congestion. Due to the limited time

(10 pm to 6 am) of repair job, rapid setting concrete is used to open the pavement section to traffic in four hours after placing concrete in the repairing section. (Figure 2) Many factors could cause early deterioration of repaired section including temperature, base preparation, curing, poor workmanship, and rapid setting concrete, but this research is focusing on the rapid setting concrete material. More specifically developing cost-effective rapid setting concrete material that minimize early deterioration and enhance performance and durability.

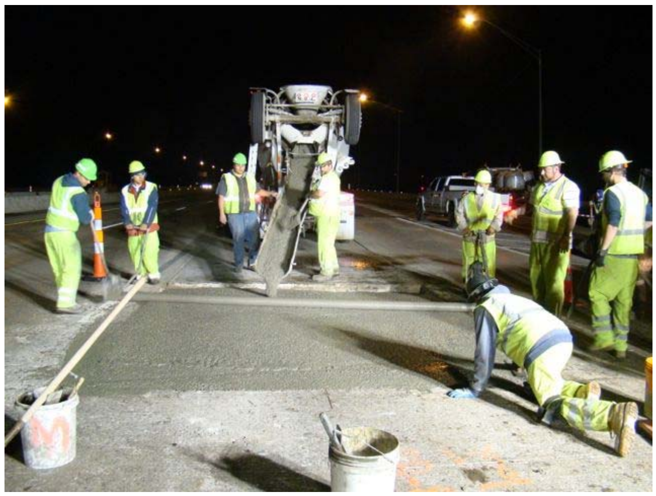

Figure 2. Full-Depth Repair of PCC Pavements

An additional need exists for a more crack resistant rapid repair material. Current materials and methods produce rapid patches that tend to exhibit moderate to severe cracking, sometimes within weeks after placement. This method tends to lead to repairing patches much earlier than intended. Several methods exist that may decrease the severity of cracking and lend to longer more durable concrete patches including the use of shrinkage reducing or compensating methods, addition of fibers and recycled materials, and the use of internal curing.

The proposed study investigated cost-effective, rapid pavement repair techniques that can reduce cost and duration. Two types of concrete materials are proposed to be investigated in this project, including crack-free early strength concrete and adaptive rheology concrete for rapid pavement repair. Reducing the construction duration and enhancing early age and long term performance, is the key solution for decreasing both the direct and indirect costs.

The first focus of this research is rapid full-depth repair (FDR) using crack-free early strength concrete. PCC pavements exhibiting severe distress such as transverse cracks and shattered slabs and corner breaks require FDR. The distress are caused by inadequate slab length and deficient slab thickness (design issues), concrete with high coefficient of thermal expansion or modulus (materials issues), or non-uniform or insufficient base support (construction issues) (Texas DOT, 2011) as shown in Figure 3. The full-depth repair (FDR) involves removing damaged area of the slab and placing full-depth pavement with tie bar in longitudinal joints and dowel bar in transverse joints. Due to the opening requirement of the pavement to traffic in few days after placing repair concrete, it is essential to achieve high early strength in repair concrete.

To promote early age strength and setting, low water to cementitious materials ratio (w/cm) with high content of type III cement are common in rapid repair. Drying shrinkage, autogeneous shrinkage, and high heat of hydration are observed in the repair materials. The gradients of shrinkage and temperature though the thickness of repair concrete with the restraints of surrounding old concrete pavement can cause premature cracking at the surface (Shin, 2000). Conventional curing methods using curing compounds and cover are not sufficient to prevent the cracking in repaired pavement.

Figure 3. Cracking in full-depth repair (TxDOT, 2011)

In this research, several methods will be considered to minimize stresses caused by shrinkage and temperature changes. Internal curing can reduce substantial autogeneous shrinkage at early age and increase long term compressive strength in high-performance blended cement mortars (Bentz, 2007). Internal curing using the light weight aggregate (LWA) and recycled concrete aggregate (RCA) was investigated. Additional water can be provided by RCA and LWA. Internal curing not only increases strength, but also reduces early age shrinkage in concretes with low water to cementious materials contents (w/cm). Bentz et al. (2005) have noted that internal curing can improve concrete properties such as compressive, flexural, and tensile strength; reduce permeability and autogenous shrinkage, and increase durability. The first method of internal curing to be discussed is the use of coarse aggregates with higher absorption capacities. Once the original mixing water is used by the hydration of the cement, water will begin to be drawn from the coarse and fine aggregates. This water is originally absorbed in the pores of the aggregate and the amount available for hydration products is dependent on both the volume and the absorption capacity of the aggregate.

The Ohio Department of Transportation (ODOT) District 12 studied bridge decks within their jurisdiction and found that cracking did not occur in mixtures that used coarse aggregates with absorption levels above two percent (Crowl et. Al, 2003). For common high performance ODOT mixtures with an aggregate content of approximately 75%, a coarse aggregate with an absorption of two percent can provide approximately 27 additional pounds of water per cubic yard of concrete (16 kg/m^3) verses only 13 lb/yd^3 (7.7 kg/m^3) for an absorption level of percent. The water provided by the aggregate represents an effective potential change in the w/cm ratio of approximately 0.056, which can greatly affect the shrinkage. This additional water supplements the original mix water that is used in the hydration process, which reduces shrinkage. It also provides enough water for the cement particles to more fully hydrate, creating a stronger microstructure and reducing the potential for cracking.

Philleo first suggested using saturated LWA to provide internal curing in the early 1990 (Delatte et al., 2007). Since the introduction of LWA for internal curing, many studies have been conducted to optimize the process. Typically, when LWA is used to provide internal curing, some of the fine aggregate is replaced with LWA. Hoff (2009) noted that the use of LWA can create a denser matrix and reduce self-desiccation and autogenous shrinkage. The amount of LWA, and the type/amount of binder. Internal curing is more necessary with concretes that use fly ash or silica fume as part of the binder. He further noted that denser matrix of the HPC developed as a result of internal curing improved strength and lowered permeability. With preconditioned or presoaked LWA, there is no need to change concrete mixing times or procedures.

Since using natural resources and disposing of construction and demolition wastes in large quantities are no longer considered sustainable because of environmental and economic implications, government policies are being directed towards reducing the use of these resources and increasing reuse and recycling. Therefore, recycling of construction/demolition waste as aggregate in new concrete pavement gives an environmentally responsible and economically feasible alternative to use the material as a valuable resource (Etxeberria et al 2007). RCA is created by demolishing or crushing concrete that is at the end of its service life. Depending on its intended application, concrete as a construction material exhibits a wide range in physical and mechanical properties. As a result of this, RCA shows inconsistencies in terms of physical properties which may make it not as desirable for usage as coarse aggregate in new concrete pavements.

The second approach to cost-effective concrete mixtures to be sued in accelerated pavement construction is develop flowable concrete with adaptive rheological properties to be used slip form paving and repair patching. The main problems associated to repair work are bonding between the repair material and the substrate and differences in shrinkage or thermal changes, leading to cracks and preferential paths for water intrusion. Based on the above methodology, the use of shrinkage reducing admixtures (SRA), expansive agents and fibers in self-consolidating concrete (SCC) can be investigated. The advantage of the expansive agents is that shrinkage is fully compensated, while the flowability of SCC result in a better bonding with the substrate, as no air gets entrapped between the two layers. The absence of consolidation can further enhance the bonding between the substrate and the repair material. Due to vibration, water is drawn near the interface, creating a weaker bond, similar to the interface transition zone (ITZ) for coarse aggregates in concrete.

Slip form paving is a process including the placement, casting, consolidating and finishing the surface of the concrete. Concrete is usually dumped in front of the paving machine and after the machine has moved over the concrete, concrete is spread out on the base while holding its slab shape. The typical concrete used for slip form paving is a mixture with less than 2.0 in. slump value. In order to consolidate the fresh concrete, extensive vibration energy is introduced to the concrete through equally spaced internal vibrators. However, if the vibration frequency is not set correctly or the paver moves slower than it should, the mixture will be over-vibrated (Tymkowicz and Steffes 1996). This may lead to a decrease in the entrained air content, as well as increasing the bleeding and segregation potential which may result in cracking along the path of vibrators if such pavement is subjected to heavy traffic load (Ardani et al. 2003). Furthermore, a decrease in the entrained air content of the fresh concrete makes the hardened concrete susceptible to damage due to freeze and thaw cycles and scaling. To solve such problems, it would be desirable to eliminate the vibration required for consolidating the concrete. This means that the concrete should be modified to reach higher workability while avoiding the shape stability to be in danger. The goal is to design a concrete mixture that reaches maximum consolidation with minimum compaction energy while maintaining the desired slab shape. This requires improving the flowability of the mixture while maintaining the green strength. Green strength is defined as the strength of the freshly cast concrete determined by the weight of sand that a cylindrical fresh concrete sample can resist until collapse happens. A typical green strength of 0.15 up to 0.6 psi (10-40 kPa) is suggested (Wang et al. 2005).

SCC mixtures suitable for use in slip form pavement applications are not as flowable as the typical SCC used for structural applications. A slump value about 8 in. (200 mm) and spread of 13-15 in. (350±25 mm) are obtained with the regular short cone shape after the slump cone was removed (Wang et al. 2005, 2011). Feasibility of producing SCC for pavement applications has been demonstrated in earlier studies (Pekmezci et al 2007). SCC was also reported to be applicable in slip form pavement constructions by Voigt et al. (2010). Increasing the fine content in the concrete mixture, as well as increasing the total cementitious materials was used as a method of producing the desired concrete. Class "F" fly ash, magnesium oxide, and three types of clay were also used as replacements for Portland cement for enhancing both the engineering properties and the environmental aspects (Voigt et al. 2010). To avoid further confusion, the "SCC" for slipforming is named "vibration-free concrete" (VFC) in the remainder of this proposal.

Due to the increasing amount of paste and the cementitious materials content in SCC/VFC mixtures, shrinkage and cracking potential will be an issue compared to the conventional concrete mixtures (Lomboy et al. 2011). It is required to focus on optimizing the mix design in terms of the paste content, Portland cement content, w/cm, and incorporation of proper types and amounts of shrinkage reducing admixtures (SRAs) to decrease the shrinkage and control cracking potential in hardened concrete.

The project performed at Iowa State University (Wang et al., 2011) has revealed the economical and ecological feasibility of slip-form VFC mixtures (Fig. 1). Although the material cost of VFC is higher, the total pavement construction cost can be made comparable to standard slipforming. In the top of Figure 4, the reference conventional concrete mixture is C3 (slip f). All other mixtures to the left of the QMC (which is an economical and ecological conventional pavement concrete) are VFC mixtures. The bottom graph shows the ecological aspect in terms of CO_2 emissions for materials, production and placement. The VFC mixtures show generally better performance than the conventional C3 (slip f) mixture. With the further advances in selection of aggregates and binders proposed in this project, the research team is convinced that the material and placement costs and CO_2 emission can be further reduced.

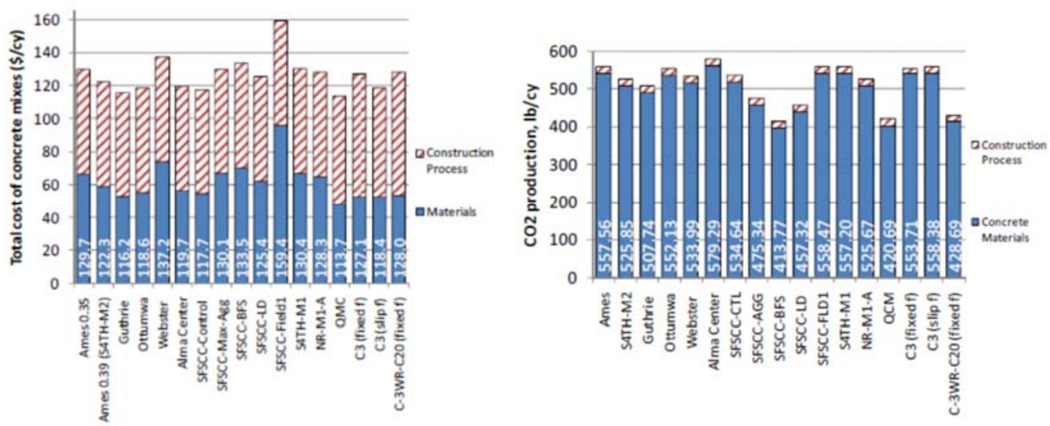

Figure 4. Cost (left) and C CO_2 emission (right) of constituent materials, mi xing and placement of slip-form SCC mixtures (all left from QMC), compar ed to conventional slipform mixtures (C3) indicate the economical and ecolo gical performance of SCC mixtures for pavements. Figure from Wang et a l., 2011

OBJECTIVE

The main objective of the proposed research is to determine the feasibility of producing cost effective materials for rapid pavement repair. The study includes mixture optimization as well as evaluating fresh and hardened properties and durability aspects of such novel materials through laboratory tests.

Two types of pavement technologies was applied in this project: 1) crack-free early strength concrete, and 2) self-consolidating concrete mixture for repair.

SCOPE

This research involves a development of rapid repair concrete to be used in full-depth repair of PCC pavements. The rapid setting concrete mixture is based on the current DOTD mixtures with a substitution of virgin aggregate with RCA and LWA to implement internal curing. The use of type III cement and silica fume silica fume was also studied to enhance setting and early age strength. For the development of VFC, Iowa mixture was used as the starting point with changing aggregate size and mixture proportion.

METHODOLOGY

Development of Rapid Setting Repair Concrete

A meeting was set up with the LA DOTD (Louisiana Department of Transportation and Development) office in Port Allen to discuss the procedure of full depth repair and the mix proportions used for the concrete they are currently using. The engineer on site used a high early strength concrete with a projected compressive strength of 4000 psi in 4 hours. Table 1 shows a mixture used in PCC pavement repair in Louisiana DOTD. RCA was not included for the high-early strength concrete by the DOTD. However, high-early strength has a drying shrinkage issue in many cases. Therefore, high-early strength concrete with recycled aggregate is being develop at SUBR to improve service life of high-early strength concrete. For this purpose, experimental tests were carried out to investigate the internal curing effect of RCA on concrete compressive strength and thus to find optimum mix proportioning for sustainable high-early strength concrete pavement. Main material properties such as specific gravity (SG) and absorption capacity (AC) were measured for each batch.

Table 1. Mixture Used in PCC Pavement Repair (DOTD provided)

MIX	LADOTD (27 ft^3)
Cement Type I or II	940
Coarse Aggregate lbs.	1663
Water oz.	25 gals
Sand lbs.	1352
Accelerator oz.	660
Super Plasticizer oz.	84. 6

Before mixing the specific gravity of RCA and LWA needed to be determined to calculate absorption capacity which is defined as:

$$\mathbf{AC = (W_{SSD} - W_{OD}) / (W_{OD}) \times 100\%} \qquad \textbf{(1)}$$

The absorption capacity of fine LWA and RCA has an absorption capacity of 24% and 4.8%, respectively. Being that the aggregates hold 24% and 4.8% moisture already, the amount of total water going into the mix was reduce by the percentage of absorption capacity. Aggregates were then pre-weighed a day before mixing to soak in water overnight to ensure reservoirs were filled with water as shown in Figure 5.

To reduce any free surface water of aggregate, the materials were drained an hour before mixing to minimize extra moisture being placed into mix. RCA and LWA were added first into the mixing drum first and then water to spin. Cement was added to bond the ingredients. While the drum is spinning, the super plasticizer was added to strengthen bond and add workability to the ingredients. Once the mix came to a consistent workability, the set accelerator was the added to overpower the super plasticizer to force the concrete to set. When the method of IC is used specifically with LWA the concrete mixture has improved workability.

Figure 5. 24-hour Soaked LWA for Concrete Mix

For early strength concrete, RCA is sieved and weighed. Initially in concrete mixes, concrete batches were proportioned for 1.11 ft3 for analyses including change of length (dry shrinkage), slump tests, thermal conductivity and heat capacity, later concrete mixes were then prepared for .5 ft^3. However, quality of mixes remained consistent and within LADOTD guidelines. Following the original LADOTD mix, the concrete mixes proportioned and measured based on the amount of concrete needed for six, eight-by-four concrete cylinder specimens. The amount was then separated in accordance to the weight in pounds of the LADOTD mix, substituting virgin coarse aggregate for RCA and LWA for sand in some mixes.

Following, absorption capacity is then determined to account for pre-soaked aggregate to ensure an adequate amount of water is present in concrete mixture. AC for RCA and LWA were calculated at 4.8% and 24% respectively.

Prior to mixture, a bucket of RCA is sieved. Sieve analysis is particularly important to determine a target mean strength on the basis of required strength, a higher standard deviation should be used when designing a concrete with RCA of variable quality than when RCA's of uniform quality or virgin aggregates are used. The proportion is based on the measured density of the RCAs intended in the job concrete (rapid pavement repair concrete). Next, RCAs larger than 1 ½ inch are removed because larger aggregates affect bond between the aggregate and the cement paste which directly influence the compressive strength. Thus, crushed, angular and well-graded aggregates tend to better bond between cement paste and aggregate, and higher strength. Even distribution of aggregate nominal size is weighed to the amount of 30.8 pounds, washed 2 to 3 times until surface dust is removed and then fully submerged in water for 24 hours. LWA aggregate is to fine to sieve, but depending on the requirements of the mix design 12.5 or 25.03 pounds of LWA is fully submerge alongside the RCA for 24 hours. Preceding aggregate preparation, 2 hours before mixture both aggregates are drained. Aggregates drain and sit until there is no visible surface water (Note: aggregates are not the same weight after fully submerge and drained). All other ingredients are measured day of in accordance to mix design.

In addition, preparing and proportioning materials, while mixing, it was necessary to add material in the same order for each mix otherwise it may have led to inconsistencies. Wet LWA is added, followed by half of required cement and sand to rotating concrete mixing drum. Next all of the wet RCA, the rest of cement and lastly water, super plasticizer is added. The accelerator is last to be added as, if added before will not force the concrete mixture to set rapidly. In trial mix prior, adding all ingredients at once led to an extremely high concrete mixture. It is recommended by a concrete specialist at DOTD to add ingredients slowly to ensure a thoroughly well-blended mixture that will result in compressive test reading. After concrete is mix, casting begins promptly. Casting involves rodding, vibrating, and then placing them in an ice cooler.

Following, cylinders and blocks are casted halfway. The concrete is rodded 20-25 time alleviating any air pockets or bubbles and vibrated on a vibrating table to settle concrete. Concrete cylinders that set with air pockets or bubble will set normally but will lead directly to a lower compressive strength being that there is no hard-concrete material fill in empty spaces. Cylinders were then filled to the top and rodded another 20-25 times and vibrated again. If more concrete is needed to top rodding should be skipped and vibrated only, capped placed in cooler tests were carried out on ELE International Accu-Tek 350 Digital Series Compression Tester to test compressive strength and performance of the casted cylinder under a load at a pace rate of 439.79 lbf/sec after 4 and sometime 8 hours to document strength progression. After a series of test, the Accu-Tek Touch 350 yields key readings in regards to the strength of the concrete mix. Figure 6 shows compression tester and concrete specimen at failure.

Figure 6. Compression Tester and 4-hour Compression Test

In order to produce a specimen that will meet our goal, first we initialize internal curing. Internal curing helps reduce drying shrinkage in a concrete mixture. “Internally cured concrete has a higher degree of hydration resulting in reduced water absorption. Furthermore, internally cured concrete mixtures are less susceptible to early age thermal cracking” (Schlitter et al.).

After each mix, the concrete was placed into a mold as shown in Figure 7 (a). Molds for test specimens used in determining the length change of cement pastes and mortars was 3”x 3” x11.25” prisms having a 10” gauge length. The gauge length shall be considered as the nominal length between the innermost ends of the gauge studs. Once the unsealed specimen hardens, it is released from the mold. For an unsealed specimen that loses moisture externally, liquid-vapor menisci also form. However, in this case, they form at the surface of the concrete. While external drying occurs at the exposed surface, self-desiccation develops throughout the interior of the material. The formation of liquid-vapor menisci corresponds with a reduction in the internal relative humidity of cement paste. In an unsealed specimen, as moisture evaporates from the surface, the radius of the menisci continues to decrease. This causes the drying front to penetrate into smaller openings and to gradually grow from the surface towards the interior of the material. The internal relative humidity is proportional to the menisci radius and thus decreases continuously as drying progresses until the internal relative humidity of the cement paste reaches equilibrium with the ambient relative humidity (Radlinska et al.). However, water must be released from the pre-wetted lightweight aggregate after internal curing if the shrinkage rate is to be reduced. The ASTM C 157 standard test method is the procedure used to measure length of change for drying shrinkage. The apparatus used to determine the specimen's length change throughout its duration is called a length comparator as shown in Figure 7(b).

(a) Concrete prism mold (b) Length comparator

Figure 7. Apparatus of Drying Shrinkage Measurements

Development of VFC for Rapid Pavement Construction and Repair

Based on the literature review, previous experimental work, and the determination of main mix design factors affecting thixotropy and the strength of thixotropic bonds through project "RE-CAST: Research on thixotropy and workability loss of vibration-free concrete in view accelerating pavement construction by slipforming.", two baseline mix designs will be selected. In this latter project, the influence of different mix design parameters on thixotropic development and breakdown was investigated. These mixtures will be evaluated for fluidity, self-consolidation, meaning how much air is removed autonomously due to the concrete fluidity, thixotropic strength development, and shape stability at Missouri University of Science and Technology (Missouri S&T). Fluidity will be evaluated using the slump flow test, while the static yield stress measurement on the ICAR rheometer and the portable vane measurement will be used to evaluate thixotropic strength development. The self-consolidation will be evaluated by comparing the mass of an unconsolidated and consolidated 4” by 8” cylinder, as a difference in mass indicates a change in air volume. The shape stability is determined by demoulding a 4” by 8” cylinder, using steel molds with screws, and measuring the decrease in cylinder height.

For each mixture, the fluidity, thixotropic strength development, and shape stability will be evaluated in 15 minute intervals until the shape is stable. The shape stability will be determined twice at each interval, once for a sample at rest since 15 min after cement-water contact (undisturbed), and once for a sample at rest for only 10 min (remixed). The undisturbed samples indicate how long the concrete needs to rest to achieve shape stability, while the remixed samples indicate at which age the concrete can achieve sufficient shape stability in a 10 minute period. Fluidity will be determined on remixed samples, to simulate transportation on-site. The thixotropic build-up will be measured on undisturbed samples.

Once the variation of fluidity, thixotropic strength development and shape stability with time is characterized, the mixture will be reproduced and re-tested to validate the time needed for shape stability, imitating transport to the site by agitation of the mixture and remixing prior to placement. Fluidity and self-consolidation are measured at the anticipated time of placement, while the shape stability is verified after an additional 10 minute rest period.

Modifications in mix design will be evaluated to accelerate or slow down the thixotropic strength development, and the impact of adding small amounts of thixotropy-enhancing materials just prior to final mixing (corresponding with the arrival of the mixture on-site) will be evaluated. In this way, guidelines for adoptions in mix design can be created as a function of the expected time needed for transport and delivery. The modifications in the mix design can be the amount and type of thixotropy-modifying agents, binder composition, aggregate amount and gradation, or chemical admixtures.

Eight optimized mix designs will be communicated to the Southern University of Baton Rouge to continue the research work on the performance of the concrete. If the concrete mixtures do not show adequate performance in the hardened state, the mixtures will be re-evaluated for fresh properties if large modifications in the mix design are needed.

Prior to starting the research, the characteristics of the materials available at SUBR and Missouri S&T will be compared to avoid large variations in the response of concrete to the induced modifications. Grain size distributions can be matched, cement types and SCM properties can be kept as close as possible to minimize the variations. Thixotropy-enhancing materials and chemical admixtures, which are expected to induce the largest variations in fresh concrete properties, will be ordered from the same producers. The first thing to do is to verify the fresh properties of the concrete by means of the flow retention and shape stability tests, and if necessary adjust the contents of the admixtures to ensure appropriate fresh properties in the fresh state. Once these are achieved, the investigation on the hardened scale can be performed.

Eight concrete mixtures identified at Missouri S&T will be used for preparing concrete mixtures. Samples will be taken for investigating the development of setting time, compressive strength, splitting tensile strength, and drying shrinkage. The benefits of incorporating superplasticizer to reduce cement content and shrinkage reducing admixture to decrease shrinkage and cracking in concrete pavement will also be investigated.

The test results of the mixtures will be used to select adequate and economic mixtures for slipforming, with the best mechanical properties, and lowest shrinkage that are cost-effective. For selected mixtures, further testing will be conducted to evaluated modulus of elasticity, as well as sorptivity, as shown in Table 2.

Table 2. Proposed Concrete Test Methods and Protocols

PROPERTY	TEST METHOD	TEST TITLE/DESCRIPTION
HARDENED MECHANICAL PROPERTY TESTS		
Compressive Strength (1 to 56 d)	ASTM C 39	Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
Splitting Tensile Strength (7 to 56 d)	ASTM C 496	Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens
Modulus of Elasticity and Poisson's ratio (28, 56 d)	ASTM C 469	Standard Test Method for Static Modulus of Elasticity
Drying shrinkage (after 7 d of moist curing)	ASTM C 157	Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete
Autogeneous shrinkage	ASTM C1698	Standard Test Method for Autogenous Strain of Cement Paste and Mortar
DURABILITY TESTS		
Permeable void ratio (56 d)	ASTM C 642	Standard Test Method for Density, Absorption, and Voids in Hardened Concrete
Sorptivity (56 d)	ASTM C 1585	Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes

Utilizing the finalized VFC mixtures (two - four mixtures) developed in earlier stage, pre-field construction of small-scale slipform pavements is planned to investigate the potential for field implementation. The construction will be in rectangular slabs (2m x 1m) and placed by a miniature slipformer outside the laboratory. The concrete properties will be monitored in terms of flowability and key mechanical properties. The testing slabs will be instrumented to monitor shrinkage and responses to thermal variations. Non-destructive tests, using the impact-echo testing equipment, will be performed to examine voids and homogeneity of concrete sections. The cross section of the slabs will be cut to observe air void and aggregate distribution through the depth. Cores will be taken at different places in the slabs to compare the in-situ mechanical properties of the slab to the intrinsic properties of the concrete.

Feedback of the pre-field implementation will be provided to adjust mixtures or placement strategy of VFC.

DISCUSSION OF RESULTS

Producing the same mix with different undergraduate students and the materials stored in the laboratory for a long time are the challenge of this period. During the summer, undergraduate students prefer to work in internship opportunity in outside rather working at the university, and I had to work with new students during this report period. The aggregate stored in the laboratory becomes drier as time elapsed, and the first few trials resulted in dry mix, and we had to adjust moisture contents of the aggregate. Moisture contents and absorption capacity of aggregate were measured according to the ASTM C 127 (coarse aggregate) and 218 (fine aggregate). Table 3 shows the measured absorption capacity and moisture contents.

Table 3. Absorption Capacity and Moisture Content of Aggregates Stored in the Laboratory

Aggregate	Sand	Fine aggregate	Coarse aggregate
Absorption capacity (%)	2	3	4
Moisture content (%)	0	0	-8

Development of Cost-effective Rapid Setting Concrete

1. Preliminary trial with Type I cement

The first mix proportioned 1.11 ft^3 with type I, II cement, RCA, and LWA. The RCA and LWA replaced the coarse virgin aggregate and sand, and would be the base mix (the aggregates were not pre-wet.) Trial mix lacked sufficient moisture, thus, adding water to concrete to develop a better consistency to cast it was necessary. The 4-hour compression test did not meet the strength requirements of DOTD.

Table 4. Concrete mix design using Type I, II Cement.

MIX	#5 (1.11 ft^3)	#9	#10
Cement Type	Type I, II	Type I, II	Type I, II
Cement, lbs	38.6	38.6	38.6
RCA, lbs	68.4	68.4	68.4
LWA Aggregate, lbs	55.6	55.6	55.6

Water, gal (oz)	93.67 (oz)	87.7	87.7
Water Reducer, oz	0	0	0
Set Accelerator, oz	3.5>4	8	6
Super Plasticizer, oz	27.1>28	30	30

Among some of the mixes that developed, high strength over time are as listed in Table 4. While the original mix 5 was dryer in consistency, 6 oz. of water was added to compensate for that. In mix 9 the super plasticizer was increased by 4 oz. because of the dryness of the documented in mix 5 but did not result in stronger concrete. It should be noted that if superplasticizer admixture should be increased if water should be decreased 5-10% as well. After adjustments to the admixtures cylinders hardened faster but still contained a lot of moisture after four hours. Mixes 5, 9, 10 are significant as those concrete mixes demonstrated the highest overall graduate strength. After demolding these cylinders for four hour testing these cylinders were still moist, thus not strong enough for results. However, over 28-day testing, these same cylinders were the strongest. Strength gains over 28-days are presented in Table 5.

Table 5. Compressive Strength Measurement for mixes 5, 9, 10 (unit: psi)

Mix	4-hours	3-day	7-day	14-day	21-day	28-day
5	0	4,555	5,633	6,218	6,805	7,191
9	0	3,810	4,466	4,891	5,152	7,028
10	0	4,451	5,238	5,954	6,503	7,046

2. Concrete Mixture with Type III cement

As this project moves forward using Type III cement, exploring different mix proportion of the current design are expected to yield us closer to recording results for 4-hour strength. After observation, mix concrete cylinders contained too much moisture, this apparent in how dark coloration in the specimen is indicating extra water is still present it. That could be tribute to access surface from aggregates and or too much water as an ingredient. The water content was reduced by the absorption capacity as stated before.

Concrete mixture 1, RCA was not submerged, to test the concrete specimen strength with extra water, super plasticizer and only LWA fully wet. LWA has a higher AC and could have potentially been all the water necessary for the mix. The concrete cement paste in return resulted undesirable consistency. HES concrete is expected to be workable in applications but heat and stiffen at the time of adding accelerant. In this case the mixture was cooler in temperature and watery. Demolding the cylinder confirmed a lower early-age strength due to lack of hydration as the concrete specimen cured in cooler. Thus, concrete mixture 2 involved fully submerged RCA and only 50% LWA submerged. The AC for both fully submerged RCA and 50% LWA submerged was accounted for with the mixture only requiring 42.25 oz of water. With the AC at 4.8% and 27%, the amount of water is reduced by 4 oz from 48 oz, to increase super plasticizer and add strength in concrete specimen at early-age testing. The result of the early age test for the specimen was small incremental increase.

Adjusting the amount of water to adequately force hydration while developing strength-maturity over 28 days required a reduction in the amount of super plasticizer necessary for accelerated-concrete pavement. Cement is the glue that binds concrete together, and as super plasticizers chemical composition influences concrete behavior it should be noted for incremental increases to super plasticizer does not yield higher strength unless incremental increases are made to cement of up to 10 % more. The cement was not increased due to availability of it.

Removing water from the following mixes would prove to be difficulty as my studies have found that with RCA in concrete mixture, the initial early strength is low. This is attributed to higher water absorption rate of the mortar adhered to the RCA as read above. Concrete mixture 3 incorporated wet RCA, 50% wet LWA, and sand. Sand tends to dry out concrete mixture and impact the bond between cement and other aggregates so full amount of water was included in. Some surface water on LWA was still present and is factor in concrete mixture as cold climate condition inhabited improper drying of the aggregate, nonetheless, a higher early-age strength is recorded. Concrete mixture 4 incorporated no LWA for the previous reason of cold climate condition and replaced with full amount of sand of 25.03lbs. This particular mixture is of a workable consistency at the time of casting cylinders. Two extra ounces of super plasticizer was added just before the accelerant to remove small chunks of concrete from stuck in the corners of blades inside the drum. We added more super plasticizer because adding more water would have affected hydration and initial strength of hardened concrete specimen when tested while adding super plasticizer has the ability to add strength to specimen if added as needed.

Based on the LA DOTD mixtures for rapid repaid as shown in Table 1, a variety of different alternatives were tried as shown in

Table 6 to reduce the amount of water in the mix that contributes to a watery mix and wet cylinders after they are demolded.

Table 6. Concrete mix design using Type III.

Materials	Mix 1	Mix 2	Mix 3	Mix 4
Cement Type	Type III	Type III	Type III	Type III
Cement (lbs)	17.4	17.4	17.4	17.4
RCA (lbs)	30.8	wet 30.8	wet 30.8	Wet 30.8
LWA (lbs)	Wet 25.03	Half wet 25.03	Wet 12.5	0
Sand (lbs)	0	0	12.5	25.03
Water (oz)	61	42.25	59.26	59.26
Set Accelerator	12.22	12.22	12.22	12.22
Superplasticizer	4	6	2	4

Being that the presence of extra water in concrete mixing, it was necessary to consider other a SCM. The presence of extra water was due to the fact the pre-wet aggregates would hold excessive surface water or climate conditions. Although there are many controllable variables in mixing concrete, how aggregates retain moisture on the surface is not one of them. Therefore, introducing silica fume, a by-product from the electric arc furnace used in the production of silicon metal or ferrosilicon alloys will be investigated. It is commonly used as a partial substitute for Portland cement through the use of less than total cementitious content while improving the durability to enhance a longer life for concrete pavement. It is an excellent way to reduce the cement productions carbon footprint. Manufacturing Portland cement is energy intensive that requires heating large quantities of grounded aggregates and other mineral extremely high temperatures. For this study, we will look for it to absorb surface water on aggregates and to improve the concretes performance. Table 7 shows the mixing ingredients and their source or vendor.

Table 7. Materials used for trial mixes.

Mixture Ingredients	Source/Vendor
Cement Type III	Continental cement company
RCA lbs.	Red stick crushed concrete
LWA lbs.	Oldcastle Inc.
Water oz.	-
Sand lbs.	Bear Industries
Accelerator oz.	Master builder solutions-BASF
Super Plasticizer oz.	Master builder solutions-BASF

Figure 8 shows that the 4-hour compressive strength of concrete mixes containing type III cement, which did not meet the target goal of 4000 psi. As this project moves forward using Type III cement, exploring different mix proportion of the current design are expected to yield us a higher recording results for 4-hour strength. After observation, mix concrete cylinders contained too much moisture, this apparent in how dark in color and wet the concrete cylinders are after demolding. That could be attributed to access surface water from aggregates and or too much water as an ingredient. The water content will be reduced by the absorption capacity as stated before.

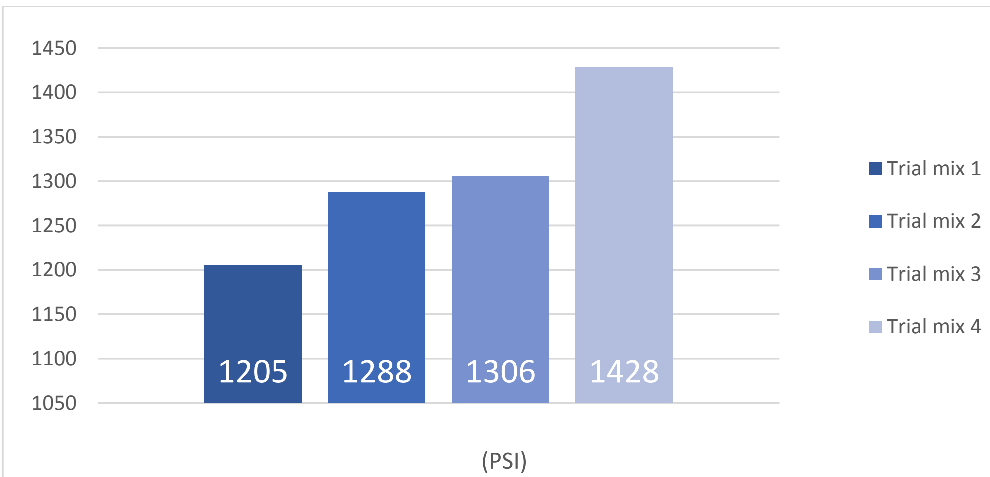

Figure 8. 4-hour Compression Strength of Concrete Mixtures with Type III Cement.

3. Concrete mixture replaced with silica fumes

Using silica fume has dramatically improved the performance of concrete under compression test. The silica fumes were replaced by total mass of cementious materials in three mixes between 6-10% as shown in Table 8. Compression test were done at 4 and 8 hours to show the feasibility to use the concrete in paid pavement repair as shown in Figure 9. All the mixes tried did not make 4,000 psi in 4-hour, however, the test results show that silica fume helps to improve the concrete strength drastically. Figure 10 shows the strength development of the mixes for the 28 days.

Table 8. Concrete mix design using silica fumes. (.5 ft³)

MIX	DOTD Mix	Mix 1	Mix 2	Mix 3
		6% Silica Fume	8% Silica Fume	10% Silica Fume
Cement Type	Type I, II	Type III	Type III	Type III
Cement lbs.	17.4	16.36	16.008	15.66
LWA lbs.	12.5	wet 12.5	wet 12.5	wet 12.5
RCA lbs.	30.8	30.8	30.8	30.8
Water oz.	59	42	42	42
Sand lbs.	12.5	12.5	12.5	12.5
Accelerator oz.	12.22	12.22	12.22	12.22
Super Plasticizer oz.	2	2	2	2
Silica Fumes lbs.	N/A	1.04	1.39	1.74

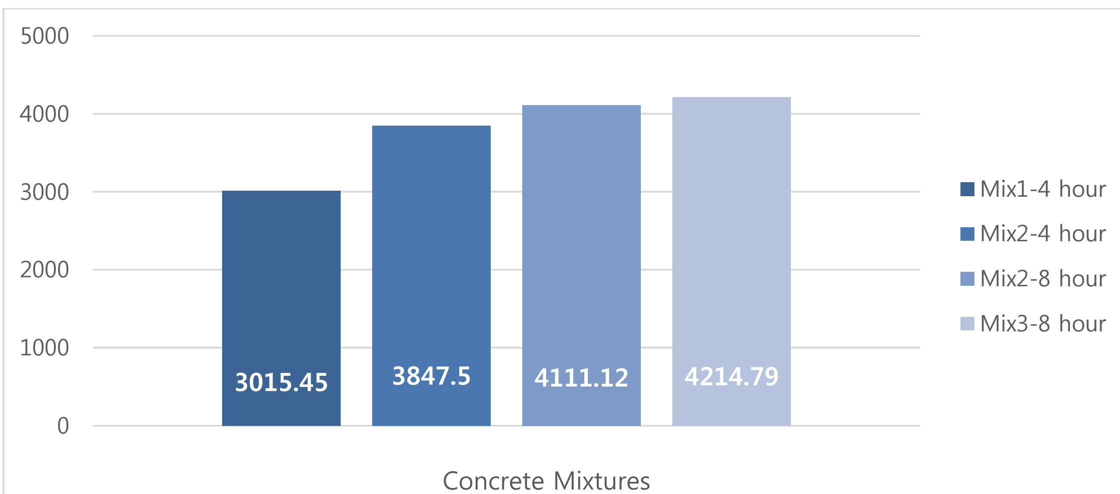

Figure 9. 4- and 8-hour Compressive strength using 6%, 8%, and 10% Silica Fumes Respectively.

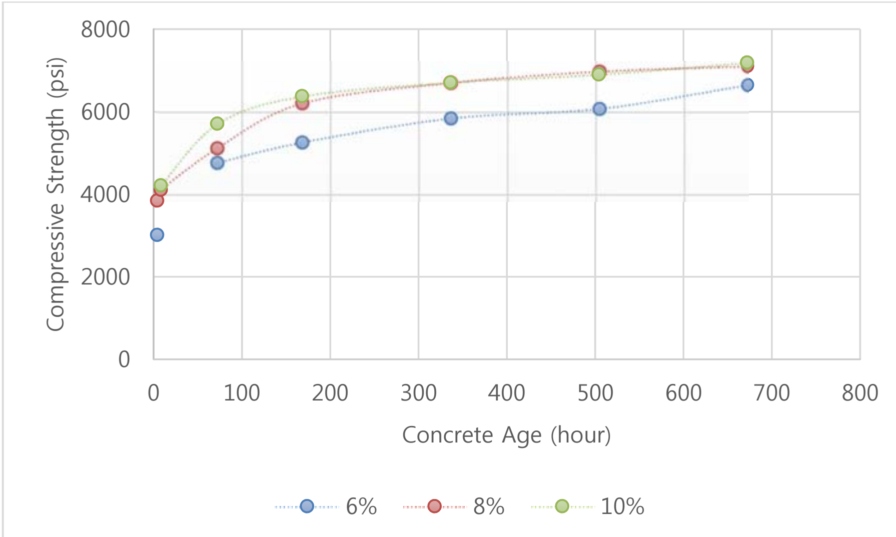

Figure 10. 28-day Compressive Strength Containing Silica Fume

4. Effects of Internal Curing

Type III Portland cement was used along with silica fume, recycled and lightweight aggregate. In later mixes, virgin (limestone) aggregate was also used. Water, super plasticizer, and accelerator were also involved in the mix to achieve the goal of reducing shrinkage as well as increasing the strength of the concrete specimen. The aggregates (both coarse and fine) for each mix design were pre-wetted for 24 hours prior to mixing. Mixture designs are presented in Appendix B.

All mixes were used with type III cement. Figure 11 shows the strengths of selected mixes. Mix 10 was too dry, and Mix 26 was too moist (despite having a w/c ratio of 36.3 %) to have successful test readings. Mix 9 was the first to reach 2000 psi in four hours as well as 3000 psi overall within a 8-hour span. Mix 15 was able to reach 3000 psi in five hours while Mix 20 reached 4000 psi in that same duration. Mix 21 was used with an additional 7.5 lbs. of Type III cement in place of 7.5 lbs. of LWA which allowed the design to nearly reach the 4000 psi goal in four hours. Mix 23 was an advancement of Mix 21. Its strength numbers were slightly greater than 21, but a little dryness kept it from reaching 4000 psi in four hours. Figure 12 shows Mix 21 cylinders after strength test. The 5-hour test broke at the bottom which caused its number to be low.

By Mix 22, virgin aggregate was being used in the designs. Mix 24 used a combination of RCA and virgin aggregate, and Mix 25 was a remix of 22 in an effort to gain higher strength using the same design.

Table 9. Strength Results & Analysis

Mix #	4-h (psi)	5-h (psi)	6-h (psi)	7-h (psi)	28-d (psi)
Mix 6	1311.1	-	2341.4	2301.1	-
Mix 7	1454.8	2012.0	2207.6	2390.3	-
Mix 8	1870.1	2249.2	2286.3	2744.7	-
Mix 9	2136.1	2532.9	2705.8	3041.7	-
Mix 11	1472.5	1818.8	2057.8	2054.9	-
Mix 12	1423.3	1849.9	2078.6	2108.7	-
Mix 13	1295.3	2194.6	1262.9	1069.8	-
Mix 14	1757.6	2088.0	2297.5	2514.2	-
Mix 15	2470.3	3127.1	3378.6	3314.2	-
Mix 17	1278.2	1639.8	1572.3	2269.8	-
Mix 18	2607.9	3037.9	3267.1	3596.4	-
Mix 19	2511.8	2944.9	3142.4	3517.1	-
Mix 20	3113.4	4071.2	3861.5	4251.2	-
Mix 21	3802.8	3841.8	4482.5	-	-
Mix 22	1214.3	1462.2	1745.8	1857.0	-
Mix 23	3851.1	4045.5	4260.3	-	-
Mix 24	1794.5	2073.4	2346.8	2296.7	-
Mix 25	1604.9	2326.0	1900.6	2148.6	5630.6

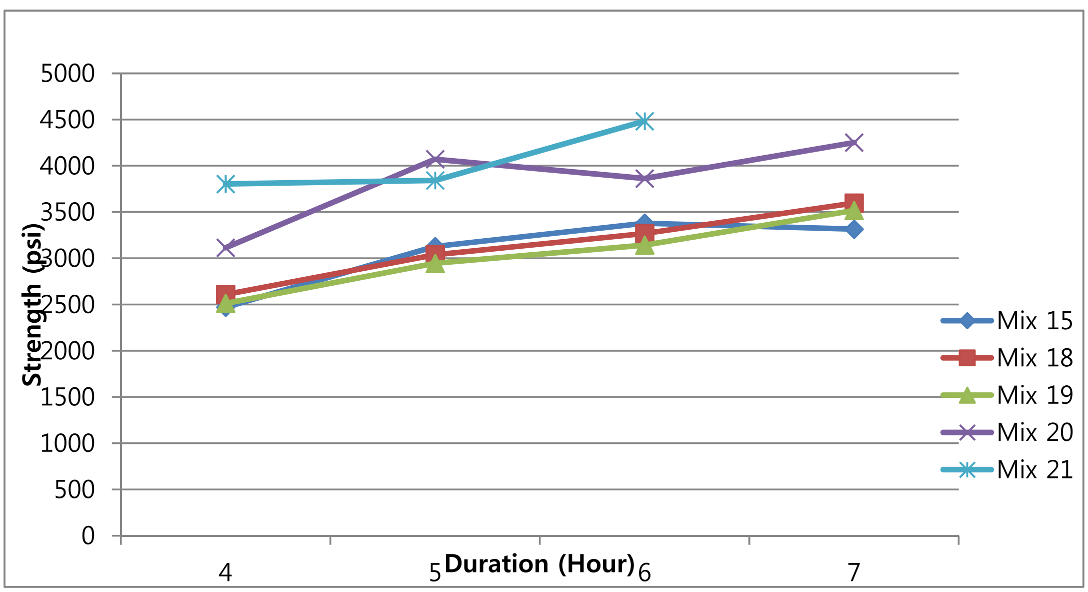

Figure 11. Strength of Mix Comparison

(a) 4-hour (b) 5-hour (c) 6-hour

Figure 12. Concrete Cylinder Tested in 4-, 5-, and 6-hour After Placing Concrete

"It should be noted that the internal supply of water from the saturated lightweight aggregate to the high-strength cement matrix caused continuous expansion, which may be related to continuous hydration" (Bentur et al.). Mix 23 was proven to have an early shrinkage when compared to other mixes that used less cement. However, from the initial reading to the 8-week (56-day) reading, it only shrunk by 0.0414%, over a 5-week period it shrunk by 0.03295%. Compared to 5-week results for other mixes; Mix 1: 0.05644%, Mix 5: 0.04299%, Mix 6: 0.0413%, and Mix 24: 0.03628%. Figure 13 displays drying shrinkage of selected mixes.

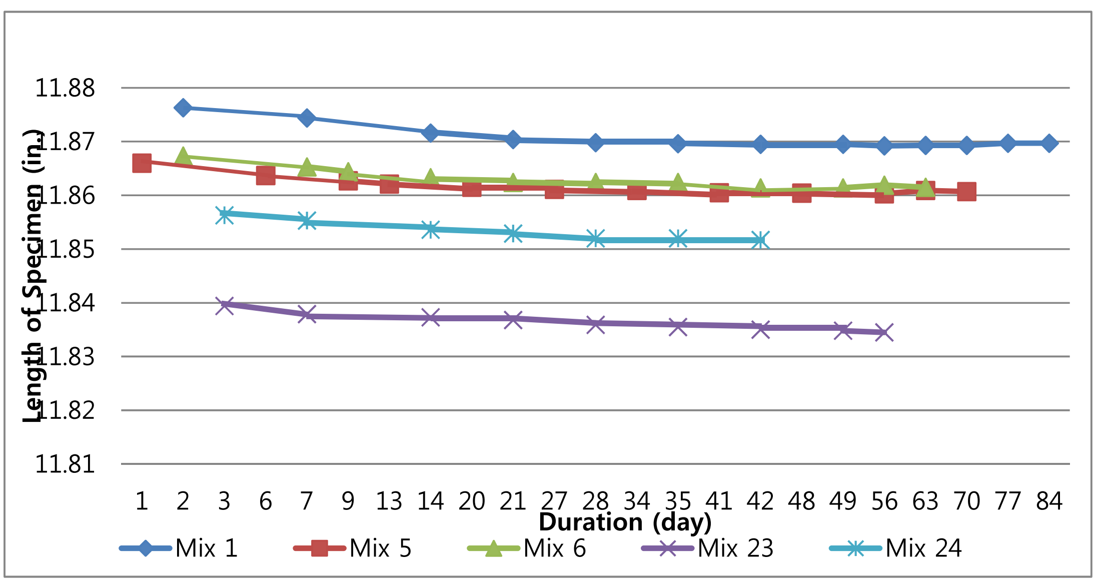

Figure 13. Comparison of Drying Shrinkage

The mixtures with various IC conditions shows high variations of early strength and drying shrinkage. At this stage, among the mixtures containing RCA, LWA, and silica fume, "Mix 21 and Mix 23" shows the highest 4 hour strength and low drying shrinkage. One of the difficulties of this study in early age strength is the high variations of the strength with a small change in the mixtures. Therefore research team is now focusing on the very strict mixing procedures that produce repeated results on the fresh and hardened properties of rapid repair concrete. Also, it is scheduled to use maturity concept to estimate early strength by measuring temperature development of the mixtures.

VFC Mixtures with RAC

The VFC mix designs of 3 flowable thixotropic concretes which could be used for (very slow) slip forming or for patching were provided by Dr. Feys in Missouri University and S&T as explained in other RE-CAST report (#00042134). Table 10 presents the mixture design.

Table 10. Mixture design of Flowable Thixotropic Concrete

Material (kg/m3)	SL-B-1	AC	SL-B-AC
Cement	355.6	478.3	352.2
Slag	118.6	-	118.2
Attapul-gite clay		2.4	2.4
19 mm aggregate	517.5	517.5	517.1
9.5 mm aggregate	369.1	369.1	369.2
Sand	890.7	890.7	898.1
Water	159.7	159.8	150.4
SP	1	2.7	3
w/b	0.35	0.35	0.35

To further understand the effect of accelerator on the strength development in the mixtures having recycled concrete aggregate (RAC), one VFC mixture (AC) was modified by replacing RAC in lieu of virgin aggregate. The mixture also replaced type I cement with type III cement to make quicker setting of the cement paste. Table 11 shows two mixtures having 16 oz and 20 oz accelerator.

Table 11. VFC Mixtures with accelerator and RAC (1 ft^3)

Material	Mixture with 16 oz accelerator	Mixture with 20 oz accelerator
Cement I	-	-
Cement III	29.78	29.78
Slag	-	-
Attapul-gite clay	0.15	0.15
19 mm agg. (RAC)	32.22	32.22
9.5 mm agg (RAC)	22.98	22.98
Sand	55.45	55.45
Water	8.955	8.955
SP	0.17	0.17
accelerator	16 oz	20 oz

The measured compressive strengths are presented in Table 12. In addition to the compressive strength of mixture having RAC, the compressive strength of the same mixture having virgin aggregate is also presented in the 4th column of the table. The results were borrowed from the VFC research project. The early strength of the mixture containing RAC has slightly lower strength compared to the mixture having virgin aggregate though the strength development. For the mixture having 20 oz accelerator, the strength development is faster than the mixtures containing 16 oz (both RAC and virgin aggregate) up to 8 hour test. However, in 10 hour compressive strength test, the concrete specimen failed in much lower compressive strength (1,804.3 psi) compared to other mixtures (2,574 psi and 3,053.6 psi). To better understand, the failure surface was inspected. Figure 14 shows the failure of the specimen. For the lower strength concrete mixtures, the failure normally occurs at the interface (known as interfacial transition zone (ITZ)) between aggregate and cement paste. In the concrete specimen failed in the low compressive strength (1,804.3 psi), it is not usual to fail through the RAC. By the inspection of the specimen, it was concluded that the RAC has very low compressive strength compared to virgin aggregate and it caused early failure thought the cement paste. So it should be carefully selected the RAC in the next mixtures. At the same time the dosage of the accelerator should be further investigated.

Table 12. Compressive strength (psi) of VFC mixtures with accelerator and RAC

Time elapsed (hour)	Mixture with RAC and 16 oz AC	Mixture with RAC and 20 oz AC	Mixture with virgin aggregate and 16 oz AC
4	145.1	195.9	166.0
6	741.8	1,457.8	1,028.7
8	1,777.7	2,567.6	2,165.7
10	2,574.0	1,804.3	3,053.6
24	5,497.8	-	5,489.9

Figure 14. Failure of mixtures with RAC and 20 oz AC.

The temperature of two mixtures containing 16 oz and 20 oz accelerator was measured with a cup test. The concrete sample was put in 6 oz. styrofoam cup and a thermocouple was inserted in the middle of concrete mix. The cup was sealed with aluminum foil and measured the temperature development of the concrete as shown in Figure 15. The Figure 16 shows the temperature changes with time for the mixtures. The figure shows that the increase dosage of accelerator shorten the time to make the peak temperature and increase the peak temperature, and it would help to expedite the development of compressive strength. This test will continue by modifying the mixtures with higher dosage of accelerator to maximize early strength in coming reporting period.

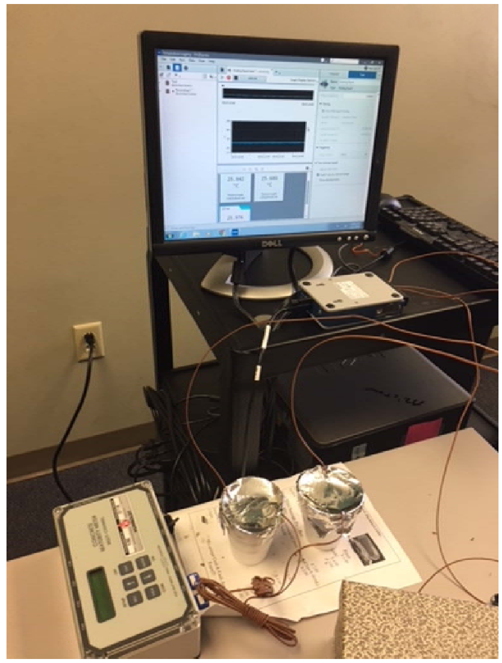

Figure 15. Temperature measurement of AC mixtures

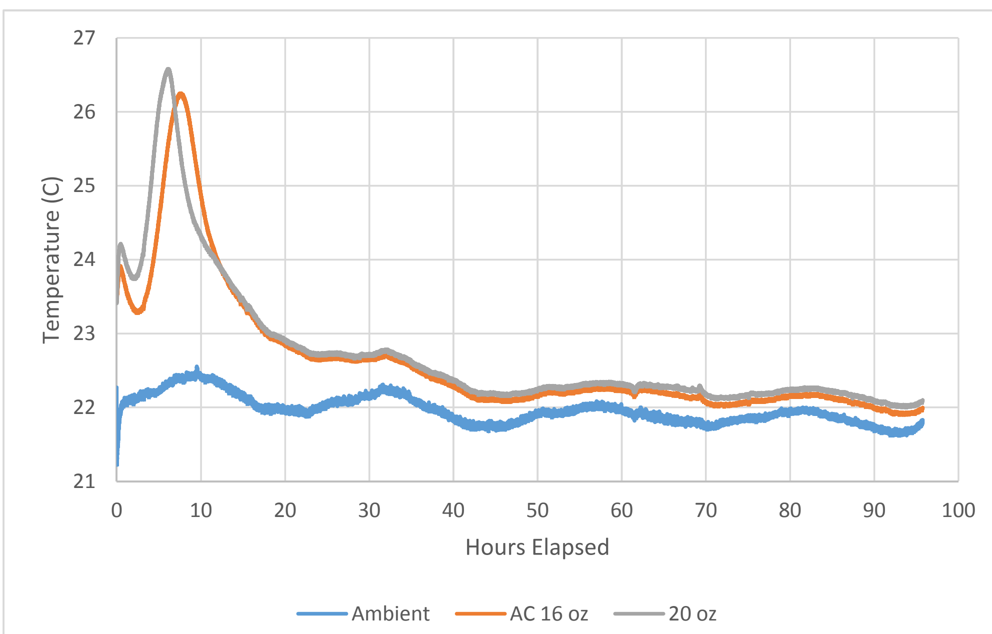

Figure 16. Temperature development of AC mixtures containing accelerator of 16 oz and 20 oz.

1. Calibration of Oven Temperature

In the previous reports, it was found that concrete cylinders placed in an oven (set at 105°F) developed much higher compressive strength compared to the cylinders placed in ambient temperature. Using the thermocouples, the temperature inside the oven was measured to make sure that the temperature is kept in the 105°F. Figure 17 shows the measured temperature inside the oven. The time zero coincides with turning on the oven that was set to 105°F. Thermocouple was placed close to the middle of the oven.

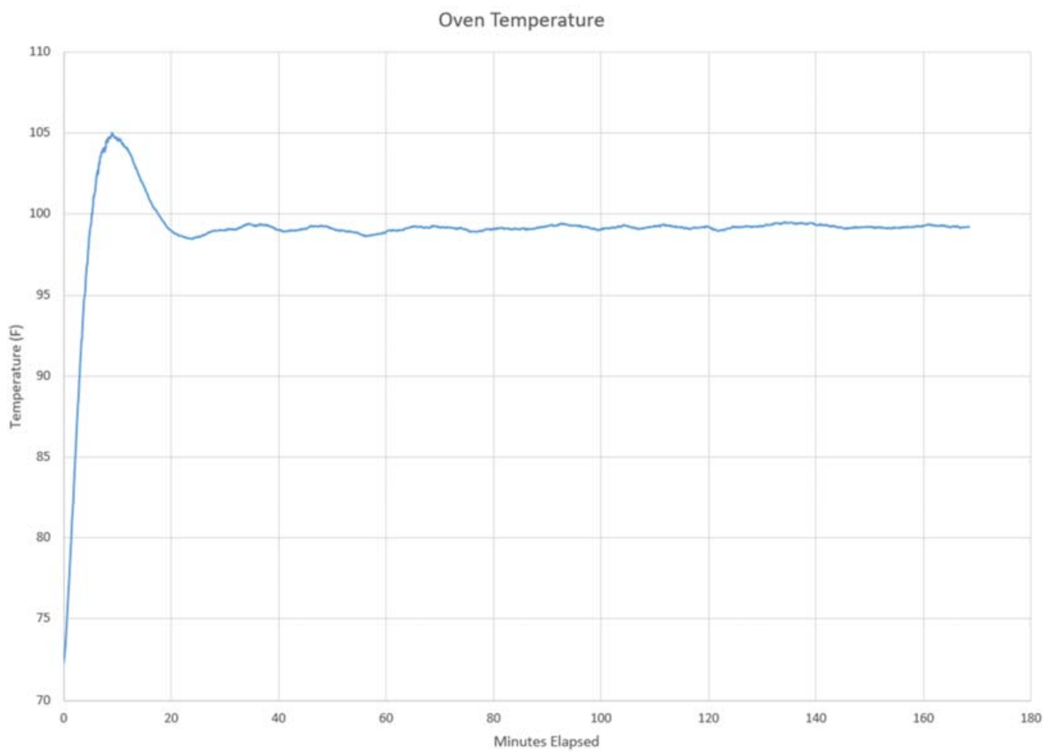

Figure 17. Temperature Measurement Inside the Oven Set at 105°F

The measured temperature shows that the oven temperature (thermocouple readings) doesn’t match with the temperature on the oven’s thermostat (oven set-up temperature). To achieve the target temperature of the oven, a calibration curve for the thermocouples using two manual thermometers and hot/cold water. The manual thermometers matched each other closely, and the thermocouple matched each other closely. The results are shown in the Figure 18.

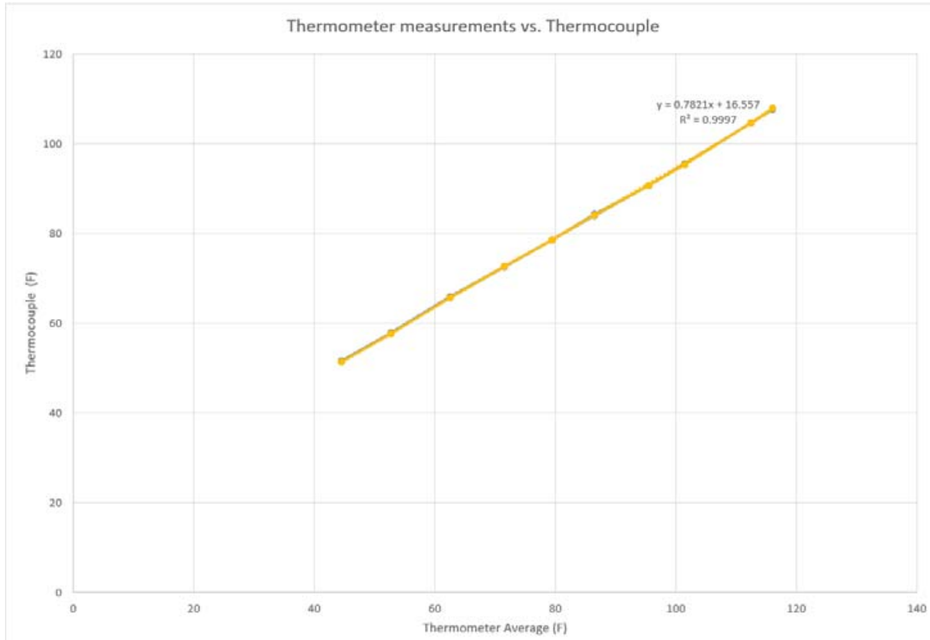

Figure 18. Regression curve of thermocouple to the thermometer

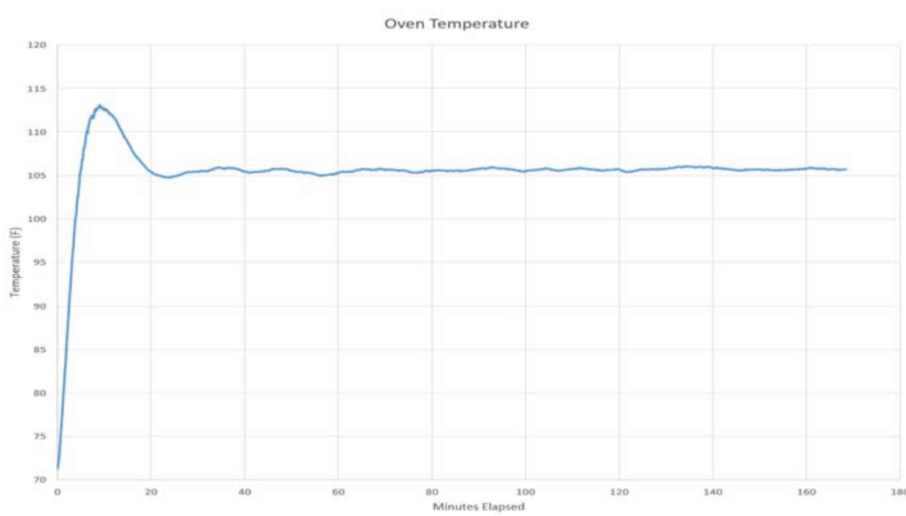

Figure 19. Corrected Oven Temperature with the Regression Curve

Because the R2 value was very good (0.9997), previous oven temperatures was corrected based on the linear regression curve above. The corrected results in Figure 19 show that the oven temperature was, in fact, very close to the thermostat temperature (105F).

2. Measurement of Blanket Temperature

To provide a constant temperature (105°F) for the curing of fresh concrete in the field, a warm electric blanket is considered. An electric blanket (Sunbeam Xpress Heat, 6 level hear setting) was selected to monitor temperature of the blanket. A hardened concrete cylinder (4x8") was mounted with six thermocouples and wrapped with the blanket as shown in Figure 20. The bottom of the cylinder was placed in the sand to provide heat dissipation in the field. The temperature level was set at Level 1 for sixty minutes and elevated to the next level with the same time internal. Figure 21 shows the measured temperature in various locations of the concrete cylinder with ambient temperature. Higher level of heat causes increase higher temperature as expected. Except at early stage of temperature balance, the bottom temperature was lower than top temperature. The different is about 5°F. Basic study will continue to determine the appropriate level of temperature to simulate 105°F inside the blanket. Once it is achieved, fresh concrete cylinder will be cured inside of the blanket to monitor strength development with the temperature.

Figure 20. Temperature Measurement Inside of the Blanket with Thermocouples

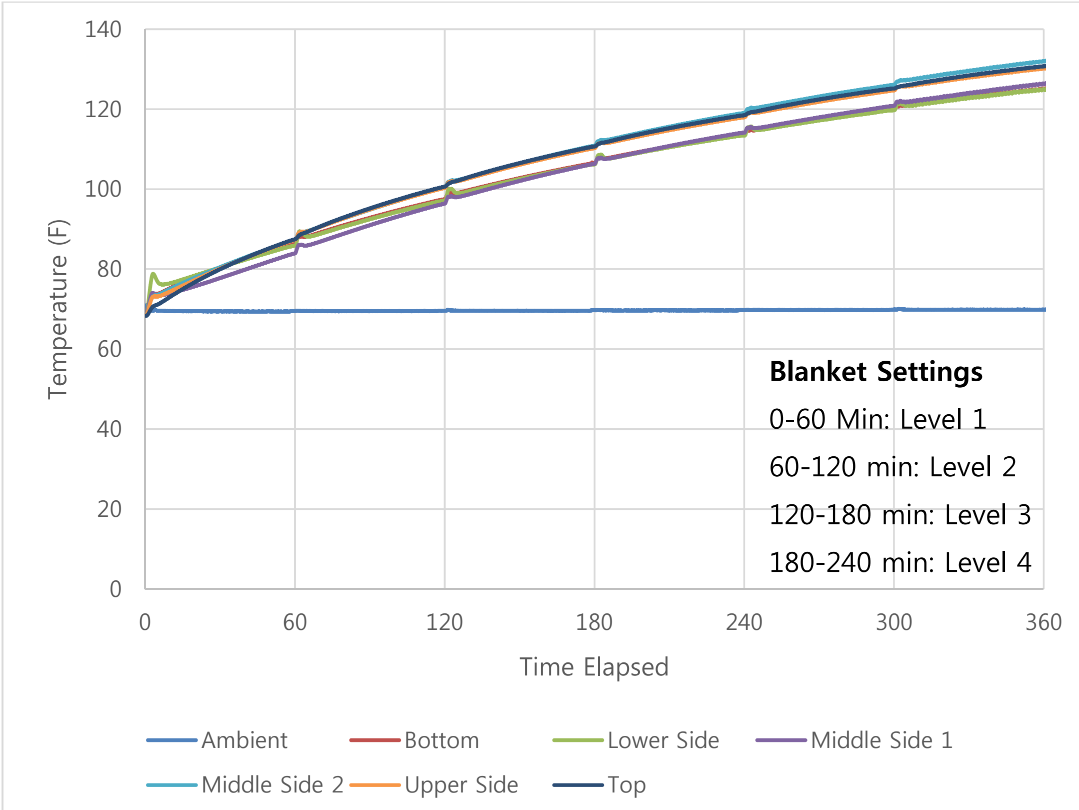

Figure 21. Temperature Measured Inside of the Blanket at Six Different Levels

Study was continued to determine the appropriate level of temperature to simulate 100°F inside the blanket. Among the six levels of temperature setting, Level 1 and Level 2 were selected to monitor the temperature at the surface of concrete cylinder covered by the blanket. Figure 22 and Figure 23 show the temperature in various locations of the cylinder at Level 1 and 2.

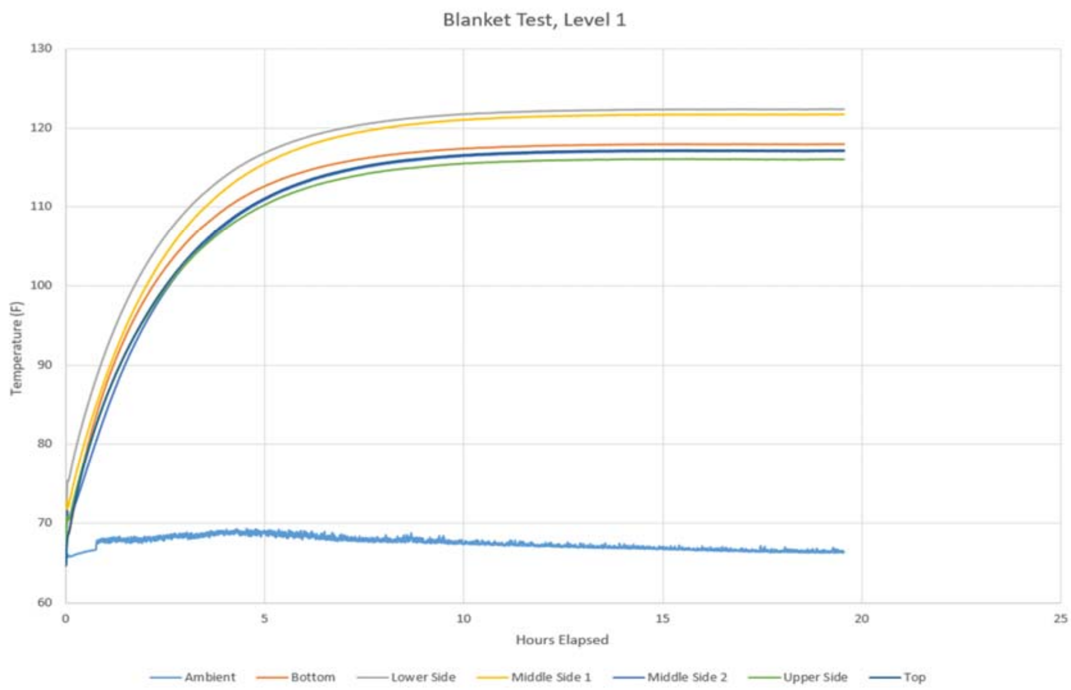

Figure 22. Temperature Measured Inside of the Blanket at Level 1

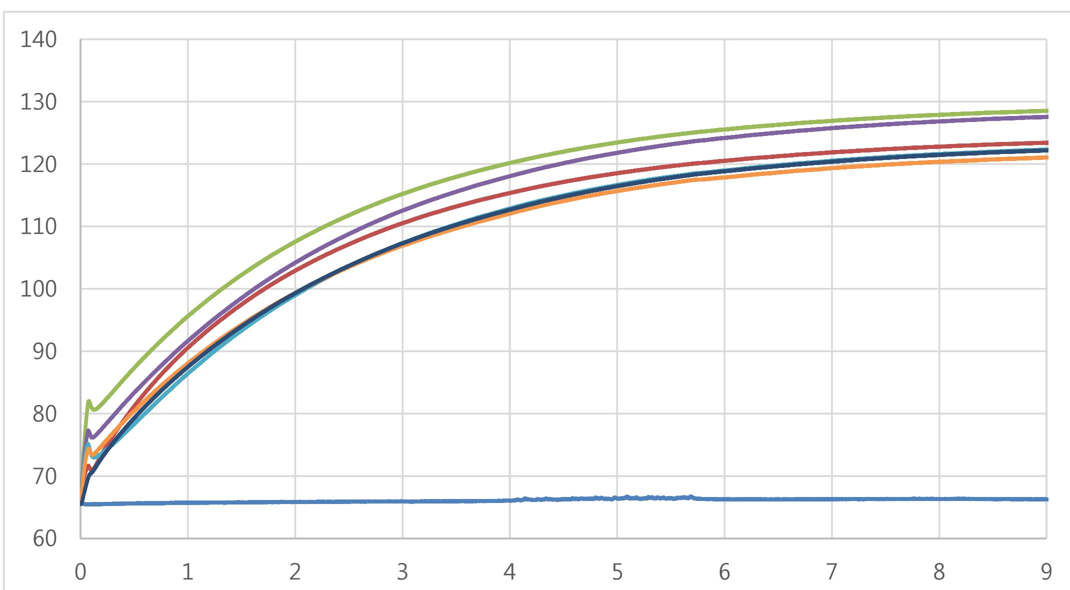

Figure 23. Temperature Measured Inside of the Blanket at Level 2

Both Level 1 and 2 started in room temperature and reached around 120°F after several hours. The temperature is somewhat higher than our target temperature (100°F), so we tried to cut off the power after 2 hours in Level 2. Figure 24 shows the temperature changes. This temperature setting and cut-off the power seems to be reasonable to simulate 100°F oven temperature, and will be used to monitor strength gain at early age.

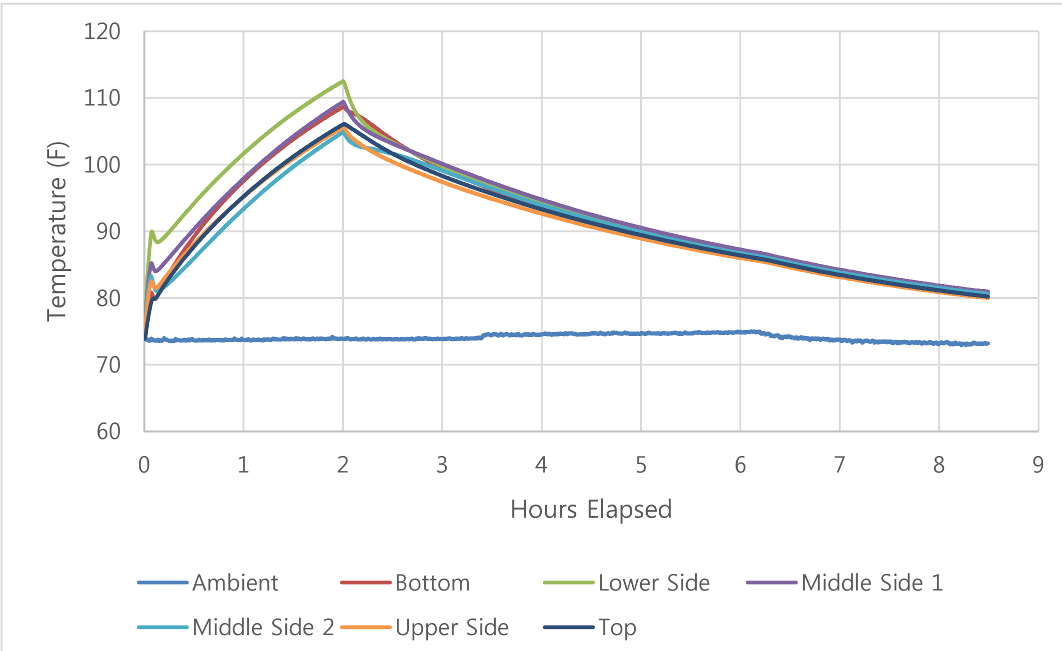

Figure 24. Temperature Measured Inside of the Blanket at Level 2 with Power Cut After 2 hours

It is scheduled to mix two mixtures selected in the VFC project and study the effects of warm blanket in the strength development. Oven drying is also separately conducted for the comparison.

Several batch of mix were made with the same mixture developed earlier and compared the strength development in three different curing conditions (ambient temperature, oven drying condition, and blanket curing condition).

Two concrete cylinders were wrapped with the blanket which kept the Level 2 temperature for two hours and turned off. Two themocouples were attached onto the two top of fresh concrete cylinders and one ambient temperature was also monitored during the test. Figure 25 shows the temperature during the first 16 hours. The sample 1 was took out for four hour compressive test and the other sample was kept for later test. The temperature on the concrete surface were increased up to 108°F at 2 hours and subsided once the blanket was turned off.

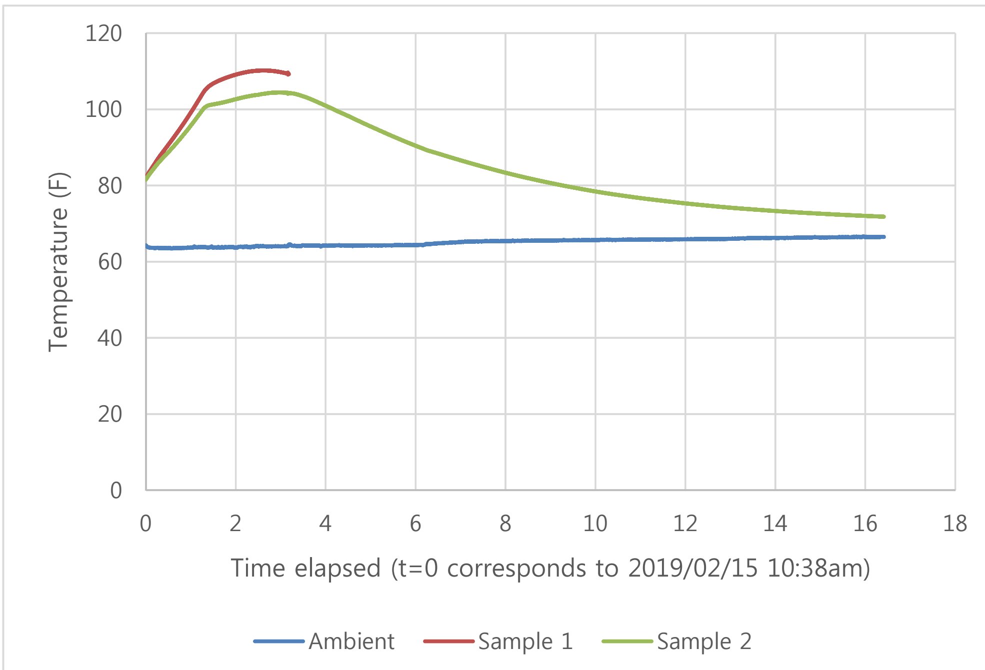

Figure 25. Temperature Measured Inside of the Blanket and Ambient Condition

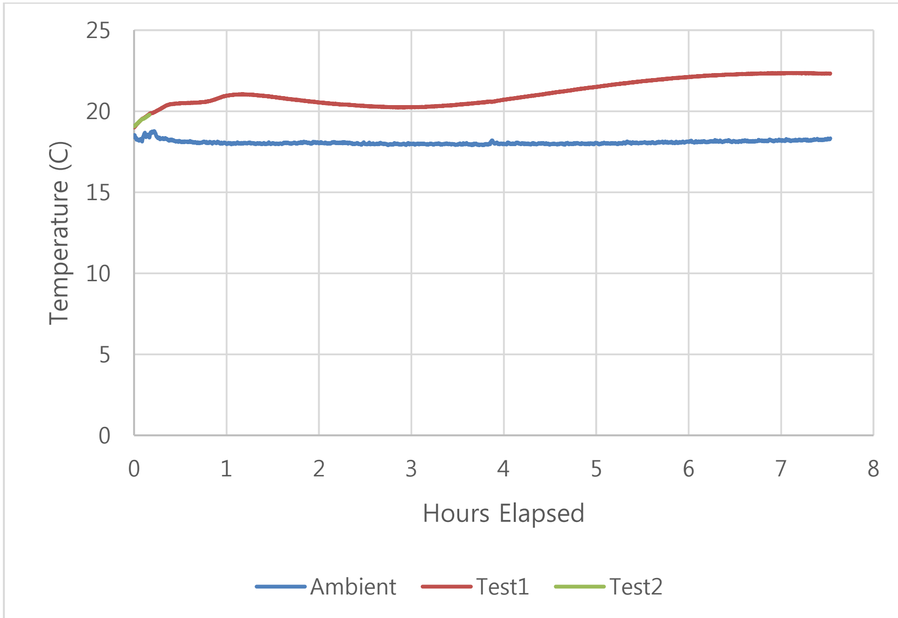

Figure 26. Temperature Measured Inside of the Blanket and Ambient Condition

The same measurement were made on March 22 test. Two cylinders were selected, and two thermos couples were mounted in the top surface of the cylinder. After 8 hours, the temperature data were collected and there was something wrong in the measurement of temperature in the cylinders. Figure 26 shows some data which shows a reasonable ambient temperature in the laboratory, but the temperature in test 1 did not show the peak at 2 hours. In case of test 2 specimen, the temperature is fluctuated, and we believe that the DAQ set-up was not made correctly. The correct procedure for the DAQ set-up and mounting thermocouples were instructed once again to prevent the same mistakes.

Figure 27. Heating Fan with temperature controlled up to 95°F.

It is scheduled to mix two mixtures selected in the VFC project and study the effects of heated pan in the strength development. Oven drying is also separately conducted for the comparison. Figure 3 shows a heated pan up to 95°F to be used in the following tests.

3. Modification of SL-B-1 Mixture

In an effort to produce other mixtures to be used in fast setting concrete, one of VFC mixtures provided by Dr. Feys (SL-B-1) was modified by having accelerator (40 oz) and slag as shown in Table 13. For the comparison, modified AC mixture is also presented. The modified SL-B-1 mixture is pretty much the same, but replacing part of cement I with slag. The accelerator was added with the amount of 40oz. According to the test program the compression tests of 4x8" cylinder were performed at a designated interval focusing on the early age, and Figure 28 shows the test results. For the purpose of comparison AC mixtures containing 40oz accelerator is also presented in the figure. It is clear that the strength development of SL-B-1 mixture is my slower that AC mixture. It is mostly contributed on the slow hydro reaction of slag, and the heat evolution of the SL-B-1 mixture is much slower than AC mixture. The peak of the heat in AC mixture was in 3 hours (October – December 2018 report), however, the heat peak of SL-B-1 mixture is about 5 hours after mixing concrete as shown in Figure 29. So the SL-B-1 mixture is not further considered in the fast setting concrete.

Table 13. Mixtures with different aggregate and w/c ratio

Material	AC mixture (1 yd^3)	AC mixture (1 ft^3)	Modified AC mixture (1 ft^3)	Modified SL-B-1 (1 ft^3)
Cement I	478.3	29.78	14.89	25
Cement III	-	-	14.89	-
Slag	-	-	-	1
Attapul-gite clay	2.4	0.15	0.15	-
19 mm agg.	517.5	32.22	32.22	32.22
9.5 mm agg	369.1	22.98	22.98	22.98
Sand	890.7	55.45	55.45	55.45
Water	159.8	9.95	8.955	8.955
SP	2.7	0.17	0.17	0.17
accelerator	-	**0**	**36 oz**	**40 oz**

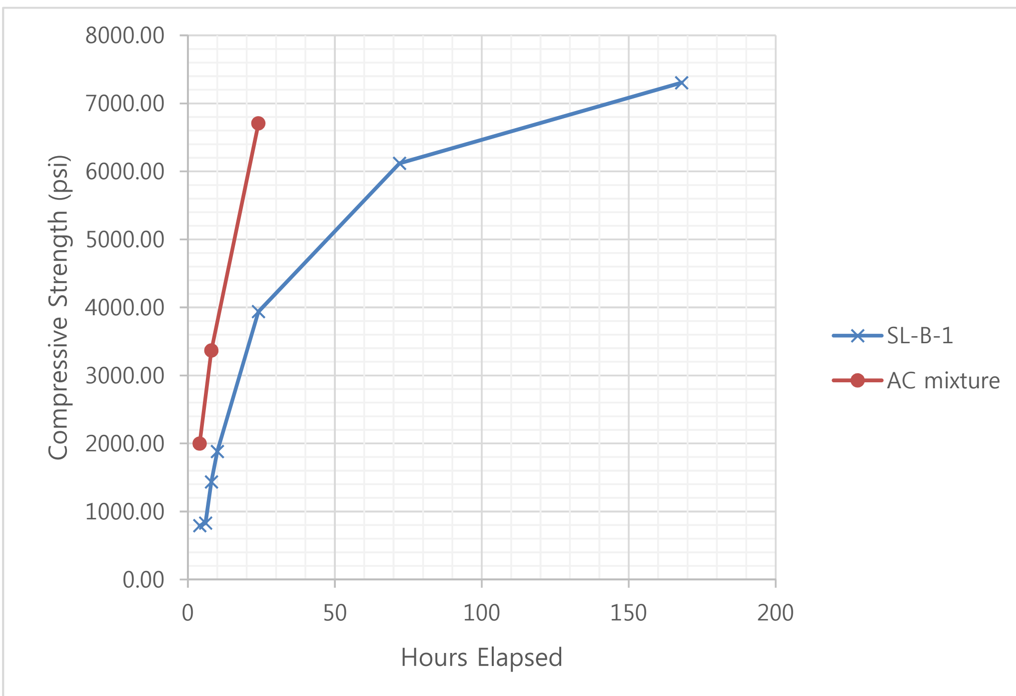

Figure 28. Strength Development of Concrete Mixtures (SL-B-1 modified and AC modified)

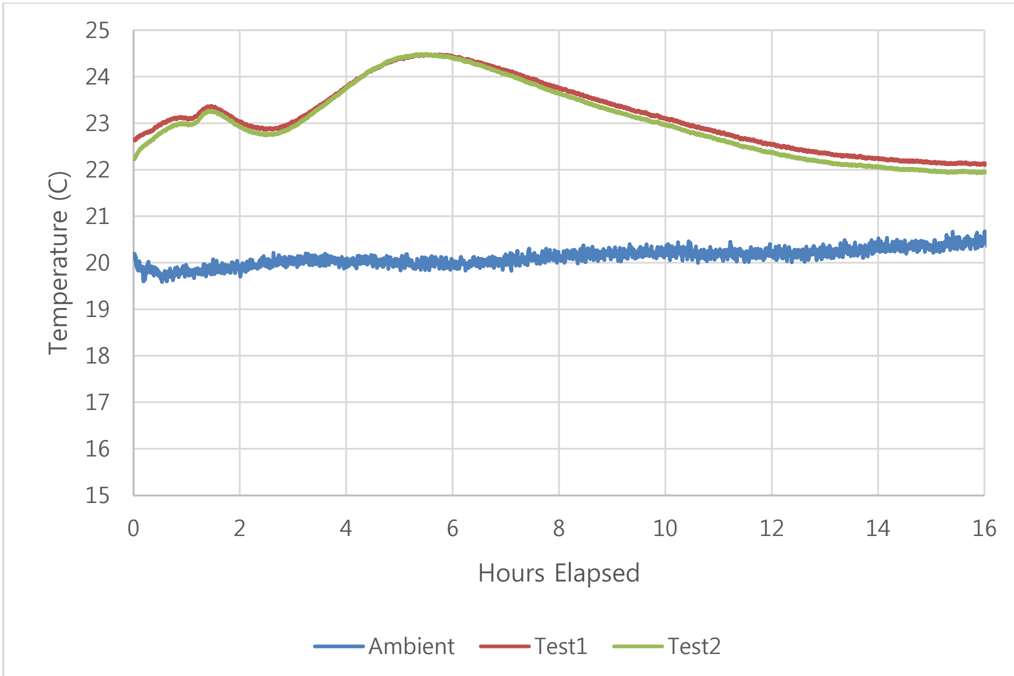

Figure 29. Temperature Measured Inside of the SL-B-1 Modified Concrete and Ambient Condition

4. Effects of Curing Conditions

The effects of heat due to electric blanket and heated fan on the strength development is presented here. Two concrete cylinders were wrapped with the blanket which kept the Level 2 temperature for two hours and turned off (Figure 30). A thermocouple was attached onto the top of fresh concrete cylinder and one ambient temperature was also monitored during the test. Four concrete cylinder were placed in front of heated fan and monitored temperature of the top surface of the cylinder (Figure 31). Four cylinders were placed in ambient condition and measured temperature also. Figure 32 shows the temperature during the first 19 hours. The ambient temperature was pretty constant at the 23 °C (73.4 °F). The specimen in front of heated fan made higher than ambient temperature, and was not high enough compared to the fan temperature (95°F). The temperature of the concrete surface is slightly higher than the specimen in ambient temperature as shown in Figure 32. The specimen wrapped with heated blanket reached higher temperature of 35°C (95°F) in 5 hours and gradually cool down.

Measured compressive strength of different curing conditions are presented in Figure 33. Even though the concrete in heated blanket reached high temperature, the concrete specimens in front of blanket achieved higher strength in the first 24 hours. It is believed that the blowing hot air help to dry the concrete cylinders while heated blanket did help much for drying. In the next tests, the concrete cylinders will be placed much closer to the heated fan to achieve higher strength development.

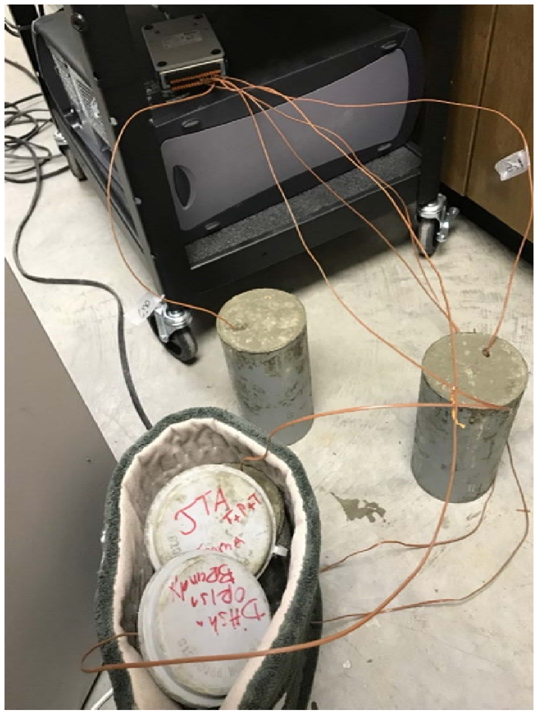

Figure 30. Specimens in heated blanket and ambient temperature

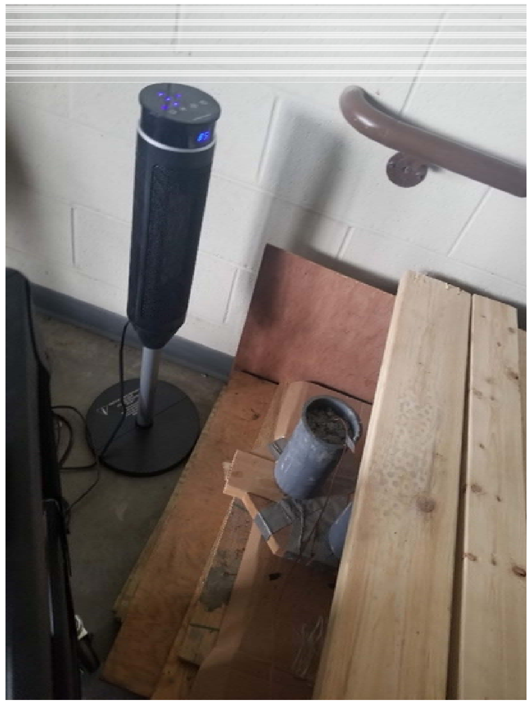

Figure 31. Specimens placed in front of heating fan with temperature controlled up to 95°F.

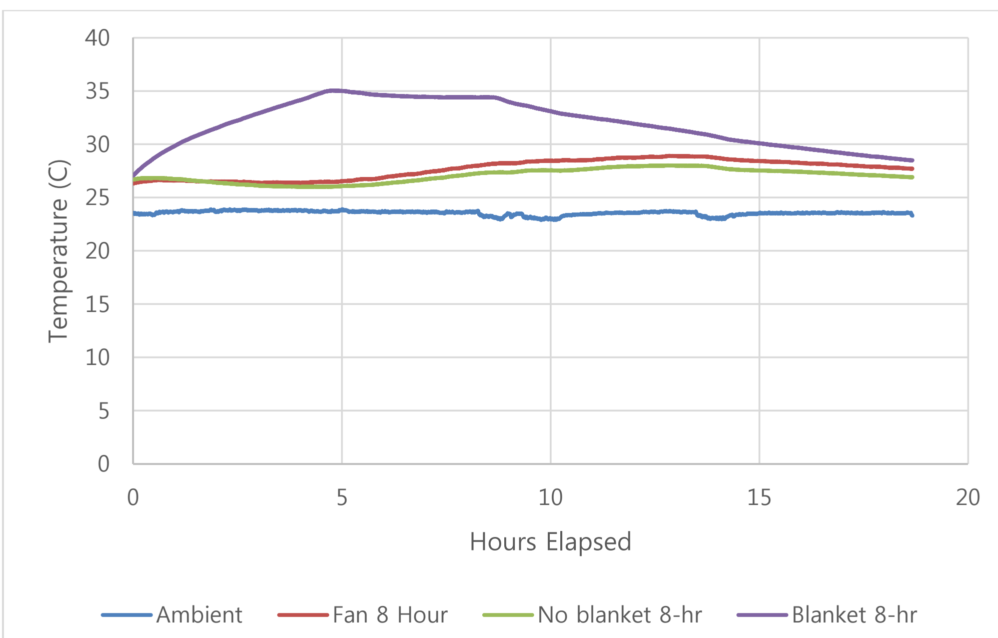

Figure 32. Temperature Measured on Concrete Surfaces of different Curing Conditions and Ambient

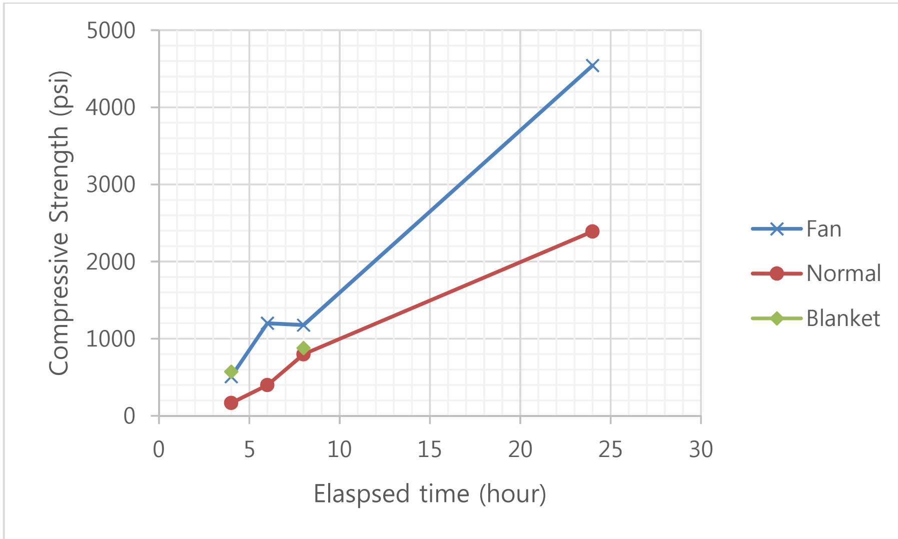

Figure 33. Measured Compressive Strength of Concrete Cylinders in different Curing Conditions

5. Adjustment of Water to Mitigate Dry Mix

For a couple of mixes, honeycomb was noticed in the concrete cylinder, and it became imperative to created mixtures with different quantities of water to determine consistency. Table 14 displays the results of the compressive strength after 4 hours and 8 hours. The 9.5 mixture was not done at 8 hours because the concrete was honeycombed.

Table 14. Displaying 4 Hour Mixture Results

Hours After Casting	Water	Compressive Strength (psi)			
		Oven	Fan	Ambient	Blanket
4 Hour	9.5 lbs	1364.3	875.3	604.8	-
	10 lbs	1273.2	1034.5	0	-
	10.5 lbs	1329.4	795.7	0	692.3
	11lbs	748.0	795.7	0	-
8 Hour	10 lbs	2756.4	2944.3	-	-
	10.5 lbs	3475.1	2785.1	-	2506.3
	11lbs	3183.0	1989.4	-	-

Based on the results from Table 14, mixtures were made 10 lbs. and 10.5 lbs. of water to determine the compressive strengths for a time period between 4 and 24 hours.

Table 15 and Table 16 display the compressive strengths for specimen cured in the oven, fan, ambient, and blanket.

Table 15. Compression Test Results of Mixture Containing 10.5 lbs of Water

Hours	Oven (psi.)	Fan (psi.)	Ambient (psi.)	Blanket (psi.)
4	550.7	241.90	196.5	422.5
6	1284.9	653.3	732.1	968.5
8	2188.0	1427.5	1445.5	-
10	2412.0	1965.4	1689.7	-

Table 16. Compression Test Results of Mixture Containing 10 lbs of Water

Hours	Oven (psi.)	Ambient (psi.)
4	1062.6	381.9
6	2430.8	1140.6
8	3183.0	1875.3
24	-	5238.3

The results are presented in the line chart as shown in Figure 34. Bond strength tests were performed with the 10 lbs. of water and the results shown in Table 17 and Table 18. Figure 49 compares the bond test strength and the regular concrete strength.

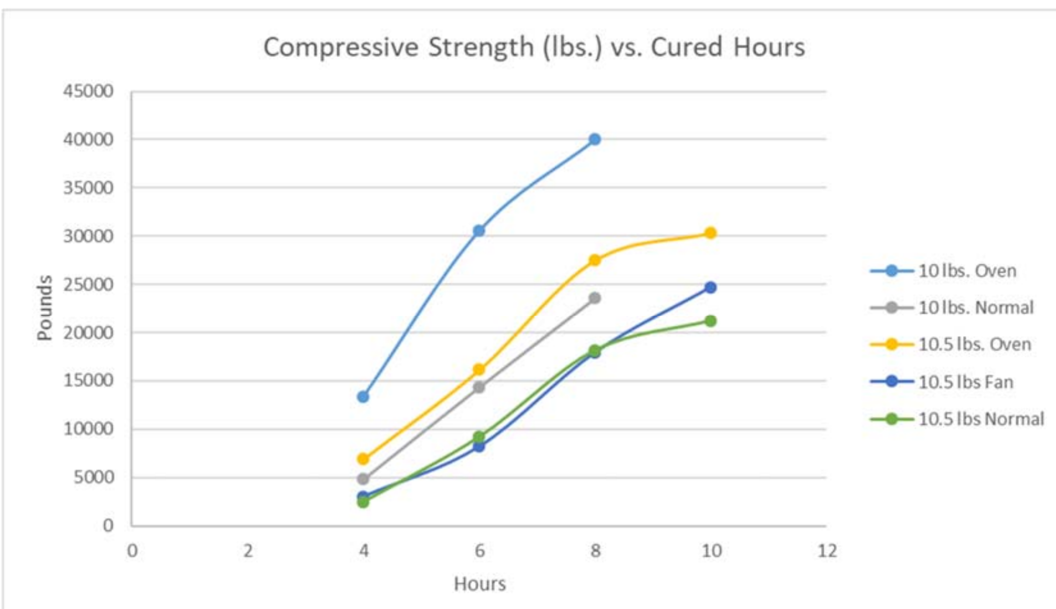

Figure 34. Comparing Compressive Strength for Different Curing Conditions

Table 17. Results of the Bond Strength Test

BOND TEST			Failed		
Hour	Oven (psi.)	Ambient (psi.)	New Concrete	Interface	Old Concrete
4	981.0	324.9	Yes O & A	Yes A	-
6	2604.2	1281.2	Yes O & A	Yes A	-
8	3521.3	1710.9	Yes O & A	-	-
24	5968.2	5465.4	Yes O & A	-	-

O- oven,   A- ambient

Table 18. Compressive and Bond Strength Test for 10 lbs. of Water

Compression Test (10 lbs. Water)					
Hour	Oven (psi)	Ambient (psi)			
4	919.5	286.5			
8	-	1830.2			
24	-	5908.5			
72	-	7699.4			
Bond Test (10lbs. Water)			Failed		
Hour	Oven (psi)	Ambient (psi)	New Concrete	Interface	Old Concrete
4	1111.8	437.7	Yes O & A	Yes A	-
8	2331.8	1171.0	Yes O & A	-	-
24	0	5894.5	Yes	-	Yes
72	0	6684.3	Yes	-	Yes

O- oven, A- ambient

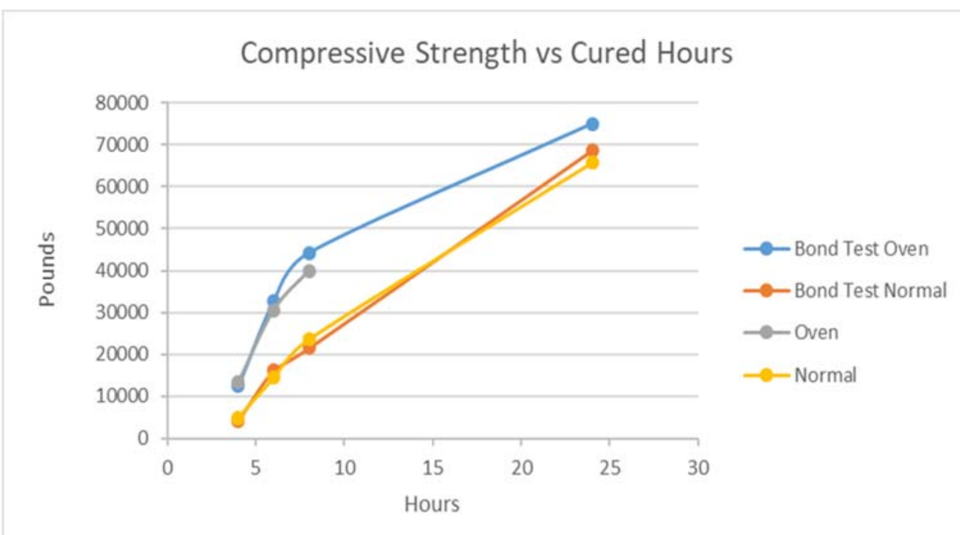

Figure 35 Comparing Bond and Regular Compressive Test

6. Discussion

The aim of this project was to develop a concrete mixture that was strong at 4 hours and was close to 4000 psi after 8 hours. Despite the 9.5 lbs. of water mixture having the strongest compressive strength, the final specimen was honeycombed as seen in Figure 36 therefore the 10 lbs. of water mixture as shown in Figure 37 was used.

Figure 36. 9.5 lbs of Water Mixture Specimen

Figure 37. 10 lbs. of Water Mixture Specimen

The curing methods for the concrete specimen included air drying (ambient), fan, oven and the blanket. Since the oven was not practical, the main focus was the blanket and the fan. The fan was placed in a heater mode to dry the concrete specimen however, despite numerous attempts the fan specimen compressive strengths were either 1000 lbs. above or below the air-dry specimen. The blanket was set at level 2 which was 2000-4000 lbs. lower than the oven specimen while the air-dry and fan were 8000-10,000 lbs. lower. The temperatures of the fan specimens were also closer to the air-dry specimens while the blanket specimens had high temperatures.

After the 8-hour test, it was found that the oven samples and the air-dry samples were approximately the same strength as seen in Table 17 for 24 hours. Therefore, the following 24-hour and 72-hour bond and compressive test following this result were only air-dry specimens as shown in Table 18.

1) <u>4 Hour Test</u>

Bond and Normal compressive strength test were done at 4 hours for every test mixture. Figure 38 displays the compressive strength specimen after they were tested. The air-dry specimen was very moist and cracked throughout the specimen while the oven specimen was dry and cracked at the bottom of the specimen. This was a result of the curing methods and temperatures that the concrete specimens were exposed to during curing. The bond strength tests were done with the same mixture using the same curing methods. Figure 39 (a) displays the specimen before and Figure 39 (b) displays one specimen after testing. Both specimens after 4 hours failed in the new concrete and cracked at the interface between the new and old concrete as seen in Figure 39. It can be inferred that after 4 hours there was a weak bond strength with the old concrete.

(a) Oven Specimen (b) Air-Dry Specimen

Figure 38. Specimen after 4 Hour Compression Test

(a) Before Test (b) After Test

Figure 39. 4 Hour Bond Strength Test Specimen

2) <u>6 Hour Test</u>

The 6-hour test was another important aspect of this experiment because road openings can be delayed to accommodate the drying of concrete. Similar to the 4-hour test, the air dry specimen was moist whilst the oven specimen was dry. However, both specimens cracked through the middle as seen in Figure 12 and 13.

(a) Air-Dry Specimen (b) Oven Dry Specimen

Figure 40. Specimens Tested after 6 Hour Curing

The bond test produced a similar specimen texture as shown in **Figure 41** however the interface had concrete spilled over as shown in **Figure 41** (a). The Air-dry specimen cracked at the interface and new concrete while the oven dry specimen cracked in the new concrete.

(a) Before Test (b) After Test

Figure 41. 6 Hour Bond Strength Test Specimen

3) <u>8 Hour Test</u>

Bond strength and Normal compressive strength test were done at 8 hours. The closest compressive strength to 4000 psi was the specimen in the oven which reached 3500 psi. The air-dry specimen cracked throughout the specimen as shown in **Figure 42** (a) and the bond strength test of air-dry specimen broken in the new concrete as shown in **Figure 42** (b). Figure 18 displays the oven specimens tested, the oven compressive strength specimen failed similarly to the air-dry specimen which was throughout the specimen while the oven bond strength specimen failed in the new concrete. It can be concluded that the bond strength between the old and new concrete is strong.

(a) Compression Test (b) Bon Strength Test

Figure 42. 8 Hour Air-Dry Specimen Tested

Figure 43. 8 Hour Oven Specimen Tested

4) <u>24 Hour Test</u>

As discussed above, the 24-hour test consisted of one air-dry compressive strength specimen and two air-dry bond strength test specimens. As shown in Figure 44, the compressive strength specimen failed at the top and side of the specimen and the bond test failed similarly but failed into the old concrete specimen on the side. In can be concluded that at 24 hours, the bond strength is strong, and the compressive strength of the new concrete is approximately equal or close to the compressive strength of the old concrete.

Figure 44. 24-Hour Specimens Tested

5) <u>72 Hour Test</u>

As discussed above, the 24-hour test consisted of one air-dry compressive strength specimen and two air-dry bond strength test specimens. Figure 45 displays the air-dry compressive strength test which failed straight down the side and Figure 46 displays a bond strength test specimen. The bond strength specimen failed throughout the specimen which meant the compressive strength of the combined concretes surpassed the two individual types compressive strength or the individual compressive strengths were unable to handle the pressure applied.

Figure 45. 72- Hour Compressive Strength Specimen

Figure 46. 72-Hour Bond Strength Specimen

Measurement of Elastic Modulus

According to Civil Engineering Terms modulus of elasticity is defined as the slope of the stress-strain curve within the proportional limit of a material. However, for concrete content, the secant modulus, as shown in **Figure 47**, is vital to the analysis. Secant modulus is the slope of the straight line drawn from the origin of axes to the stress-strain curve, which indicates some percentage of the ultimate strength. This project on concrete also tested the elastic modulus because it was a significant mechanical parameter reflecting the ability of the concrete to deform elastically.

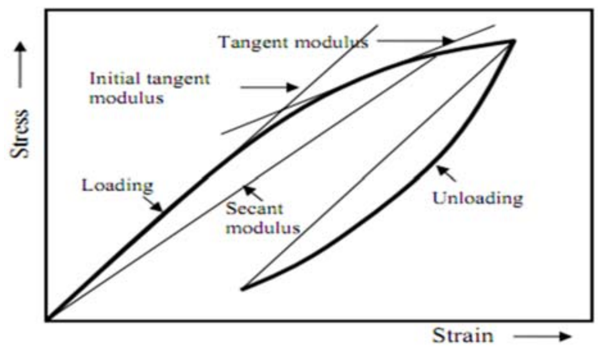

Figure 47. Stress vs. Strain Graph Displaying Loading

ASTM C469 / C469M - 14 Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression was used to provide a stress to strain ratio value and a ratio of lateral to longitudinal strain for hardened concrete at whatever age and curing conditions may be designated. The modulus of elasticity and Poisson's ratio values, applicable within the customary working stress range (0 to 40 % of ultimate concrete strength), were used in sizing of reinforced and non-reinforced structural members, establishing the quantity of reinforcement, and computing stress for observed strains. The equation used after results were measured was $E = (\sigma2 - \sigma1)/ (\varepsilon2 - \varepsilon1)$.

Elastic modulus of concrete cylinders at early age was measured according to the ASTM C469. 4x8" concrete cylinder is placed in the test frame and performed compressive strength test as shown in the Figure 48. The longitudinal and radial strain was measured and used to calculate elastic modulus of concrete. Figure 49 shows a test result. This test was performed for the early stage of high early strength concrete, 4 hour and 8 hour to understand stress development of the concrete. **Table 19** displays the results of a 4-hour normal specimen and Figure 49 displays the stress-strain relationship of the results from the specimen. The elastic modulus using the equation was calculated to be 118784.7 psi.

Table 19. Displaying Results for the Elastic Modulus Test

Pounds	V	H	Area	ε_x	ε_y	Stress	E_y	E_x	υ
370	0.0022	0.0006	12.57	0.00012	0.00036	29.4351	80277.7	245293.0	0.32
460	0.0024	0.0007	12.57	0.00014	0.0004	36.5950	91487.6	261393.3	0.35
616	0.0024	0.0007	12.57	0.00014	0.0004	49.0055	122513.9	350039.7	0.35
780	0.0026	0.0006	12.57	0.00012	0.00043	62.0525	143198.0	517104.2	0.27
1004	0.003	0.0007	12.57	0.00014	0.0005	79.8727	159745.4	570519.3	0.28
1198	0.0032	0.0007	12.57	0.00014	0.00053	95.3062	178699.2	680759.1	0.26
1531	0.0036	0.0009	12.57	0.00018	0.0006	121.797	202996.5	676655.1	0.3
1998	0.0037	0.0013	12.57	0.00026	0.00061	158.949	257756.5	611345.6	0.42
2002	0.0039	0.0014	12.57	0.00028	0.00065	159.268	245027.8	568814.6	0.43
2542	0.0035	0.0015	12.57	0.0003	0.00058	202.227	346675.7	674091.7	0.51
3216	0.0031	0.0032	12.57	0.00064	0.00051	255.847	495188.2	399761.3	1.23

Strain X (ε_x) *= Horizontal (H)/ 5*

Strain Y (ε_y) *= Vertical (V)/ 6*

Stress (σ)*= Pounds/ Area*

Elastic Modulus in y-direction (E_y) = σ/ε_y

Elastic Modulus in x-direction (E_x) = σ/ε_x

Poisson's ratio (υ) = $\varepsilon_x/\varepsilon_y$

Figure 48. Test Set-up for the Elastic Modulus of Concrete Cylinder

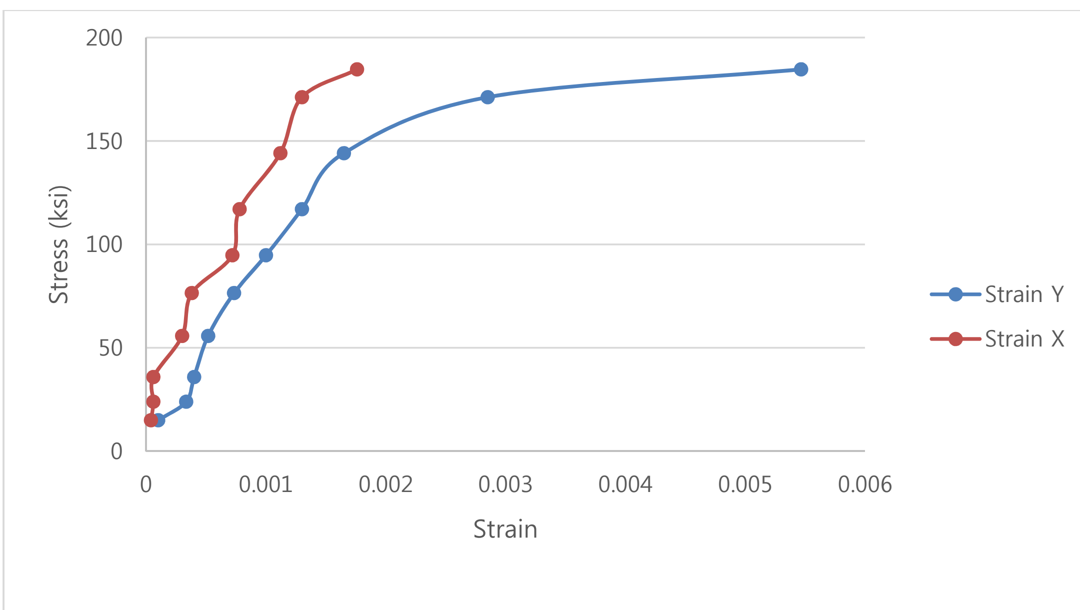

Figure 49. Stress-Strain Diagram of 4-hour Oven Cured Specimen

SUMMARY

Deterioration of pavements are problems due to high traffic volume, delay of rehabilitation, and lack of repair demands for better optimization of HPC for today's current standards and practices. The continuous rehabilitation and repair of damaged section of the pavements as a result of dry shrinkage mainly are of concern in many highway pavements in the U.S. Thus, internal curing is a technique examine throughout the research. Internally cured LWA in concrete has a higher degree of hydration resulting in reduced water absorption but is applicable when silica fumes are present to absorb extra surface water of the pre-soaked aggregate to achieve high early strength concrete. Silica fumes will help to absorb the unnecessary surface water yet improve performance. Its use thickens cement-aggregate bond which creates a stronger or additional binder for a large, coarse aggregates and fine aggregates to enhance properties.

Using Type III cement is a more appropriate cement due to its high fineness to produce early-age strength concrete. In tests comparing Type II and Type III, at significant rate Type III is more applicable for scenarios needing HPC for durability or HES concrete needed for rapid pavement repair in EOT. Initial set times using Type III were at 4-hour and strengths were achievable. However, not acceptable for today's infrastructure needs. Analyzing the lower strengths of concrete leads us to investigate further what resulted in such unsatisfactory early-age strength.

This research project consists of two folds. One fold is to develop high early strength using the LWA and RCA to minimize surface cracking. Different mix designs were used to determine which scenario best meets our goal of reducing cracking through drying shrinkage and high-early strength. This process including the addition and/or removal of aggregates, adding pre-soaked to non-pre-soaked aggregates, and implementation of silica fume as a SCM. It is due to thorough testing that a near 4000 psi strength of 3,847 psi can be achieved at early ages and at 8-hour stage 4,111 psi can be achieved. In using such scenarios when trying to decide how to increase the strength of each mix design, we understand that 12. 5 lbs of internal cured LWA (which accounts for 50% of fine aggregates) as a technique provides moisture throughout concrete to prevent cracking through dry shrinkage. Concrete specimens with pre=soaked aggregate were measured over 28-day period recorded a high durability and strength but lack early age strength characteristics. Thus, SCM like silica fumes (acting as an additional binder) is necessary to improve hydration of concrete. Silica fumes in this case is added to absorb surface water not drained or dried prior to mixing. LWA is a fine aggregate proven to absorb water but is so fine and permeable that additional surface water cannot be adequately dried in control climate conditions.

Hence, replacing 10% silica fumes increases performance of concrete in conjunction with 50% pre-soaked fine aggregate (LWA) is viable method for rapid road repair at 8-hour stages. Utilizing RCA in HES concrete is a probable material that supports studies of producing high-performance concrete whilst reducing the level of effort and environmental impact required to generate virgin aggregate for an equally durable if not more durable material for applications requiring HES concrete.

In conclusion, adding silica fumes are necessary to absorb extra surface water of the pre-soaked aggregate to achieve high early strength concrete. Silica fumes helps to absorb the unnecessary surface water yet improving performance. Different mix designs were used to determine which scenario best meets our goal of reducing cracking through drying shrinkage and high-early strength. In using such scenarios when trying to decide how to increase the strength of each mix design, we understand that water absorbed in internal curing technique does not evaporate or dry if properly drained but will desorb into concrete mixture allowing for greater hydration of concrete and an increase in cement will result in less dry shrinkage over time. Lastly, utilizing internally cured RCA is a viable, sustainable technique and material that has proven to support other studies of high-performance concrete being achieve whilst reducing early dry shrinkage and can be equally as durable if not more durable in pavement repair applications.

One of the difficulties of this study in early age strength was the high variations of the strength with a small change in the mixtures. Therefore further research should focus on the very strict mixing procedures that produce repeated results on the fresh and hardened properties of rapid repair concrete.

The second fold of this UTC project is to develop quick setting repair concrete material utilizing VFC mixtures developed at the Missouri University of Science and Technology. This effort focused on enhancing early strength of the repair concrete using four different methods (hot blanket, heating fan, oven dry, and ambient air). Keeping the maximum temperature of 100°F, the compressive strength of repair concrete were measured at early age. The results shows that the oven curing is the most effective, while heating fan and hot blanket shows some potential. Since the oven drying is not practical, the heating fan and hot blanket methods should be further studied with higher capacity of heating method. Bond strength tests were performed by casting the developed repair concrete on top of the aged normal concrete. 4x8” cylinder was used on the tests. The failed compressive strength is almost the same as the compressive strength of the repair concrete. The oven drying condition of the bonded specimen shows higher failure strength, and it once again shows a promising to enhance early age strength with curing.

RECOMMENDATIONS

A great efforts were made to develop rapid repair materials using RCA, LWA, silica fume, and type III cement. New adaption of the materials with mix proportioning has a potential to have cost-effective PCC repair material that may less problem in short and long term performance. Even though the efforts, the repeatability of the strength and making four hour strength requirements of DOTD has not been achieved yet.

The bond test results showed promise, but a better mixture should be found which has a strong 4-hour bond strength in case the roadway is opened earlier than expected. If this mixture is chosen for the roadway, the air-dry curing method would not work because the road will crack very quickly which is not in the best interest of the engineers or the drivers.

An efficient curing method should be found because the oven was not practical and the fan did not heat the concrete enough in the allotted time. The blanket would be a good option, but the financial resources would have to be put in place to purchase for the different parts of the road.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

LWA	Lightweight Aggregate
RCA	Recycled Concrete Aggregate
HES	High Early Strength
UTC	University Transportation Center
RE-CAST	Research on Concrete Applications and Sustainable Transportation
IC	Internal Curing
ACI	American Concrete Institute
(w/cm)	Water to Cementious Materials
SAP	Super Absorbent Polymers
HPC	High Performance Concrete
SRA	Shrinkage Reducing Admixtures
(w/c)	water/cement
SSD	Saturated-Surface Dry
LA DOTD	Louisiana Department of Transportation and Development
AC	Absorption Capacity
LTRC	Louisiana Transportation Research Center
CTE	Coefficient of Thermal Expansion
PCC	Portland cement concrete
JPCP	Jointed Plain Concrete Pavements
SCM	Supplementary Cementing Materials
VFC	Vibration-Free Concrete
FDR	Full-Depth Repai

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APPENDIX

APPENDIX A

Aggregate Preparation Procedure

1. Recycled Concrete Aggregate
    a. Sieve
    b. Weigh out 30.8 lbs. of sieved sample
    c. Wash RCA by putting the weighed and sieved sample in an empty bucket and filling the bucket with water about 2 or 3 inches above the RCA and shaking the bucket to wash off any lose dirt. Pour the dirty water out of the bucket being careful not pour out any of the RCA. Repeat this process until the water is clear after the bucket has been shaken.
    d. Once the water is clear leave the RCA submerged for 24 hours.
2. Sand
    a. Weigh out 12.51 lbs. of sand and place in an empty bucket
3. Light Weight Aggregate
    a. Weigh out 12.52 lbs. of LWA and place in empty bucket
    b. Slowly add water to LWA mixing as water is being added until entire sample is fully saturated
    c. Let soak for 24 hours

<u>Draining procedures</u>

After allowing RCA and LWA to soak for 24 hours drain both aggregates using the following procedures.

1. Place No. 4 sieve over a drain and pour RCA onto the sieve.
2. Place a pan over a drain and pour saturated LWA onto the pan. Slightly tilt the pan by propping it onto something stable and allow excess water to drain from LWA for 30 minutes to 1 hour.

Mixing procedures

1. Weigh out 2 ounces of Super P, 12 ounces of accelerator, and 58 ounces of water
2. Weigh out 15.6 lbs. of type III cement and silica fumes until total weight of silica fumes and type III cement together is 17.4 lbs.
3. Turn on mixer
4. Pour aggregates into the mixing drum in the following order
    a. RCA
    b. Sand
    c. LWA
    d. Type III cement
5. Add water by pouring the 58 ounces into the mixing drum slowly and as needed
6. Add super p
7. Add accelerator last
8. Once all materials are in the mixing drum and mixed completely scoop the sample into 6-8 cylinders using the following procedures
    a. Scoop sample into cylinder filling the cylinder to the halfway point
    b. Shake cylinder by carefully hitting it against the ground 3 or 4 times.
    c. Rod the cylinder to the bottom of the layer 25 times.
    d. Place the half full cylinder on the vibrator and vibrate until sample is compressed
    e. Fill the cylinder all the way and repeat steps “b” through “d”
    f. Top off cylinder and place on vibrator for about 1 minute.
    g. Put cap on cylinder and place it in the cooler
    h. Repeat steps “a” through “g” until all 6-8 cylinders are full.

APPENDIX B

Mixture Design for Internal Curing

Table B-1. Mixture Designs for Internal Curing - I

Mixtures	Mix 6 (6/7)	Mix 7 (6/10)	Mix 8 (6/14)	Mix 9 (6/16)	Mix 10 (6/21)	Mix 11 (6/24)	Mix 12 (6/28)
RCA-Dry (lb.)	30.8	30.8	30.8	30.8	30.8	30.8	30.8
RCA-Wet (lb.)	32.5	31.8	31.4	31.2	30.6	31.6	31.8
LWA-Dry (lb.)	12.51	12.52	12.51	12.51	12.51	12.51	12.51
LWA-Wet (lb.)	15.01	16.71	13.2	15.1	13.4	14	15.1
Sand (lb.)	12.52	12.52	12.52	12.5	12.5	12.52	12.52
Type III Cement (lb.)	15.6	15.6	15.7	16.1	16.1	16.1	16.1
Silica Fume (lb.)	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Water (oz.)	44	50	50	44	70	68	56
Super Plasticizer (oz.)	4	3	4	4	6	4	6
Accelerator (oz.)	12	12	12	12	12	12	16
w/c ratio (%)	39.94	47.79	25.23	32.07	28.3	36.54	39.61

Table B-2. Mixture Design for Internal Curing - II

Mixtures	Mix 13 (7/1)	Mix 14 (7/7)	Mix 15 (7/12)	Mix 16 (7/14)	Mix 17 (7/19)	Mix 18 (7/21)	Mix 19 (7/26)
RCA-Dry (lb.)	30.8	30.8	30.8	30.8	30.8	30.8	30.8
RCA-Wet (lb.)	30.9	31.4	31.4	32.2	31.2	33.4	33.6
LWA-Dry (lb.)	12.51	12.51	12.51	12	12	9	9
LWA-Wet (lb.)	13.9	15.1	16.4	13.6	14.3	11.1	11.4
Sand (lb.)	12.52	12.52	12.52	12.5	12.52	15.5	14
Type III Cement (lb.)	16.1	15.6	16.1	16.1	15.6	16.1	17.6
Silica Fume (lb.)	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Water (oz.)	52	50	50	47	50	44	44
Super Plasticizer (oz.)	4	10	10	16	12	10	10
Accelerator (oz.)	16	14	16	16	14	16	16
w/c ratio (%)	26.48	36.29	42.54	33.17	33.48	41.62	40.98

Table B-3. Mixture Design for Internal Curing - III

Mixtures	Mix 20 (8/2)	Mix 21 (8/9)	Mix 22 (9/23)	Mix 23 (10/14)	Mix 24 (10/28)	Mix 25 (11/3)	Mix 26 (11/10)
RCA-Dry (lb.)	30.8	30.8	30.8	30.8	30.8	30.8	30.8
RCA-Wet (lb.)	30.7	30	31.7	31.7	32.1	31.4	31.4
LWA-Dry (lb.)	9	5.02	12.52	2.02	12.52	12.52	12.52
LWA-Wet (lb.)	10.9	6.6	15.7	2.5	15.8	15.1	16.1
Sand (lb.)	12.52	12.51	12.51	12.51	12.51	12.51	12.51
Type III Cement (lb.)	19.1	23.1	16.1	25.67	16.1	16.1	16.1
Silica Fume (lb.)	1.8	1.8	1.8	2.23	1.8	1.8	1.8
Water (oz.)	54	70	50	84	50	40	37
Super Plasticizer (oz.)	10	10	10	10	10	10	10
Accelerator (oz.)	16	16	16	16	16	16	16
w/c ratio (%)	25.24	23.92	41.65	23.76	43.04	31.73	36.3

APPENDIX C

Measurements of Drying Shrinkage

Table C-1. Drying Shrinkage of Mix 1

Mix 1 (5/17/16)	Initial Reading w/ reference bar)*	Reading w/ specimen	Actual Length of Specimen
2-day	0.0100”	0.2613”	**11.625 + 0.2513 = 11.8763”**
7-day	0.0100”	0.2594”	**11.625 + 0.2494 = 11.8744”**
10-day	0.0100”	0.2587”	**11.625 + 0.2487 = 11.8737”**
14-day	0.0100”	0.2566”	**11.625 + 0.2466 = 11.8716”**
21-day	0.0100”	0.2554”	**11.625 + 0.2454 = 11.8704”**
28-day	0.0100”	0.2548”	**11.625 + 0.2448 = 11.8698”**
35-day	0.0200”	0.2646”	**11.625 + 0.2446 = 11.8696”**
42-day	0.0200”	0.2645”	**11.625 + 0.2445 = 11.8695”**
49-day	0.0200”	0.2645”	**11.625 + 0.2445 = 11.8695”**
56-day	0.0100”	0.2542”	**11.625 + 0.2442 = 11.8692”**
63-day	0.0200”	0.2643”	**11.625 + 0.2443 = 11.8693”**
70-day	0.0200”	0.2643”	**11.625 + 0.2443 = 11.8693”**
77-day	0.0100”	0.2547”	**11.625 + 0.2447 = 11.8697”**
84-day	0.0100”	0.2547”	**11.625 + 0.2447 = 11.8697”**

*Reference bar length: **11.625”**

Table C-2. Drying Shrinkage of if Mix 5

Mix 5 (6/1/16)	Initial Reading w/ reference bar*	Reading w/ specimen	Actual Length of Specimen
1-day	0.0100”	0.2510”	**11.625 + 0.2410 = 11.866”**
6-day	0.0100”	0.2487”	**11.625 + 0.2387 = 11.8637”**
9-day	0.0100”	0.2477”	**11.625 + 0.2377 = 11.8627”**
13-day	0.0100”	0.2471”	**11.625 + 0.2371 = 11.8621”**
15-day	0.0100”	0.2471”	**11.625 + 0.2371 = 11.8621”**
20-day	0.0200”	0.2565”	**11.625 + 0.2365 = 11.8615”**
27-day	0.0200”	0.2561”	**11.625 + 0.2361 = 11.8611”**
34-day	0.0200”	0.2559”	**11.625 + 0.2359 = 11.8609”**
41-day	0.0100”	0.2455”	**11.625 + 0.2355 = 11.8605”**
48-day	0.0200”	0.2554”	**11.625 + 0.2354 = 11.8604”**
56-day	0.0200”	0.2553”	**11.625 + 0.2353 = 11.8603”**
63-day	0.0100”	0.2459”	**11.625 + 0.2359 = 11.8609”**
70-day	0.0100”	0.2457”	**11.625 + 0.2357 = 11.8607”**

*Reference bar length: **11.625”**

Table C-3. Drying Shrinkage of Mix 6

Mix 6	Initial Reading w/ reference bar)*	Reading w/ specimen	Actual Length of Specimen
2-day	0.0100”	0.2523”	**11.625 + 0.2423 = 11.8673”**
7-day	0.0100”	0.2503”	**11.625 + 0.2403 = 11.8653”**
9-day	0.0100”	0.2494”	**11.625 + 0.2394 = 11.8644”**
14-day	0.0200”	0.2583”	**11.625 + 0.2383 = 11.8633”**
21-day	0.0200”	0.2574”	**11.625 + 0.2374 = 11.8624”**
28-day	0.0200”	0.2574”	**11.625 + 0.2374 = 11.8624”**
35-day	0.0100”	0.2474”	**11.625 + 0.2374 = 11.8624”**
42-day	0.0200”	0.2564”	**11.625 + 0.2364 = 11.8614”**
49-day	0.0200”	0.2564”	**11.625 + 0.2364 = 11.8614”**
56-day	0.0100”	0.2469”	**11.625 + 0.2369 = 11.8619”**
63-day	0.0100”	0.2465”	**11.625 + 0.2365 = 11.8615”**

*Reference bar length: **11.625”**

Table C-4. Drying Shrinkage of Mix 23

Mix 23	Initial Reading w/ reference bar*	Reading w/ specimen	Actual Length
3-day	0.0100”	0.2244”	**11.625 + 0.2144 = 11.8394”**
7-day	0.0100”	0.2229”	**11.625 + 0.2129 = 11.8379”**
14-day	0.0100”	0.2223”	**11.625 + 0.2123 = 11.8373”**
21-day	0.0100”	0.2218”	**11.625 + 0.2118 = 11.8368”**
28-day	0.0100”	0.2209”	**11.625 + 0.2109 = 11.8359”**
35-day	0.0100”	0.2205”	**11.625 + 0.2105 = 11.8355”**
42-day	0.0100”	0.2200”	**11.625 + 0.2100 = 11.8350”**
49-day	0.0100”	0.2198”	**11.625 + 0.2098 = 11.8348”**
56-day	0.0100”	0.2195”	**11.625 + 0.2095 = 11.8345”**

*Reference bar length: **11.625”**

Table C-5. Drying Shrinkage of Mix 24

Mix 24	Initial Reading w/ reference bar)*	Reading w/ specimen	Actual Length
3-day	0.0100”	0.2413”	**11.625 + 0.2313 = 11.8563”**
7-day	0.0100”	0.2403”	**11.625 + 0.2303 = 11.8553”**
14-day	0.0100”	0.2386”	**11.625 + 0.2286 = 11.8536”**
21-day	0.0100”	0.2379”	**11.625 + 0.2279 = 11.8529”**
28-day	0.0100”	0.2370”	**11.625 + 0.2270 = 11.8520”**
35-day	0.0100”	0.2370”	**11.625 + 0.2270 = 11.8520”**
42-day	0.0100”	0.2367”	**11.625 + 0.2267 = 11.8517”**

*Reference bar length: **11.625”**

Appendix. List of Participating Students and Activities

Post-doctoral Research Associate:

Dongkeun Lee

Research Associates:

Walid R. Alawan
Ronald S. Lee
Nathaniel D. Denu
Julesa C. Barnes

Minority students:

Toi F. Bonnet
Joseph A. Cotton (non-black)
Trenton J. Culbert
Joseph R. Delpit
Kiera S. Dorsey
Joshua G. Duncan
Cody E. Gay
Julian-Milan Green
Leroy Hunter
Michael A. Louis
Jamal Smiles
Eric T. Thompson
Raul K. Viera
Denita D. Walker (graduate student, female)
Jonathon R. Whisnant (non-black)
Tiffany White (female)
Clovis R. Williams
Dakota Williams (female)
Benjamin Zeno
Harry Pieterson

Graduate students:

Shiva Anumula

Denita D. Walker

Dakota Williams

Mustafa Najeeb

One of undergraduate student (Mr. Joseph Delpit) working on this project presented some research results in the 76th annual joint meeting of Beta Kappa Chi and National Institute of Science on March 28 in Fort Valley State University. He involved in this research since Summer 2018 and will continue through the summer 2019.