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Development and Characterization of Ultra-High Performance Concrete with Slag Cement for Use as Bridge Joint Material

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Abstract— The purpose of this study was to develop non-proprietary, cost-effective ultra-high performance concrete (UHPC) mix designs able to obtain comparable mechanical properties to commercially available products while limiting the cement content. First, UHPC mixes were developed using materials easily obtained in the state of Oklahoma. Then, the three top performing mixes were further studied by evaluating compressive strength with and without heat curing, modulus of rupture, and modulus of elasticity. A non-ASTM heat curing procedure was used to mimic potential heat curing temperatures possible in the field to assess the behavior of the in-place material. Results showed that 36 hours of heat curing was optimal for compressive strength, an unusual modulus of rupture crack pattern was observed suggesting additional energy absorption capabilities, and the modulus of elasticity was consistent with previous research. In conclusion, non-proprietary UHPC mix designs containing high replacement levels of slag cement can obtain comparable performance to proprietary mixes.

Keywords— ultra-high performance concrete; mix design; mechanical properties; slag cement; steam curing

1. Introduction

Conventional concrete is one of the most widely used structural materials in the world. It is a cost-effective material that is relatively easy to make, transport, and place. However, concrete has its limitations when it comes to strength gain and durability. There is currently a significant effort in the research community to mitigate these issues. One solution to both issues is the use of ultra-high performance concrete (UHPC). For a concrete to be classified as UHPC, the Federal Highway Administration (FHWA) developed the following guidelines; a water-to-cementitious material ratio of less than 0.25, a minimum compressive strength of 150 MPa, a mix design incorporating fibers to protect against brittle failure, and a post-cracking flexural strength of at least 5 MPa [1]. The enhanced mechanical and durability properties of UHPC make a strong case for this material replacing conventional concrete in selective structural applications. However, UHPC is known for its very large cement content, which exacerbates the carbon footprint issues associated with conventional concrete.

Currently the most widely used and commercially available UHPC product is Ductal®, produced by LafargeHolcim. This product has been proven to exceed the FHWA requirements for UHPC [2]. However, its use has been limited due to a cost of approximately $3,000 per cubic yard, which is nearly 30 times more expensive than conventional concrete. This issue has led many organizations to develop less costly UHPC mix designs that are viable alternatives to the commercially available products.

There have been numerous efforts to duplicate the performance of commercially available products using local materials. One such study was conducted by the FHWA wherein researchers used materials available in the northern regions of the United States to develop non-proprietary UHPC mix designs with compressive strengths that exceed the FHWA requirements. The mix designs used cement: silica fume: supplementary cementitious material (SCM) ratio of 1: 0.25: 0.25, water-to-cementitious material ratios of 0.2-0.3, an aggregate: cementitious ratio of 1.0-2.0, and a fiber content of 1.0-2.0% by volume. The researchers were able to create seven different mix designs that exceeded the FHWA UHPC strength requirements, while one was able to achieve a 200 MPa compressive strength [3].

Further study was also conducted on the use of high replacement levels of cement with SCMs. Researchers developed mix designs with water-to-cementitious material ratios of 0.3, 0.33, and 0.37. Various mix designs were developed ranging in different replacement levels of cement with SCMs, with the largest replacement level being 70%. All mix designs were compared to a corresponding mix design with the same water-to-cementitious ratio and 100% cement. Results showed that, at even up to 70% replacement, several mix designs with low water-to-cementitious ratios had comparable compressive strengths as the 100% cement mix designs. However, the water-to-cementitious material ratios were higher than the FHWA prescribed limits and no mix design was able to exceed 90 MPa in compressive strength [4].

Curing conditions have also been shown to have a large impact on the strength and durability of UHPC. One study examined the effects of various curing conditions on the strength of reactive powder concrete, a form of UHPC consisting of cement, silica fume, and quartz powder as the dry ingredients. The mix design was subject to different durations of curing at 20°C, 60°C, and 90°C, with some specimens completely submerged in water and some steam cured. The effectiveness of each curing condition was evaluated by comparing the resulting compressive strengths. The results show that higher temperature curing conditions for up to seven days improved the strength over curing at room temperature. Also, there was no significant difference between steam curing and water curing when temperature was held constant [5].

Despite the cost of Ductal®, several construction projects have used this product. One of the first full-scale applications of UHPC was using the material for the bulb-tee girders on a bridge in Iowa in 2006. Several other vehicle and pedestrian bridges used Ductal® in large quantities [6]. Also, a special product called Ductal® NaG3 TX was used as an overlay material on another bridge in Iowa due to its outstanding durability properties [7]. UHPC has also been found to have outstanding performance as a connection material between adjacent box girders [8]. While there have been many instances where UHPC was used in the field, the use of more cost-effective, locally available mix designs can make this material an appealing option for more widespread use. The abovementioned studies have determined the behavior of UHPC in both lab curing and uncured conditions. However, the behavior of UHPC under field heat curing conditions have not been thoroughly studied. With the difficulty of obtaining lab heat curing conditions in the field, it is important to understand the behavior of UHPC when subject to an environment similar to field curing conditions.

UHPC has nearly unlimited potential for use as a structural material. Its implementation by the Oklahoma Department of Transportation (ODOT) is mainly inhibited by its cost. As an alternative, ODOT commissioned the University of Oklahoma to develop a non-proprietary UHPC mix design using materials that can be easily and inexpensively purchased in or shipped to the state of Oklahoma. Furthermore, emphasis was placed on developing mix designs with high levels of SCM's to lower the mix cost by limiting the cement content.

2. Experimental Study

The following section outlines the experimental study used to develop a non-proprietary UHPC mix design and determine its mechanical properties.

A. Materials

One method for improving the mechanical properties of UHPC is by using various cementitious materials with differing particles sizes and shapes to increase the dry density of the combined materials. This is beneficial since the water-to-cementitious material ratio is so low, not all of the cementitious material is hydrated, leaving it to act as an aggregate in the mix. The UHPC mix designs developed in this study use a combination of cement and SCMs with differing particle sizes to create the binder paste. One benefit to using various SCM's in UHPC mixtures is the variation in particle size to facilitate density improvements. Two different cement types, Type II and Type III, were used from two different manufacturers. The Type II cement was produced by Ash Grove. The Type III cement was produced by Buzzi Unicem. The Class C fly ash used was produced by Headwaters Resources. The ground-granulated blast-furnace slag (GGBFS) was produced by LafargeHolcim. The silica fume used in this study was undensified and produced by Norchem. The product VCAS™ 140 White Pozzolans was produced by Vitro Materials. This product is much more expensive than GGBFS and, while similar, was evaluated due to its more consistent gradation and chemical composition. Due to the low water content of UHPC, a high-range water reducer (HRWR) was used to improve workability. The HRWR chosen for this study was Glenium 7920, produced by BASF.

As with most UHPC, there was no coarse aggregate used in these mix designs. The fine aggregate used in this study was a fine masonry sand meeting ASTM C33 and provided by Metro Materials. Lastly, UHPC requires the use of steel fibers to counter the brittle behavior of the concrete. Stainless steel, Grade 430, Flex-Ten® steel fibers produced by D&C Supply Co., Inc. were used in this study. The fibers were 25 mm long, with an aspect ratio of 47. The steel fiber dosage was 2% by volume.

B. Mixing Procedure

UHPC requires a specific mix procedure due to the small particle sizes, very low water-to-cementitious material ratio, and high HRWR dosage. High shear mixers are beneficial when mixing UHPC due to the energy required to break apart the very small particles and complete the wetting process. Different mixers were used for the mix development and the mechanical property test specimens. For the mix development process, where smaller quantities of material were required, a Blakeslee planetary mixer was used to make 0.003 m^3 mixes. For the mechanical property specimens, an Imer Mortarman 120 Plus electric mortar mixer was used to make 0.04 m^3 mixes. The same mixing process was used for both mixer types.

For the first step in the mixing process, the dry ingredients were added to the mixer for 10 minutes to blend the materials together. Then, half of the HRWR was added to the mix water and the water was slowly poured into the mixer over the course of 2 minutes. The concrete was allowed to mix for 1 minute before the remaining HRWR was added. Once all of the ingredients were added, the mixer was allowed to run until the HRWR was activated and the concrete transformed from a powder to a fluid mass. This step in the process took approximately 5 to 10 minutes. Once the fluid state was achieved, the steel fibers were added and allowed to mix for an additional 2 minutes. The concrete was then ready to be placed in the specimen molds.

C. Mix Development Process

The mix development process was conducted in steps to evaluate specific alterations to mix designs separately. In each series, the mix proportions were altered based on which material the series was evaluating. Each mix design was evaluated based on flow and compressive strength, with a target flow of 250 mm for enhanced workability and a target strength of 150 MPa to meet the FHWA standards. The flow was tested using ASTM C1856, and the compressive strength was tested using cubes following ASTM C109. The initial series, series A, set a starting point by evaluating two mix designs, Q and NE, from the study conducted by Graybeal evaluating local materials in various northern regions of the Unites States [3], along with a third unpublished mix design developed by Dr. Royce Floyd. The remaining mix designs were created by adjusting the water-to-cementitious material ratio (w/cm), the aggregate-to-cementitious material ratio (agg./cm), and adjusting relative proportions of the cement, silica fume, and fly ash. A sample of these mix proportions are shown in Table 1 and the 7-day strength data is shown in Figure 1.

	Q	**NE**	**Floyd**	**A1**	**A2**	**A3**	**A4**
Type III Cement	0.67	0.67	0.75	0.7	0.7	0.73	0.75
Silica Fume	0.167	0.168	0.15	0.15	0.15	0.14	0.13
Fly Ash	0.163	0.162	0.1	0.15	0.15	0.13	0.12
w/cm	0.23	0.23	0.18	0.23	0.23	0.23	0.23
agg./cm	1	1	0.75	1	1	1	1
HRWR (oz./cwt)	21	22	22	18.7	18.7	18.7	18.7

Table.1: Weight proportions of mix series A

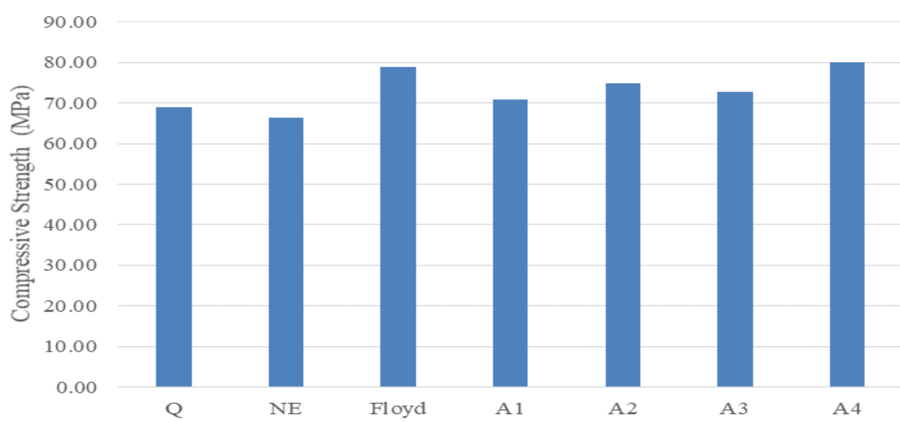

Fig. 1: Series A compressive strengths

7-day strengths were used to expedite testing and the use of Type III cement allowed for fast strength gain.

The series showed that the local materials were not able to replicate the results in the Graybeal study, indicating they are of different compositions. The highest strength mix was A4 and it also correlated to the highest flow for this initial series.

One issue that arose from mix A4 was the presence of unused HRWR at a dose of 18.7 oz./cwt. Therefore, the next series, series B, focused on keeping constant cementitious proportions with the same SCM's while changing the w/cm with the same HRWR dose and changing the HRWR dose at different w/cm. The series B mix proportions are shown in Table 2 and the 7-day strength data is shown in Figure 2. As expected, w/cm had a larger effect on flow than the HRWR content. The 0.23 w/cm had lowest strength with the best workability and flow while the 0.18-0.2 w/cm had comparable strengths, with the 0.18 and 0.19 w/cm being sticky and difficult to consolidate. Therefore, a w/cm of 0.2 was used throughout the rest of the mix development process to balance flow and strength while using less HRWR.

	B1	**B2**	**B3**	**B4**	**B6**	**B7**	**B8**	**B9**
Type III Cement	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Silica Fume	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
Fly Ash	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
w/cm	0.2	0.19	0.18	0.23	0.23	0.19	0.19	0.19
agg./cm	1	1	1	1	1	1	1	1
HRWR, oz./cwt	18.7	18.7	18.7	16.3	11.67	21	23.33	25.66

Table 2: Weight proportions of mix series B

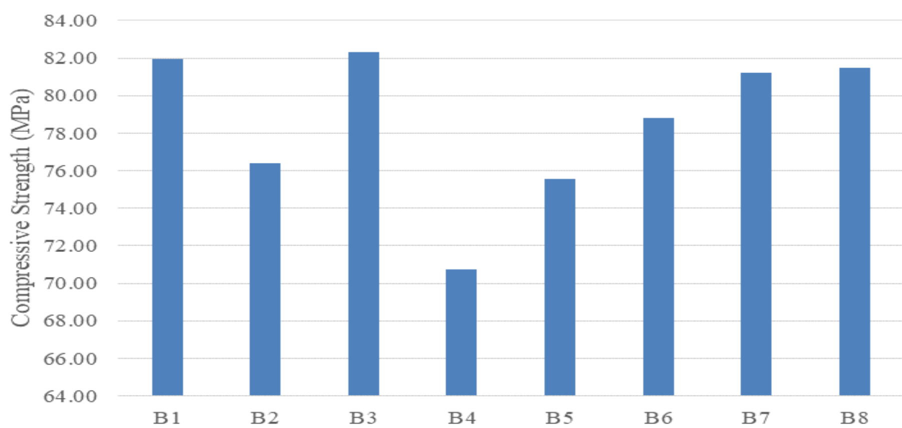

Fig. 2: Series B compressive strengths

The next series, series C, sought to add different SCM's, VCAS^{TM} and GGBFS, to improve late age pozzolanic reactions, particle parking, and lower cement content. Also, Type II and Type III cements were evaluated to assess the benefits of using Type II for later age strength gain. A sample of these mix proportions are shown in Table 3 and the 28-day strength data is shown in Figure 3. Strength testing was extended to 28 days to account for the presence of Type II cement. Unfortunately, no clear pattern arose form varying the different SCM's with Type II and Type III cement.

	C1	C2	C3	C4	C5	C6	C7
Type III Cement	0.65	0.6	0.65	0.55	0.45	0.8	0.75
Silica Fume	0.125	0.125	0.05	0.05	0.05	0.1	0.15
VCAS ™	0.1	0.15	0	0	0	0	0
Fly Ash	0.125	0.125	0.1	0.1	0.1	0.1	0.1
GGBFS	0	0	0	0	0	0	0
Type II Cement	0	0	0.2	0.3	0.4	0	0
w/cm	0.2	0.2	0.2	0.2	0.2	0.2	0.2
agg./cm	1	1	1	1	1	1	1
HRWR, oz/cwt	18.7	18.7	18.7	18.7	18.7	18.7	18.7

Table 3: Weight proportions of mix series C

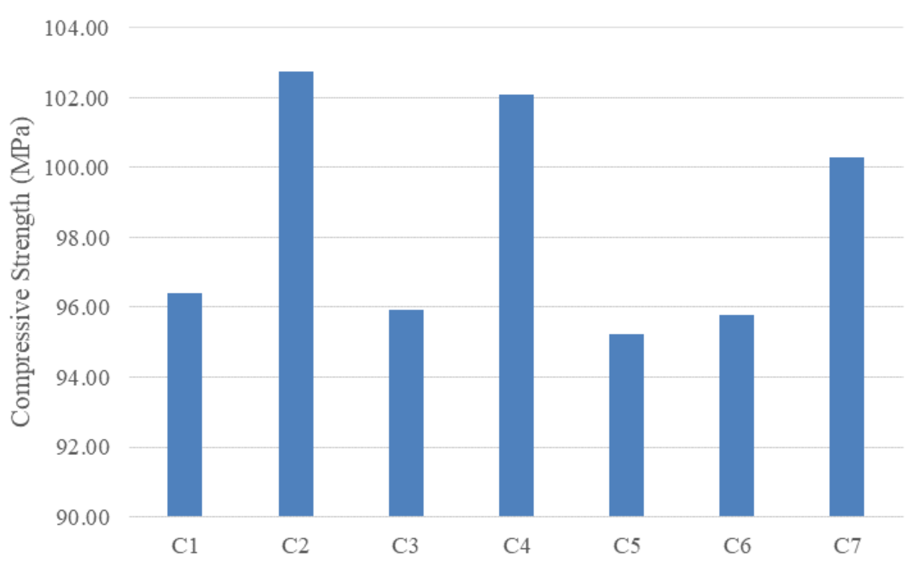

Fig. 3: Series C compressive strengths

Up to this point, no mix tested exceeded a 105 MPa 28-day strength. Therefore, the particle packing potential of the materials was evaluated to see if that would improve compressive strengths. The Modified Andersean and Anderson particle packing model was used to develop the next series of mix designs [9]. The model is shown below as Equation 1,

$$D(P) = \frac{D^q - D^q_{min}}{D^q_{max} - D^q_{min}} \qquad (1)$$

where D(P) is the percent passing for each diameter evaluated, D is the particle diameter being evaluated, D_{min} is the smallest particle diameter used in the mix design, and D_{max} is the largest particle size used in the mix design. A value 0.22 was used for q.

Using a computer spreadsheet, 17,600 different mix designs were created, changing the proportions of Type

II and III cement, silica fume, fly ash, GGBFS, and VCAS^{TM}. The proportions were used for each agg./cm of 0.8, 0.9, 1.0, and 1.1, and their combined percent passing curve was compared to the optimum packing curve created using Equation 1. Each mix was evaluated by how close each curve was to the optimum curve at each particle size evaluated. Then, several mixes with the smallest difference from the optimum gradation curve were chosen to test, as well as various mixes developed from the previous series and adjusted to improve packing potential. A sample of the mix designs chosen for testing are shown in Table 4 with corresponding strengths in Figure 4.

	D1	D2	D3	D4	D5	D6	D7	D8
Type III Cement	0.15	0.1	0.05	0	0	0	0.55	0.45
Silica Fume	0.35	0.35	0.35	0.1	0.15	0.2	0.125	0.125
VCAS ™	0	0	0	0	0	0	0.2	0.3
Fly Ash	0.5	0.5	0.5	0.2	0.15	0.1	0.125	0.125
GGBFS	0	0	0	0	0	0	0	0
Type II Cement	0	0.05	0.1	0.7	0.7	0.7	0	0
w/cm	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
agg./cm	1	1	1	1	1	1	1	1
HRWR, oz/cwt	18.7	18.7	18.7	18.7	18.7	18.7	18.7	18.7

Table 4: Weight proportions of mix series D

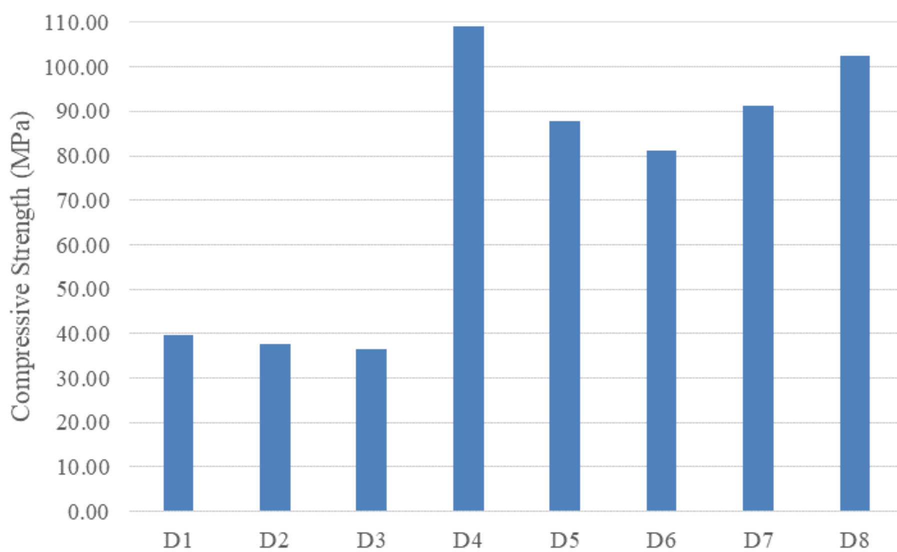

Fig. 4: Series D compressive strengths

Mixes D1-D3 had gradations closest to the optimum gradation curve but did not liquefy during mixing. This could be due to the large quantities of silica fume, which are necessary for particle packing since they are the only particles that can fill in the smaller particle size portion of the gradation curve but have an increased specific surface, thus increasing their water demand. Mixes that were at least 60% cement were able to liquefy and were workable even at flows as low as 150 mm. However, altogether there did not appear to be any strong correlation between particle packing, strength, and flow. It appeared that the chemical composition of the mix designs was the main driver behind strength development. Only one mix design provided a strength that was comparable to previous series and, along with two mix designs from the previous series, were carried over for further study. Next, series E sought to determine the effects of several factors. First, the effect of both Type II and Type III cement was evaluated with mixes only containing those as cementitious materials. While there was no significant difference in 28-day strength between all different proportions, Type II cement appeared to improve the flow at higher contents. This is due to the lower water demand of Type II since it has a smaller specific surface. Then, the effect of agg./cm was evaluated by looking at ratios of 0.8, 0.9, 1.0, and 1.1 using mixes C2, C4, D4, and D8. Results show that the flow decreased as the agg./cm increased. However, there was no clear correlation between agg./cm and strength. Therefore, an agg./cm of 1.0 was chosen for the rest of the mix development process to balance the flowability of the mixes with cost.

Series F investigated the effect of using GGBFS as the primary SCM, based on the recommendations of Kim et al. [10]. Various proportions of Type II and III cement, along with GGBFS and silica fume contents were considered with the w/cm and agg./cm chosen from the previous series. This series showed that high levels of Type II and GGBFS, along with a lower silica fume content had good flow and strength characteristics. However, no mix design was able to exceed 100 MPa. Finally, series G used the most promising mixes from all of the previous series with a 0.2 w/cm and 1.0 agg./cm. These mix changes included the following: only GGBFS and Type II cement, an increase in HRWR with high levels of Type III and low silica fume, and replacing Type III with Type II in the best performing mixes of the earlier series. A sample of the mix designs chosen for testing are shown in Table 5 with corresponding strengths in Figure 5. The mixes with high levels of GGBFS and Type II cement, mixes G1 and G7, were the strongest and most workable. Incorporation of the slag cement helped improve not only the strength of the mix designs, but also improved workability and reduced the typical "stickiness" of the mixes commonly associated with UHPC containing silica fume. Therefore, those mix designs were chosen for mechanical property testing and labeled UHPC2 and UHPC3, respectively. Finally, the best mix design with no GGBFS (mix G2), using fly ash and VCAS^{TM} as the primary SCM's, was also chosen to evaluate the effect of different SCM's on mechanical properties compared to GGBFS mix designs. This mix is labeled UHPC1. The flows of all three chosen mixes exceeded the target flow of 250 mm.

	G1	**G2**	**G3**	**G4**	**G5**	**G6**	**G7**
Type III Cement	0	0	0	0	0.55	0.3	0.1
Silica Fume	0.1	0.1	0.05	0.1	0.05	0.1	0.1
VCAS ™	0	0.15	0	0	0	0	0
Fly Ash	0	0.15	0.1	0	0.1	0	0
GGBFG	0.3	0	0	0.2	0	0.2	0.4
Type II Cement	0.6	0.6	0.85	0.7	0.3	0.4	0.4
w/cm	0.2	0.2	0.2	0.2	0.2	0.2	0.2
agg./cm	1	1	1	1	1	1	1
HRWR (oz./cwt)	18.7	18.7	18.7	18.7	23	18.7	18.7

Table 5: Weight proportions of mix series G

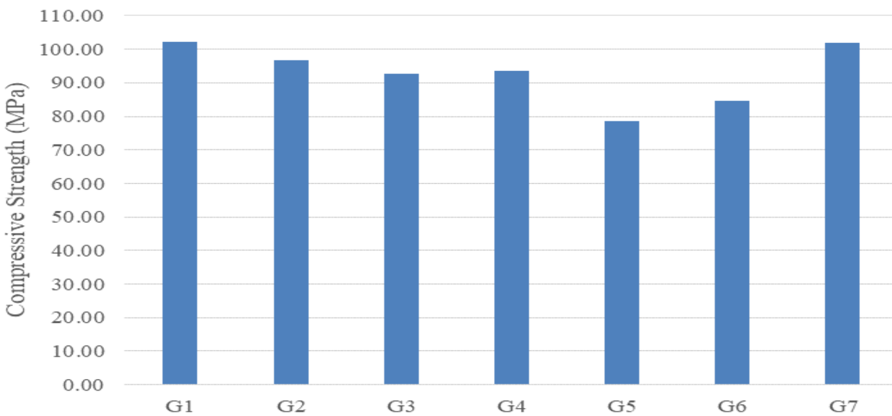

Fig. 5: Series G compressive strengths

The final step in the mix development process involved incorporating the steel fibers. During this process, it was found that the target flow of 250 mm was too high since the fibers would not stay suspended at that flow. Therefore, various HRWR doses were tested for each mix design to determine new target flows that would be sufficient to suspend the fibers as well as maintain workability. The target flows to suspend the fibers was found to be 175 mm for UHPC1 and 195 mm for UHPC2 and UHPC3.

D. Heat Curing

The specimens were demolded twelve hours after casting then placed in their respective curing conditions. The heat cured specimens were placed in an oven set to 80°C and enclosed in an oven-safe bag with water to mimic steam curing. This specific temperature was chosen to match the approximate temperature met in field casting trials. Test specimens were heat cured for 12, 36, and 48 hours. After heat curing, the specimens were allowed to cool to room temperature for two hours, then placed in a water bath at a temperature of 20°C for the remainder of time before testing. The heat cured specimens were tested against a control specimen that was placed in the water bath directly after demolding. The above curing conditions were tested for each UHPC mix design both with and without steel fibers.

E. Test Procedures

Test specimens were cast to test for the compressive strength, modulus of rupture (MOR), and modulus of elasticity (MOE) of each mix. For the compressive strength test, 75x150 mm cylinders were cast and tested according to modified version of ASTM C1856. Three cylinders were created for each tested configuration of each mix design, which included both fiber reinforced and unreinforced specimens for each heat curing time limit, as well as fiber reinforced and unreinforced specimens for the control conditions. All compressive test specimens were tested at three days after casting and an additional set of control specimens were tested at 28 days to compare to the strengths of the heat cured specimens at three days.

The MOR was determined for both the fiber reinforced and unreinforced UHPC mix designs. All MOR test specimens were cured in a water bath at 20°C and tested at 28 days. The MOR test specimens were 75x75x280 mm test specimens and were tested with a span length of 230 mm. Each test specimen was loaded at the maximum allowable rate of 1.2 MPa/s. The first-peak load, which corresponds to the load at which the fiber reinforced specimens experiences its first crack, were determined following ASTM C1856. The MOR of the unreinforced test specimens was determined following ASTM C78 and C1856 and was then compared to the first-cracking MOR for each mix design.

The MOE was determined for the unreinforced UHPC mix designs. All MOE test specimens were cured in a water bath at 20°C and tested at 28 days. The MOE test specimens were 100x200 mm cylinders following ASTM C1856. The tested MOE was then compared to the ACI 318 [11] equation 19.2.2.1.b, as well as a modified version of that equation proposed by Russel and Graybeal [6], both shown below as Equation (2) and Equation (3), respectively:

$$E_c = 4{,}700\sqrt{f_c'} \qquad (2)$$

$$E_c = 3{,}800\sqrt{f_c'} \qquad (3)$$

where E_c is the calculated modulus of elasticity and f'_c is the concrete strength at the time of testing. The MOE test setup is shown in Figure 12.

3. Discussion of Results

A. Compressive Strength

First, the effect of heat curing of UHPC was tested without fibers. The compressive strength test results without fibers are plotted in Figure 6. Each specimen was tested at three days, except the control test at 28 days. As expected, the heat curing increased the rate of hydration of each UHPC mix design, allowing all three mixes to outperform the control concrete at three days for each heat curing duration. The UHPC1 mix design, which contained VCAS™ and fly ash as the SCM's, showed a large increase from 12 hours to 36 hours of heat curing, indicating the pozzolanic reactions require more time to complete. Both UHPC2 and UHPC3, which use GGBFS as the primary SCM, did not exhibit a large change in the strength gain with longer heat curing durations. Heat curing allowed all three mix designs to reach the 28-day strength of their control test with heat curing, however UHPC1 required 36 hours to reach this strength.

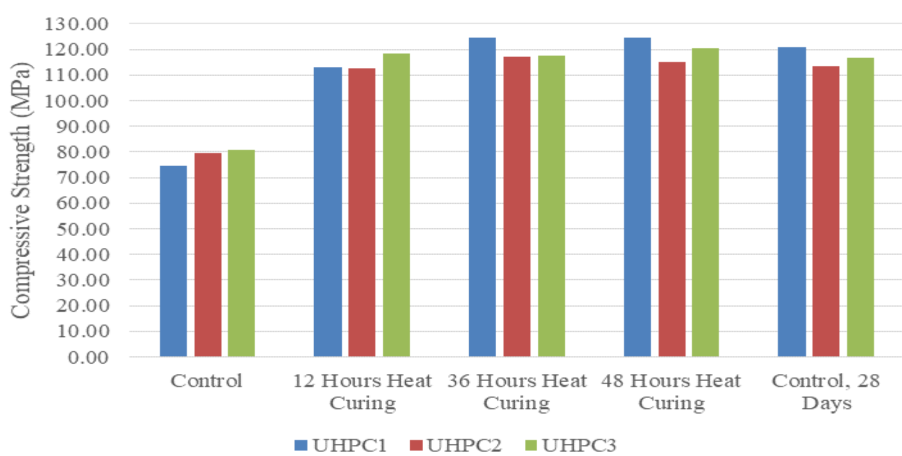

Fig. 6: Compressive strength test results without fibers

After evaluating the effect of heat curing on the unreinforced UHPC mix designs, the effect of heat curing with fibers was evaluated. The compressive strength test results with fibers are plotted in Figure 7. The strongest mix design, UHPC2, reached a strength approximately 6% lower than the 150 MPa strength defined by the FHWA even without complete lab curing conditions. All mix designs developed higher strength than their respective strengths without fibers after 36 hours of heat curing. This could be due to the ability of steel fiber reinforcing to more evenly distribute the heat throughout the concrete cross section, creating a more effective heat curing environment. Again, UHPC1 gained more strength with additional heat curing after twelve hours. All mix designs were less at 48 hours than 36 hours of heat curing. This could indicate an upper bound for the duration of heat curing. Similar compressive strength results were found by Alsalman et al. [12].

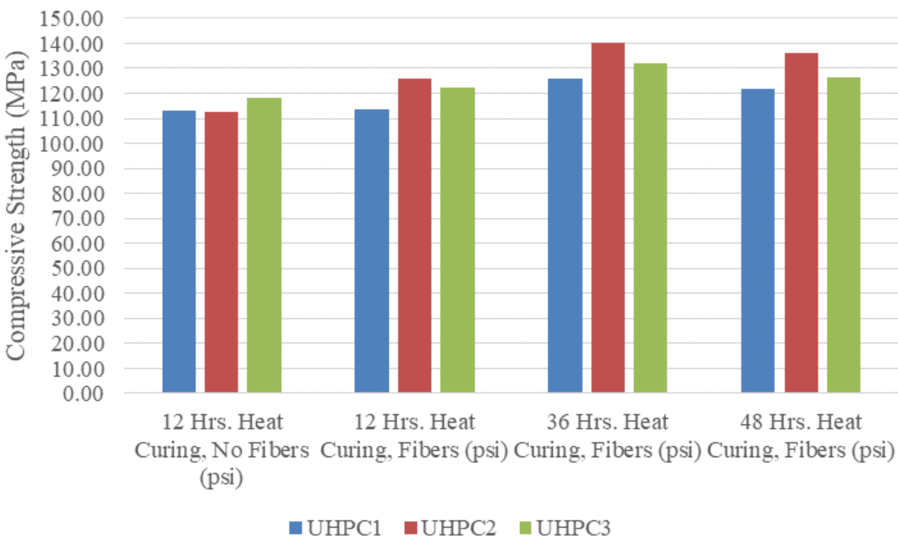

Fig. 7: Compressive strength test results with fibers

B. MOR

The MOR was evaluated for both unreinforced and fiber reinforced conditions. The MOR test results are plotted in Figure 8. Both UHPC1 and UHPC2 performed at the same level. However, UHPC3 was much stronger than the other two mixes, approximately 12.5%. Also, the first-cracking stress was lower than the MOR for each concrete mix design. The crack pattern for the unreinforced MOR specimens is shown in Figure 9. The cracking of the fiber-reinforced specimens is typical of fiber reinforced MOR beams. However, the crack pattern exhibited by the unreinforced UHPC mix designs is unusual. Rather than a straight, vertical crack typical of unreinforced concrete, all of the cracks had a progressively steep curve pattern until it reached approximately 6 mm below the top of the beam, where the crack reversed direction at approximately a 45° angle. This crack pattern indicates there is more energy absorption by the UHPC mix designs than typical concrete.

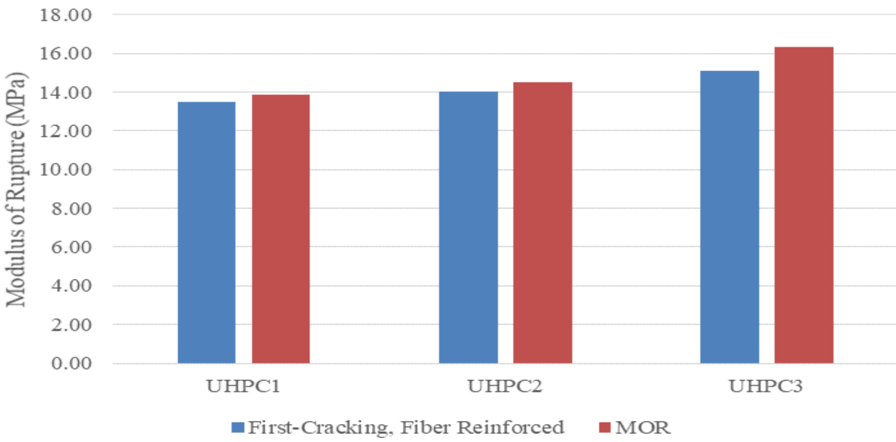

Fig. 8: MOR test results

Fig. 9: Typical crack patter for the unreinforced MOR specimens

C. MOE

The MOE test results, along with the results of the ACI equation and the Russel and Graybeal equation [6] are plotted in Figure 10. UHPC1 and UHPC3 have similar MOE values and UHPC2 is just below. As expected, the ACI equation greatly over-estimated the MOE value. However, the Russel and Graybeal equation closely matched the experimental values, with the differences between them being less than 10% for all mixes. This show that the developed UHPC mixes were able to reach comparable stiffnesses even with the reduced heat curing.

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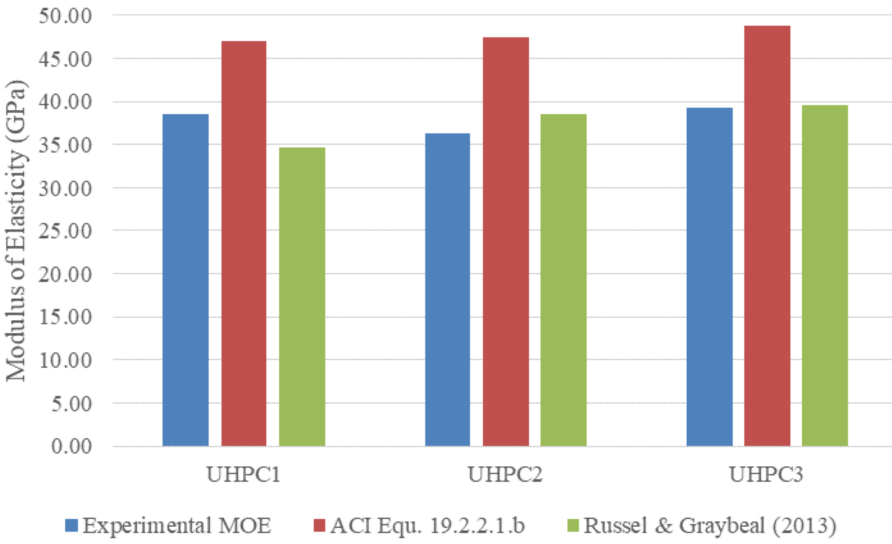

Fig. 10: MOE test results plot

4. Conclusions

Three separate UHPC mix designs with high cement replacement levels with SCM's were developed and tested to determine the effect of heat curing and fiber reinforcement on compressive strength, as well as to determine the MOR and MOE of each mix design. Below are the conclusions of this study:

- Chemical composition of mix constituents appeared to be the main driver of compressive strength, as opposed to particle packing.
- Type II cement appeared to improve the flow of mixes at higher quantities due to its lower water demand.
- UHPC2 and UHPC3 were able to perform better than similar mixes with only cement during mix trials while containing 30% and 40% of GGBFS, respectively.
- The UHPC mix designs created were approximately 6% lower than the 150 MPa compressive strength when subjected to heat curing conditions similar to that obtained in the field.
- Heat curing at 80°C for at least 36 hours allowed each UHPC mix design to reach its 28-day strength.
- UHPC1, containing VCAS^{TM}, required a longer duration of heat curing than UHPC2 and UHPC3 to reach its 28-day compressive strength, indicating VCAS^{TM} requires more time to hydrate than GGBFS.
- Heat curing was more effective with the addition of steel fibers.
- Heat curing for 48 hours with steel fibers appeared to degrade the concrete slightly and reduce its strength.
- The MOR of the UHPC mix designs were consistently higher than the first-cracking stress of the reinforced beams.
- The unreinforced beams exhibited unusual cracking patterns than typical concrete, potentially absorbing more energy.
- The tested UHPC mix designs had MOE values less than 10% different than the equation developed by Russel and Graybeal [6].

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