Effect of Lightweight Aggregates on early-age behavior of High Performance Concrete

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Abstract. Laboratory experiments were conducted to investigate the effects of locally available natural lightweight aggregates (LWA’s) on volume changes and mechanical properties of high-performance concrete (HPC). The normal aggregates fraction of high-performance concrete was replaced with fine and coarse LWA’s at three different replacement levels, 5%, 10% and 20% by volume. The test results indicated a significant reduction in the autogenous shrinkage of high-performance concrete at 56 days without a corresponding considerable reduction in compressive strength of the same concretes. The test results have also shown that up to 20% volume fraction of coarse LWA’s could be used for mitigating the volume changes of HPC with a slight reduction in compressive and splitting tensile strengths, and elastic modulus. Therefore, this investigation recommends the use of locally available natural LWA’s as a viable curing technique for minimizing the volume changes and risk of cracking of HPC’s without compromising their mechanical properties.

1. Introduction

Recent construction depends more and more on the utilization of HPC due to its high strength and reduced permeability. Besides cost reduction, HPC offers the engineer an outstanding combination of properties including enhanced durability and improved mechanical performance. Recently, the use of high-performance concrete has become increasingly important in high rise buildings, bridge decks, marine structures and airport pavements. As HPC is created by a high cement content and low water to cement ratio, it may have significant autogenous deformation at early ages as well as low shrinkage cracking resistance at later ages [1,2]. Proper curing of concrete structures is essential to ensure that they meet the requirements of their expected efficiency and durability. This is often achieved through external curing in ordinary building. External curing procedures are not effective in eliminating the autogenous deformation that limits the strength of HPC [3]. Many techniques were proposed to reduce the influences of autogenous shrinkage [4]. They include using shrinkage reducing admixtures [5] or expansive additives [6,7], addition of fibers [8,9], and by using different LWA [10]. Porous aggregates have been successfully used in the last few decades to mitigate shrinkage between established methods of shrinkage mitigation. Lightweight aggregates are defined as materials lighter than water and distinctly more porous than sand, gravel and ground rock, which are commonly referred to normal weight aggregates [11]. The aggregate is classified as LWA when it satisfies a dry density not higher than 2000 kg/m³ and a bulk unit weight not higher than 1200 kg/m³ [12]. Lightweight aggregate is capable of providing sufficient volume of water, and has a structure that enables the water to be discharged to the paste as needed, and is little enough to be spaced within the matrix [3,13]. The distribution, size, absorption and volume of LWAs are important factors that determine its effectiveness [14]. Four different mixes of HPC were designed at 0%, 5%, 10% and 20% with locally available natural coarse
LWA replacement of total volume of aggregates. Similar mixes were also designed with fine LWA to determine the effectiveness of the size of aggregates. Volume change properties including autogenous shrinkage and some mechanical properties were determined for the HPC mixtures.

2. Experimental Program

2.1. Materials
Type I cement white sand, crushed sand, coarse aggregates, water, silica fume, superplasticizer and natural lightweight aggregates are the materials used. The cement had a specific gravity of 3.15 and followed ASTM C150-16 specifications [15]. The fine aggregates used consist of 20% crushed sand and 80% white sand on weight basis. The physical properties of the normal aggregates were determined by ASTM C33-18 [16] in the laboratory and are shown in table 1. The concrete mixes are filled with drinking water. The powdered silica fume has a specific gravity of 2.2. The superplasticizer used is high range water reducer admixture (HRWRA).

Table 1. Normal aggregates' physical properties

| Material       | Specific gravity | Water Absorption (%) | Size (mm) | Fineness modulus |
|----------------|------------------|----------------------|-----------|------------------|
| White sand     | 2.6              | 0.3                  | 0.1-2     | 1.88             |
| Crushed sand   | 2.59             | 1.67                 | 2-4       | 4.66             |
| Coarse aggregates | 2.62            | 1.45                 | 4-10      | 7                |

The lightweight aggregates used in this study were coarse and fine volcanic tuffs of scoria origin as shown in figures 1 and 2, respectively. The physical properties of LWA were determined in the laboratory according to ASTM 330-04 [17] and are presented in Table 2 [18,19].

Table 2. Lightweight aggregates’ physical properties

| Material     | Specific gravity | Water Absorption (%) | Unit Weight kg/m³ | Moisture content |
|--------------|------------------|----------------------|-------------------|-----------------|
|              | SG_10 | SG_20 | SG_30 | Loose | Dense |               |
| Fine LWA     | 1.78   | 2.0   | 2.40  | 9.7   | 995   | 1120  | 5.23          |
| Coarse LWA   | 1.54   | 1.72  | 1.87  | 10.6  | 762   | 860   | 2.88          |

Figure 1. Natural coarse lightweight aggregates from Saudi Arabia
Figure 2. Natural fine lightweight aggregates from Saudi Arabia
2.2. Concrete Mixtures

A series of concrete mixtures were designed at a water to cement ratio of 0.3 and a cementitious materials content of 550 kg/m³. The mixtures are designated as N, C05, C10, C20, F05, F10 and F20 as shown in Table 3. Mixture N is the reference concrete with no LWA, and Mixtures C05, C10, C20, F05, F10 and F20 are with pre-saturated natural LWA; C stand for coarse LWA and F stands for fine LWA followed by the replacement percentage 5%, 10% and 20% of the total volume of normal weight aggregates. The fine LWA replacement amount was determined by replacing the 5%, 10% and 20% of both crushed sand and white sand amounts which combine the fine aggregates by 20% for crushed sand and 80% for white sand on weight basis. The silica fume used in mixes as 10% of cement volume to get high strength concrete. The superplastizer was added as 7% of water amount. The cementitious materials to coarse aggregate ratio and cementitious materials to fine aggregate ratio are 0.59 and 0.75, respectively.

| Mix | Cement (kg/m³) | Silica Fume (kg/m³) | Coarse Aggregates (kg/m³) | Crushed Sand (kg/m³) | White Sand (kg/m³) | Coarse LWA (kg/m³) | Fine LWA (kg/m³) | Water (kg/m³) | HRWRA (Liter/m³) |
|-----|----------------|---------------------|---------------------------|---------------------|-------------------|-------------------|-----------------|--------------|---------------|
| N   | 500            | 50                  | 930                       | 150                 | 582               | 0                 | 0               | 165          | 11.5          |
| C05 | 500            | 50                  | 883.5                     | 150                 | 582               | 30.5              | 0               | 165          | 11.5          |
| C10 | 500            | 50                  | 837                       | 150                 | 582               | 61.1              | 0               | 165          | 11.5          |
| C20 | 500            | 50                  | 744                       | 150                 | 582               | 122.1             | 0               | 165          | 11.5          |
| F05 | 500            | 50                  | 930                       | 142.5               | 552.9             | 0                 | 28.2            | 165          | 11.5          |
| F10 | 500            | 50                  | 930                       | 135                 | 523.8             | 0                 | 56.4            | 165          | 11.5          |
| F20 | 500            | 50                  | 930                       | 120                 | 465.6             | 0                 | 112.7           | 165          | 11.5          |

2.3. Vacuum Saturation
The LWAs were prewetted at a vacuum of 0.04 MPa for 3 hours to provide water for internal curing and full saturation. First, the saturated LWA was placed in the glass barrel. The bucket was then filled with water and the valve which connected the water to the barrel was closed. The valve connected to the vacuum has been opened and the vacuum is turned on for the first hour to eliminate the air from the aggregates as shown in figure 3. After one hour, the water valve was opened and the water was added until it submerged the total amount of LWA then the valve was closed. The process was maintained under constant pressure to saturate the LWA for two hours. After vacuum saturation, the coarse LWA was dried with a towel to achieve saturated surface dry (SSD) condition [14]. The SSD condition for fine LWA was determined using the cone method presented in ASTM C33-18 [16].
2.4. Mixing
The concrete mixtures were prepared using a pan type mixer of 500 Liters capacity in accordance to ASTM C192-18 [20]. Firstly, to prevent absorption, the inside of the mixer was cleaned with water. The coarse aggregates were mixed first, followed by fine aggregates. Then, the quantity of water absorbed by the aggregates was added; then cement, silica fume were added. Based on the performance of trial mixes; to extend the activity time of HRWRA, it was preferred to add firstly about 75% of the water containing about 50% of the HRWRA. After that, the remaining amount of the water containing the remaining amount of the superplasticizer was added over the last 3 minutes. of the time for mixing. After casting, the samples were covered with plastic sheet and stored at 23o C and 65% relative humidity in the laboratory for 24 hours, then demolded and kept under water. Each sample was labeled as to the date of casting, mixture used, sample number, and the direction of studs for the prisms.

2.5. Autogenous Shrinkage Test
Autogenous shrinkage was measured on 75×75×350 mm prism specimens every week until 56 days. Three samples were measures for each mix. Stainless steel studs were embedded at the ends of the samples. The samples were removed from the molds at an age of 24 h. Upon removal of the specimens from the molds, they were placed in lime-saturated water and kept at 23 °C for 45 min before being measured for length. The samples were kept in water at 23 °C after the initial comparator reading until they reached 7 days of age, including the period in the molds. At the end of the curing time, the prism samples were sealed with two layers of aluminum foil using adhesive tape as shown in Figure 4 [2], and a second comparator reading was taken. The samples were placed in the drying room after measurement at the end of the curing time. The readings were taken for each specimen at 7, 14, 21, 28, 35, 42, 48 and 56 days. The difference between the two readings was used for calculating the length change of the specimen at the required age [21].

2.6. Mechanical Properties Tests
Compressive strength test was performed using 150×150×150 mm cube samples following ASTM C39-18 test procedure [22]. Three specimens were tested at 28 days for each mixture. Molds were lubricated and compacted using a vibrating table. One day after casting, the concrete samples for the aforementioned tests were stored in the laboratory at 23± C for 24 hours, labeled and then cured in water till the testing day. The splitting tensile strength test was performed using three 100×200 mm cylinder specimens at 28 days following the test procedure outlined in ASTM C496-14 [23]. The Static elastic modulus test was performed using 100×200 mm cylinder specimens. Three specimens were tested at 28 days for each mixture. The sample was positioned with the strain measuring device connected to the test machine to ensure that the load transfer system is balanced properly. The elastic modulus was determined following the guidelines outlined in ASTM C469-14 [24].

3. Test Results and Discussion

3.1. Autogenous Shrinkage
The autogenous shrinkage can be considered as the result of self-desiccation. The results of autogenous shrinkage of the mixtures with coarse and fine LWA are shown in figures 5 and 6, respectively. It can be observed that the partial replacement of normal aggregates of HPC mixtures with LWAs lead to a decrease of autogenous shrinkage. The test results indicated that by increasing the content of LWAs in HPC, the autogenous shrinkage will decrease. The decrease of autogenous shrinkage is due to the presence of LWAs particles that served as water reservoirs for providing additional moisture to concrete. At 20% replacement level, the fine or coarse LWA lead to mitigating the autogenous shrinkage at 28 days. The fine LWA at 5% and 10% replacement levels was more effective than coarse LWA in decreasing the autogenous shrinkage. At 5% and 10% levels, fine LWA reduced the autogenous shrinkage by 38% and 93%, and the coarse LWA reduced it by 14% and 64%, respectively. The use of LWA with smaller particle size fraction filled in more spaces within the concrete mix and resulted in the distribution of the water reservoirs in the proximity of the cement paste that lead to better internal curing compared to coarse LWA [4,13].
3.2. Mechanical Properties

Figures 7 through 9 show the 28-days results of compressive strength, splitting tensile strength and elastic modulus, respectively for the concrete mixtures cast in this investigation. It can be observed from figure 7 that, replacing the normal aggregates fraction of HPC with LWAs caused a slight reduction in compressive strength. The low strength of LWA lead to the compressive strength reduction [1, 13]. Infact, using a 20% replacement level of LWAs resulted in about 20% loss in compressive strength, where the 86 MPa compressive strength of the control concrete decreased to as low as 70 MPa for both coarse and fine LWA mixtures. Furthermore, it can be seen that using coarse LWA at 5% and 10% replacement level resulted in 8% to 11% loss of the compressive strength, whereas, using fine LWAs mixtures at the same replacement levels caused up to 8% strength loss.

The test results shown in figure 8 indicated that using up to 20% of coarse LWA did not cause a noticeable loss in the splitting tensile strength, whereas, using fine LWAs caused up to 30% loss at 20% replacement level. The results of LWA mixtures shows a higher standard deviation than the control mixture which may explain the reduction in C05 result. The test results shown in figure 9 indicated that both types of LWAs, coarse and fine caused up to 8% and 20% loss in elastic modulus of HPC respectively at a replacement level of up to 20% on volume basis.
3.3. Discussion
The test results presented in figure 10 showed a significant decrease in the autogenous shrinkage of HPC due to the use of both types of natural lightweight aggregates, coarse and fine. This could be due to the porous microstructure of the natural lightweight aggregates which served as a moisture reservoir inside the concrete and thus helped in mitigating the self-desiccation of HPC with time. On the contrary, the interconnected pores coupled with the high absorption capacity of LWAs would definitely cause some losses in its mechanical properties such as compressive, and splitting tensile strengths, and elastic modulus. However, the preliminary test results of this investigation indicated that the percentage reduction in the mechanical properties, compressive strength in particular was within the range of acceptable strength limits of HPC investigated in the literature. Further investigation is going on to explore the potential application of the natural lightweight aggregates available in the kingdom for improving the performance of high strength and high performance concretes.
4. Conclusion

Based on the experimental test results of this investigation the following conclusions can be drawn:

1. The autogenous shrinkage of high performance concrete (HPC) could be significantly reduced by replacing the normal aggregates fraction of HPC with natural fine or coarse LWA’s at a various replacement levels of 5%, 10% and 20% on volume basis.

2. The test results reported indicated that at the highest replacement level, 20% of LWAs used, the HPC mixtures were able to maintain a residual compressive strength above 80% of the compressive strength of the control HPC mixtures without LWAs at 56 days of age.

3. This investigation recommends using locally available natural LWAs as a partial replacement of normal weight aggregates for mitigating the autogenous shrinkage and minimizing early age cracking of high performance concrete without compromising its compressive strength.

5. References

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