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Reducing the Risk of Cracking in High Volume Fly Ash Concrete by Using Internal Curing

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ABSTRACT

Sustainability has become an important issue in the concrete industry in recent years. One way to make concrete production more sustainable is through the use of alternative cementitious materials like fly ash. Fly ash is increasingly being looked at as a strategy to mitigate early-age cracking due to its reduced heat generation and slower rate of reaction. However, concerns about the rate of early-age strength development and longer curing times arise when high volumes of fly ash are used.

Internal curing may aide in solving some of these challenges. The use of internal curing may provide a method to utilize lower water-to-cementitious materials ratio (*w/cm*) materials to increase early-age strength and supply the necessary curing water. This paper reports some results of an on-going federal highway administration (FHWA) project dealing with the use of higher volumes of fly ash in transportation structures. This paper discusses the influence of HVFA on mechanical properties of the concrete. In addition, this work has introduced a new test method called the dual ring test which is used to quantify the early-age stress development when the concrete is prevented from shrinking freely. The results of this research show that high volume fly ash mixtures with internal curing provided sufficient early-age strength compared to a typical concrete bridge deck mixture design. Autogenous shrinkage and residual tensile stress are reduced in high volume fly ash mixtures with internal curing.

1.0 INTRODUCTION

Fly ash has been used in concrete production for many years as a simple way to improve the workability, durability and sustainability of concrete [1]. Fly ash has also been proposed as a method for mitigating the effects of early-age thermal volume change in concretes [2]. This is accomplished by replacing a portion of cement with fly ash. While a portion of the fly ash can react hydraulically like portland cement, a portion of the fly ash undergoes a pozzolanic reaction [3], in which the silica present in fly ash reacts with the calcium hydroxide formed in cement hydration, causing fly ash to react at later ages. This delayed reaction reduces the rate of heat evolution, which therefore reduces the temperature of the overall system at early ages. Recent research has shown that higher curing temperatures increase the potential for thermal cracking [4], thus suggesting that fly ash can mitigate early-age cracking in concretes by lowering curing temperature. The potential for mitigating early age cracking, together with the desire for improved sustainability, has led to an increased interest in replacing cement with higher volumes of fly ash (HVFA). Replacing cement with large volumes of fly ash (>40% by volume) can improve durability which can make concrete more sustainable and economical. The tradeoff to the benefits of fly ash is the slow early-age strength development associated with the slower reaction. One potential way to overcome early-age strength development is by utilizing lower water-to-cementitious materials ratios (*w/cm*). The use of low *w/cm* in concretes increases the early-age strength development of concretes by reducing porosity in the concrete, creating a tighter, stronger pore structure. Additionally, this pore structure improves the service life of the concrete. [5]

However a potential problem associated to low *w/cm* is the difficulty to properly implement external curing due to the potential for pore depercolation. Internal curing (IC) is one alternative to conventional curing that may overcome this problem [6]. IC is achieved by distributing a pre-wetted absorptive material (e.g., pre-wetted lightweight aggregate) throughout the cement paste [7-10]. Once the concrete sets, the water held within the absorptive material is released back to the paste [11]. The purpose of internal curing is to replenish the water consumed by the hydrating cement after set. If not replenished, the paste becomes water starved and begins to dry out pores, which generates capillary stress. This is known as self-desiccation. In High Performance Concretes (HPC), where the pore network is smaller and tighter, larger capillary stresses develop, according to Kelvin-Laplace equation (Equation 1), leading to bulk shrinkage.

$$\sigma = -\frac{2 \cdot \gamma \cdot \cos\theta}{r} \qquad (1)$$

where σ is the stress in the pores, γ is the surface tension of the pore solution, θ is the contact angle, and r is the radius of curvature.

Internal curing has a secondary benefit of increasing the degree of hydration by allowing more water to be available to the hydrating cement at early ages. This further tightens the pore structure, thereby reducing permeability and further improving durability. [5]

One method to provide internal curing to concrete is through pre-wetted lightweight aggregate (LWA) [7]. LWA is a porous material that absorbs and holds water that can be released into the pore network of the concrete at the appropriate time, increasing the degree of hydration and effectively preventing self-desiccation. All IC provided in this research was through the use of pre-wetted fine LWA, and mixture proportioning is based on the Bentz equation [7, 10].

IC and HVFA are two independent methods that can improve the durability and early-age cracking performance of concrete. The use of IC may provide a method to increase early-age strength gain and may enable the mixture to react for a longer time since water can be supplied to the concrete over a longer time period.

2.0 EXPERIMENTAL APPROACH

Fly ash reduces the heat developed due to the hydration reaction. This can result in decreased residual tensile stress development and reduced potential for thermally induced cracking. The thermal cracking behavior of the HVFA mixtures was quantified using the dual ring test. The dual ring test was specifically designed to account for expansion at early ages and to apply a nearly constant level of restraint during temperature changes [12]. This allows for the quantification and study of restrained shrinkage behavior due to thermal effects and autogenous deformations.

3.0 OBJECTIVES

This study describes the mechanical properties (i.e., compressive strength and modulus of elasticity) of a typical mortar that would be consistent of the mortar fraction of concrete used in standard Department of Transportation applications. These results demonstrate that HVFA mixtures and HVFA mixtures with IC provide sufficient early-age strength. The second part of the study reports results from the dual ring test which evaluates cracking potential. The goal of this research is to show that utilizing IC in conjunction with HVFA concrete mixtures may potentially produce the benefits of reduced shrinkage and shrinkage cracking without sacrificing early-age strength gain. The results indicate that when HVFA mixtures incorporate IC the cracking propensity can be reduced and the degree of hydration and durability can be increased. This shows benefits in using materials that are more sustainable.

4.0 MATERIALS AND EXPERIMENTAL PROCEDURE

4.1 MATERIALS

An ordinary portland cement (OPC) (ASTM C150-09 Type I/II) was used in this study, with a Blaine fineness of 476 m^2/kg, a specific gravity of 3.17, an estimated Bogue composition of 52 % C_3S, 18 % C_2S, 8 % C_3A, 9 % C_4AF, and a Na_2O equivalent of 0.5. A class C fly ash (ASTM C618-08a) was also used at 40 % and 60 % volume replacements of cement and a specific gravity of 2.63.Chemical analysis are summarized in Table 1.

Table 1. Chemical Composition of the Cement and Fly Ash Used in This Study

	Cement	***Fly Ash***
Class	I/II	C
Silicon Dioxide (SiO_2), %	19.97	38.71
Aluminum Oxide (Al_2O_3), %	4.81	19.15
Iron Oxide (Fe_2O_3), %	2.89	6.49
Sum of SiO_2, Al_2O_3, Fe_2O_3, %	27.67	64.35
Calcium Oxide (CaO), %	63.27	23.51
Magnesium Oxide (MgO), %	1.54	5.29
Sulfur Trioxide (SO_3), %	3.27	1.36
Pottasium Oxide (K_2O), %	0.38	0.58
Sodium Oxide (Na_2O), %	0.28	1.64
Loss on Ignition, %	2.85	0.30
Moisture content, %	-	0.11

The fine aggregate consisted of regular river sand with a fineness modulus of 2.71 and an apparent specific gravity of 2.58. Rotary kiln expanded shale (i.e., a fine lightweight aggregate) was used with a fineness modulus of 3.97 and a specific gravity (dry) of 1.38. The LWA was measured to have a 24 h water absorption of 15.9 % by mass, when this material was tested using the paper towel technique [13-14]. A high-range water-reducing admixture (HRWRA) was added at variable dosage by mass of cement in order to maintain the same slump in all mortars. It is interesting to note that the amount of HRWRA was reduced as the fly ash content was increased (see Table 2).

4.2 MIXTURE PROPORTIONING

Six different mixtures were utilized in this study. Each of the mixtures was designed to have a similar workability as determined using a mini-slump cone test. Four of the mixtures were mortars with a conventional fine aggregate (55 % by volume), different *w/cm* and different amount of fly ash replacing a volume of cement (designated in Table

2 as 0.42-0%, 0.30-0%, 0.30-40%, and 0.30-60% - with the number on the left representing *w/cm*, and the number on the right representing the volume fraction of fly ash replacing the same volume of cement). The mortar with highest *w/cm* (0.42-0%) corresponds to a typical bridge deck concrete mixture design used by many Departments of Transportation (DOT's). Both fly ash mortar mixtures were also prepared with a portion of the fine aggregate replaced by pre-wetted LWA. These mixtures are designated in Table 2 as 0.30-40%-L and 0.30-60%-L. The volume of mortar occupied by the LWA corresponds to 14.9 % and 14.5 % for the 40 % and 60 % fly ash mortars, respectively. It is important to note that though these designations are based on a total volume basis, the volume of aggregate (LWA and sand) remained constant at 55 % since only the sand was replaced with LWA. The amount of LWA was that necessary to eliminate self-desiccation, according to Bentz approach for determining the LWA replacement volume [7, 10].

Table 2 – Mixture proportions

Mortar Mixture	0.42-0%	0.30-0%	0.30-40%	0.30-60%	0.30-40%-L	0.30-60%-L
Volume Fraction of Aggregate, %	55	55	55	55	55	55
water/cementitious material (w/cm)	0.42	0.30	0.30	0.30	0.30	0.30
Cement, kg/m^3	612	731	453	307	453	307
Fly Ash, kg/m^3	0	0	252	384	252	384
Fly Ash, %	0	0	40	60	40	60
Water, kg/m^3	257	219	211	207	211	207
Water for IC, kg/m^3	-	-	-	-	38	37
Fine Aggregate, kg/m^3	1418	1418	1418	1418	998	1006
LWA, kg/m^3	0	0	0	0	236	232
HRWRA, g/100g cementitious material	0.0	0.5	0.2	0.1	0.2	0.1

1 Kg/m^3 = 1.69 lb/yd^3

4.3 MIXING PROCEDURE

The mixing procedure was performed in accordance with ASTM C305-06. The normal weight sand was oven dried and air cooled for 24 h before mixing, while the LWA was oven dried, air cooled, and then submerged in water for 24 ± 1 h prior to mixing. The volume of water used to submerge the LWA included both mixing water and the water the LWA would absorb in 24 h. The excess water (water not absorbed in 24 h) was then decanted and used as the mixing water. The fly ash and cement were conditioned for 24 h at room temperature.

The fine aggregate was added to a "buttered" mixer, along with a small amount of mixture water, and then mixed for a short amount of time to minimize dust. If LWA was used, it was added right after the normal fine aggregate and mixed with it for a short amount of time. The cement and fly ash (if any) were then added to the mixer. Water was then added, noting the time of water-to-cement contact, followed by the HRWRA. The materials were mixed for three minutes, rested for three minutes while the bottom of the bowl was scraped with a spoon, then mixed for an additional two minutes.

4.4 COMPRESSIVE STRENGTH

The compressive strength was determined in accordance with ASTM C192-07. A set of 100 mm diameter x 200 mm tall [4-in x 8-in tall] cylinders for each mixture was cast to study the compressive strength up to 91 days. The cylinders were cast in three lifts, being rodded 25 times and vibrated between each lift, then sealed and cured in a constant temperature chamber at 23 °C ± 1 °C [73.4 ± 1.8 °F].

4.5 MODULUS OF ELASTICITY

The modulus of elasticity was determined in accordance with ASTM C469-02. A set of 100 mm diameter x 200 mm tall [4-in x 8-in tall] cylinders for each mixture was cast to study the elastic modulus up to 91 days. The cylinders were cast in three lifts, being rodded 25 times and vibrated between each lift, then sealed and cured in a constant temperature chamber at 23 °C ± 1 °C [73.4 ± 1.8 °F]. The cylinders were fitted with a compressometer that had a linear variable differential transformer (LVDT) displacement transducer and tested on a 3000 KN [675 kip] hydraulic compression machine. Each sample cylinder was loaded to 40 % of its ultimate load, with the resulting slope of the stress-strain curve taken as the modulus of elasticity. On each day of testing, two cylinders were tested of every mixture with no cylinder being tested at more than one age.

4.6 SEMI - ADIABATIC CHAMBER

A semi-adiabatic chamber with a thermal conductivity of 0.019 w/m°K at 20 °C [68 ºF] was used to monitor the early-age temperature evolution of the three mixtures. A 150 mm diameter x 150 mm tall [6-in x 6-in] sample was cast and placed inside the semi-adiabatic chamber. The temperature of the sample was measured with a Type J thermocouple which was placed inside the sample at a depth of 75 mm [3 inches].The temperature was monitored for 4 days at 5 minute intervals.

4.7 DUAL RING

The restrained shrinkage behavior can also be quantified with the dual restraining ring test [12]. The dual ring operates by casting an annulus of mortar between two restraining rings in two lifts, being vibrated with a handheld vibrator after each lift. The temperature of the test is controlled by placing copper tubing coil that is connected to an ethyl glycol system on top of the rings and sample. Due to the low coefficient of thermal expansion of the rings (i.e., they are made of Invar), the dual ring test has the ability to retain a stable degree of restraint over varying temperatures. The rings, sample, and temperature control coil are sealed in a highly insulated chamber. The temperature of the ethyl-glycol is controlled through an external water bath. The rings are instrumented with four equally spaced CEA-00 strain gages that measure the strain developed in the inner and outer restraining rings. A data acquisition system was set up so that the strain and temperature of the rings was recorded every 5 minutes. The recorded strains are used to calculate the residual stress accumulation in the sample. The induced stresses from temperature changes can be used to show the reserve capacity and determine how near the specimen is to cracking.

5.0 RESULTS AND DISCUSSION

5.1 STRENGTH DEVELOPMENT

One concern associated with using HVFA mixtures is the strength development. When fly ash is added to concrete as a replacement of cement it is typical that lower early-age strengths are obtained (e.g. Figure 1).

It is important to recall that the reference mixture is the mortar with *w/cm* of 0.42. Mortar with a *w/c* of 0.30 containing 40% fly ash has equivalent 1 day strength, and 60% fly ash mortar has equivalent 14 day strength.

When internal curing (IC) is used with the HFVA mixtures the 1-day strength is slightly higher (yet nearly the same) however the later age strengths are greatly improved due to a higher degree of hydration. IC enhances the 1 d strength by 13 % and 61 % in the 40 % and 60 % fly ash mortars, respectively. The HRWRA dosage was the same in both IC mortars with respect to their non-IC mortars.

The strength results reported in this study prove the possibility of using IC-HVFA mixtures with sufficient early-age strength.

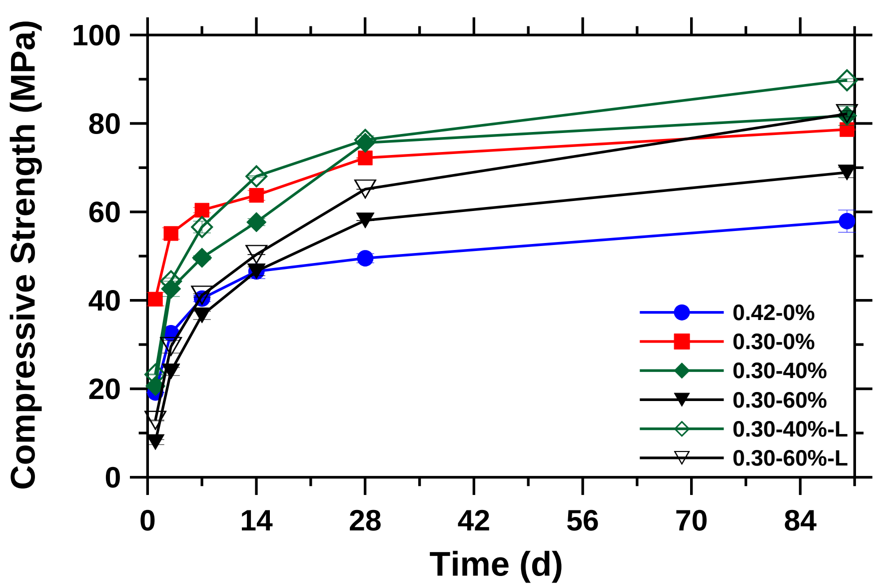

Fig. 1 – Strength Development as a Function of Time (Error bars represent standard deviation on the average of two samples) [15]

5.2 MODULUS OF ELASTICITY

The results of the elastic modulus testing are shown in Figure 2. The mortars with *w/cm* of 0.30 containing fly ash showed a reduction in modulus of elasticity when compared with 0.30-0% up to approximately 28 days. After that, their modulus of elasticity increased presumably due to the pozzolanic reaction. That means that both fly ash and LWA cause a reduction in elastic modulus at early ages. This reduction in elastic modulus is important when discussing the potential for restrained shrinkage. This lower stiffness makes the concrete more extensible and as a result the concrete will generate less stress when it undergoes the same shrinkage length change.

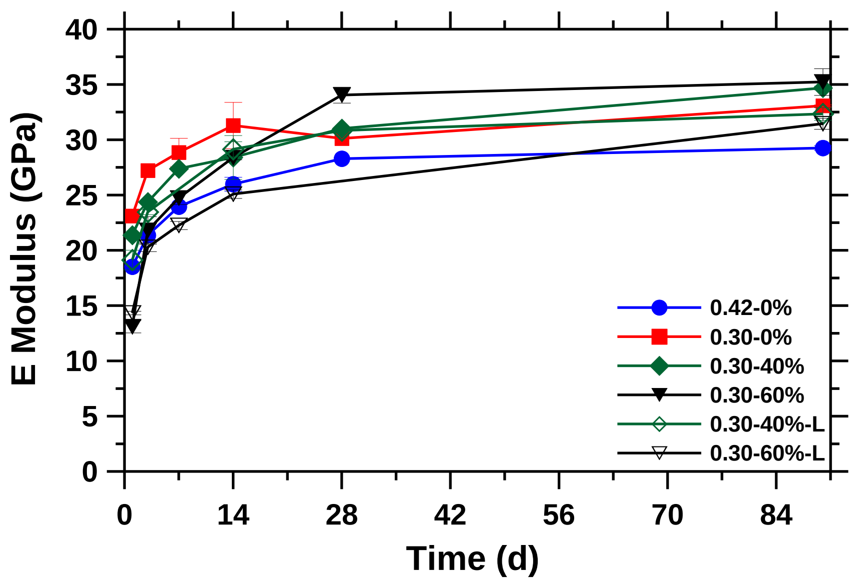

Fig. 2 – Modulus of Elasticity as a Function of Time (Error bars represent standard deviation on the average of two samples) [15]

5.3 SEMI-ADIABATIC CHAMBER

Early-age cracking can also be due to thermal effects which can be very common in high performance concrete due to the high cement content and high paste volume. As mentioned above, if the temperature increases, the rate of reaction (i.e. rate of shrinkage) will be also increased. HVFA mixtures are characterized for decreasing the temperature rise, as it is observed in Figure 3. The maximum heat that was developed by the 0.30-40% mortar is approximately the same as the reference 0.42-0% mortar; however a delay of 9 hours in the time that the peak temperature was noted for the fly ash mixture. A lower temperature rise was observed in the 0.30-60% mortar. A 10 ºC decrease in maximum temperature was observed for the 0.30-40% mortar, which would be expected to reduce the potential for thermal cracking of concrete structures. IC does not significantly change the temperature profile, which means that the controlling factor in the heat evolution of the mixture is the fly ash.

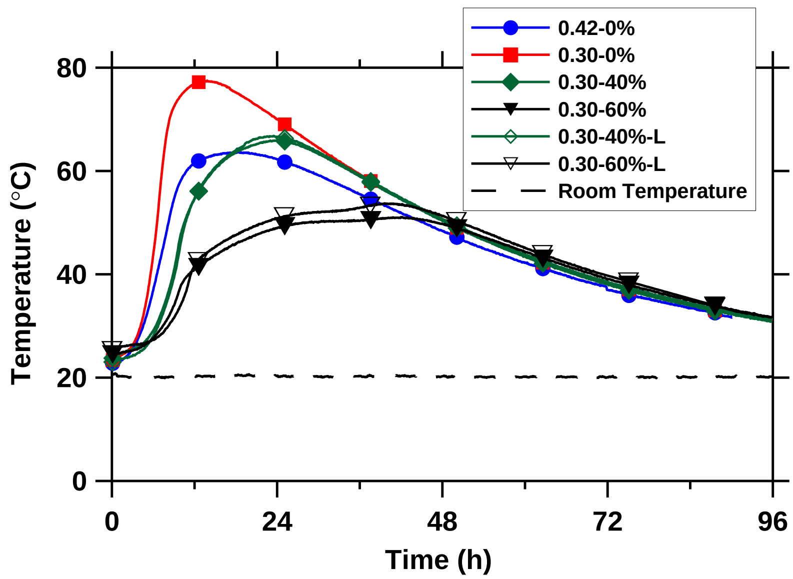

Fig. 3 – Semi-Adiabatic Temperature Profiles

These temperatures profiles could be generated in the dual ring in order to see the benefits that HVFA mixtures have not only due to the slower rate of reaction, but also due to the lower change in temperature that would induce less thermal stresses in practice and make these concretes less likely to experience thermal cracking. This will be the aim of future research.

5.4 DUAL RING

The dual ring test was utilized to study the effects of fly ash and IC on restrained shrinkage. To do so, each of the cast specimens were held at constant temperature of 23 °C ± 0.2 °C [73.4 ± 0.4 °F] for 2, 4, or 7 days, at which point the temperature was dropped at a constant rate of 2 °C/hour [3.6 °F/hour] . As the temperatures of the specimens were dropped, a sharp increase was observed in the residual stress. In some samples, this increase in stress reached the tensile strength of the sample which resulted in cracking, shown by the instantaneous drop in stress in the figures. Figure 4 shows a comparison of the 7 day residual stress plots of the 0.30-0%, 0.30-60%, and 0.30-60%-L mixtures. From this data, the residual stress and the reserve capacity of the material can be utilized to assess the cracking capacity of the mixtures.

The effects of utilizing HVFA replacement in the mixture can be assessed by comparing the 0.30-60% mixture with the 0.30-0% reference mixture. At 7 days, the 0.30-60%

exhibited a 57% average reduction in residual tensile stress. This reduction can be attributed directly to the high volume of fly ash replacement in the system. The fly ash reacts at a slower rate than the cement it replaced, leading to a slower rate and quantity of shrinkage, thus reducing the residual stress accumulation. Unfortunately, the reduction in residual stress comes at the cost of early-age strength, as discussed in Section 5.1.

The effects of including LWA for the purpose of internal curing on residual stress can be assessed by comparing the 0.30-60% mixture with the 0.30-60%-L mixture. The fly ash mixture with internal curing resulted in relatively low residual stress accumulation when held at a constant temperature, an 86% reduction in residual stress over the reference mixture and a 68% improvement upon the 0.30-60% mixture. This can be attributed to a low modulus of elasticity, increased stress relaxation due to creep as a result of IC with LWA [16], and the significant reduction in autogenous shrinkage from the inclusion of IC [15]. The result is a material that has the benefits of a low *w/cm*, such as increased early-age strength and reduced permeability, while not incurring the detrimental effects of restrained autogenous shrinkage.

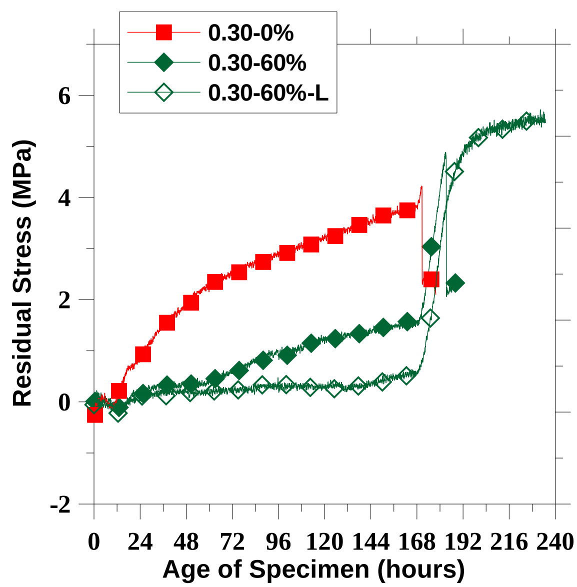

Fig. 4 – 7 Day Residual Stress Comparison

The increase in stress due to thermal volume change, induced by reducing the temperature, can be used to quantify how close the specimen was to cracking. This excess stress, termed reserve stress, is the measure of remaining tensile stress capacity that the specimen has. A comparison of the reserve stress of each mixture can be seen in Figure 5. In some instances, the sample was unable to be cracked, signified by the arrow symbolizing the potential for higher capacities than measured. At early ages, the mortars have a relatively low modulus of elasticity and have yet to undergo significant residual stress development, which results in larger quantities of reserve stress. As shrinkage occurs in the system, the residual stress developed begins to reduce the net effective tensile capacity of the sample, thereby reducing the reserve capacity. The use of HVFA replacement alleviates some of the residual stress accumulation at early ages, but the slower reaction reduces the overall tensile capacity of the material. The resulting effects are roughly equivalent cracking capacities between the 0.30-60% mixture and the 0.30-0% mixture at early ages. At 7 days, the reduction in shrinkage due to the hydration of cement in the 0.30-60% mixture results in 6.6 times the reserve stress over the reference mixture.

When IC is utilized, the residual stresses are significantly reduced, resulting in a material that has not experienced a reduction in the net effective tensile capacity. Since damage from shrinkage is not incurred, the material is much more resilient toward cracking, and most importantly, the samples do not experience a reduction in reserve capacity over time, but rather an increase due to the development of strength at later ages. At 7 days of age, the 0.30-60%-L mixture showed a reserve capacity of 10 times that of the reference. These results demonstrate that HVFA replacement with the inclusion of IC can be effectively used to improve the cracking capacity of concretes.

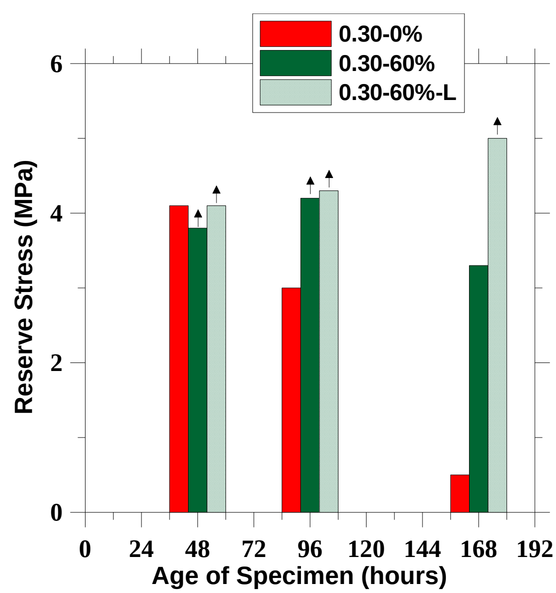

Fig. 5 – Reserve Stress Comparison at 2, 4, and 7 Days of Age

6.0 CONCLUSIONS

High volume fly ash concretes are used in conjunction with internal curing (i.e., through pre-wetted lightweight aggregate). Reducing the *w/c* of the HVFA mixtures produced sufficient early-age strength in comparison to a typical mixture used in Department of Transportation applications. When IC was applied to the low *w/c* HVFA mixtures with IC showed a reduced potential for early-age cracking. High volume fly ash was shown to have a slight increase in the capacity for thermally induced cracking at early ages, while the inclusion of pre-wetted lightweight aggregate was shown to significantly reduce residual stress accumulation and increase the cracking capacity of concretes. The results of this study show that HVFA replacement with the inclusion of IC is a feasible method of improving the sustainability and durability of concrete.

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8.0 DISCLAIMER

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