Performance of High Strength Cementitious Composites with High Volume Supplementary Cementitious Materials

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Abstract. Portland cement (PC) is the major binder used for cementitious composites. However, due to the increase in the demand for cementitious composites for the construction of infrastructures, there’s a consequential effect of the production of this binder (i.e. PC) on the sustainability of our environment. The production of PC emits huge amounts of carbon dioxide into the environment and possesses a huge strain on the natural deposits of its raw material. In order to create a sustainable environment while meeting the high demand for cementitious composites; it is paramount to replace the PC with locally available waste materials. This study incorporates a high volume of slag alongside silica fume at a ratio of 2.2 to that of PC to produce high strength cementitious composites. The effects of these compositions were determined experimentally on its fresh and hardened properties. Results from this study showed that high strength cementitious composites can be produced with a high volume of supplementary cementitious composites up to 80%. The use of slag as 80% replacement of slag resulted in a 9.3% increase in the compressive strength and a 48.1% decrease in sorption.

Keywords: Cementitious Composites; Slag; Strength; Durability; Sustainability.

1. Introduction

The primary binder used in the production of various cementitious composites is Portland cement (PC). However, the production of PC causes a huge menace in the environment due to the high carbon dioxide emissions and the high consumption of raw materials (Purnell, 2013; Sivakrishna et al., 2019). Hence, PC is the major contributor to the embodied carbon and energy in cementitious composites.

High strength cementitious composites with a compressive strength greater than 50 MPa are in huge demand due to their outstanding performance and the viability to reduce the size of structures made with those composites while conserving the performance. However, the high content of PC required in such mixtures
has resulted in high strength cementitious composites having higher embodied energy and carbon (Thomas and Chandra Gupta, 2016). In order to promote more sustainable construction practices; alternative materials with lower environmental impact must be used as components in cementitious composites. Of such promising and viable sustainable alternatives that can be used to produce high strength cementitious composites are blast furnace slag (BFS) and silica fume (SF) which are waste products from the production of metals. These materials can be used to partially replace the PC, hence, classified as supplementary cementitious materials (SCMs).

BFS and SF have been incorporated over the years to improve the sustainability and performance of cementitious composites (Dimitriou, Savva and Petrou, 2018; Awoyera and Adesina, 2019a; Booya et al., 2019). However, there is limited study on its use in high volume to produce high strength cementitious composites. Also, studies on the use of these SCMs have incorporated them at low volumes (i.e. less than 50%) and only focused on either the mechanical or durability performance. Therefore, there is a limited comprehensive study on the influence of the high-volume use of these SCMs on the fresh, mechanical and durability properties.

Hence, this study was carried out to investigate the influence of using high volume BFS and SF on the properties of high strength cementitious composites. The BFS was used to replace the PC up to 80% while the SF was used as a replacement of the BFS up to 20%. The performance of the composites was evaluated in terms of slump, air content, density, compressive strength, porosity, and water absorption.

2. Experimental Program

2.1 Materials

The primary binder used in this study is Portland cement (PC) with an average particle size of 15 μm and satisfying the requirements of ASTM C 150 (2012). The supplementary cementitious material (SCM) used to replace the PC are the Slag and silica fume with an average size of 10 μm and 0.4 μm, respectively. The specific gravity of the PC, BFS and SF used is 3.13, 2.84, and 2.21, respectively. The chemical composition of the PC and SCMs are presented in Table 1. Only fine aggregate with a specific gravity of 2.63 and a maximum size of 3 mm was used as aggregate. Superplasticizer (SP) was used as the chemical admixture to improve the workability of the mixtures.

### Table 1. Binder composition

|          | PC   | BFS | SF  |
|----------|------|-----|-----|
| CaO      | 62.43| 37.6| 0.1 |
| SiO₂     | 19.78| 36.9| 96.3|
| Al₂O₃    | 5.38 | 9.08| 0.2 |
| Fe₂O₃    | 2.67 | 0.81| 0.3 |
| SO₃      | 3.47 | 1.96| 0.2 |
| Na₂O     | 0.12 | 0.25| 0.1 |

2.2 Mixture Design, Sample Preparation and Curing

The composition of all mixtures was kept constant except for the composition of the binder. SCMs (i.e. combined BFS and SF) were used to replace up to 80% the content of PC while the SF was used as a replacement of BFS up to 20%. The water to binder ratio was kept at 0.35 for all mixtures and the binder to sand ratio was fixed at 0.40. SP was premixed with the mixing solution at a dosage of 0.8 kg/m³ for all mixtures. Table 2 presents a detailed composition of the mixtures evaluated in terms of ratio to the binder content. The mixture ID used represents the composition of the binder.

Each mixture was produced by first mixing the dry component (i.e. binders and aggregates) before adding water to the mixture as the mixing continues. When the mixing was completed, the fresh mixtures were
poured into moulds and covered with a plastic sheet to avoid loss of water from the samples. All samples were demoulded after one day of casting and cured in water for 28 days before testing.

Table 2. Composition of mixtures

| Mixture ID   | PC  | BFS | SF  | Fine aggregate | Water |
|--------------|-----|-----|-----|----------------|-------|
| 100PC        | 1   | 0   | 0   | 0.40           | 0.35  |
| 80BFS        | 0.2 | 0.80| 0   | 0.40           | 0.35  |
| 75BFS5SF     | 0.2 | 0.75| 0.05| 0.40           | 0.35  |
| BFS10SF      | 0.2 | 0.70| 0.10| 0.40           | 0.35  |
| BFS15SF      | 0.2 | 0.65| 0.15| 0.40           | 0.35  |
| 60BFS20SF    | 0.2 | 0.60| 0.20| 0.40           | 0.35  |

2.3 Test Methods
The air content of each mixture was measured following the test procedures in ASTM C 231 (2014). The air content test was carried out immediately after the mixing was completed. The compressive strength was evaluated using cubic samples with a dimension of 50 mm x 50 mm x 50 mm and following the test procedure in ASTM C 109 (2012). For each mixture, a total of four samples were tested and the average results presented.

Cylindrical samples with a height and diameter of 50 mm and 100 mm, respectively were used to evaluate the porosity (i.e. permeable voids), absorption, and sorption of the mixtures. The permeable voids and absorption were measured as per the test procedure in ASTM C 642 (2006) while the test procedures in ASTM C 1757 (2013) were used to assess the sorption of the mixture. Four samples were used for each test, and the result section presents the average obtained from the four samples for each mixture.

3. Results and Discussion

3.1 Air content
The effect of BFS and SF content on fresh content is shown in Figure 1. It can be observed that the replacement of 80% PC with BFS resulted in a 33.4% reduction in the air content. This reduction in the air content can be associated with the smaller particle size of the BFS which reduced the air voids in the fresh mixture. However, replacing BFS with SF in the range of 5% to 20% resulted in an increase in the air content 14.2% to 28.6%.

![Figure 1. Air content of mixtures](image)
3.2 Density

Figure 2 shows the effect of the SCMs on the dry density of the cementitious composite. It is being observed that the replacement of 80% PC with BFS resulted in a significant reduction in the density. This reduction can be associated with the lower specific gravity of the BFS. However, the replacement of BFS with SF up to 20% resulted in a slight increase in the density by up to 3.4%. This observation was not expected as SF particles have lower specific gravity compared to PC and BFS. This phenomenon could be attributed to the SF particles acting as a nucleation site resulting in the formation of more products and a corresponding increase in the density (Adesina, 2019, 2020). Nonetheless, the density of composites incorporating SF is lesser than that made with only PC as the binder (i.e. 100PC). However, it is recommended that more studies should be carried out in order to fully understand the results.

![Figure 2. Density of mixtures](image)

3.3 Compressive strength

Compressive strength is an essential property of cementitious composites and a good pointer of the overall mechanical performance. It can be observed from Figure 3 that the replacement of high content of PC with SCMs (i.e. BFS and SF) improved the compressive strength. The compressive strength of cementitious composite made with BFS as 80% replacement of the binder is 9.3% higher than that made with PC as the binder. However, the replacement of BFS with SF does not result in any significant improvement in the compressive strength with the compressive strength reducing at SF content greater than 15%. The increase in compressive strength with the use of up to 80% BFS and SF up to 15% can be associated with the possible refinement of the microstructure coupled with the formation of additional pozzolanic reaction products. The effect of 20% replacement of BFS with SF (i.e. mixture 60BFS20SF) contradicts the hypothesis made for the density results due to the decrease in compressive strength observed. This reduction in compressive strength when SF was used as a 20% replacement of BFS can be attributed to the possible excess silica in the matrix.
3.4 Porosity

The effect of the SCMs content on the porosity (i.e. permeable void) of the mixtures is shown in Figure 4. It is evident from Figure 4 that the incorporation of BFS and/or BFS as replacement of the PC resulted in a lower the porosity of the composites. The reduction in the porosity of the high strength cementitious composite with the incorporation of the SCMs can be associated with the pore refinement and pozzolanic capability of BFS and SF.

It can also be observed that more reduction in the porosity of the mixture was evident when the content of SF used as the replacement of BFS increased. This phenomenon can be attributed to the very fine particles of SF which proffer more refinement to the microstructure. The pozzolanic products from the pozzolanic reaction of the SF particles would also contribute significantly to the pore refinement of the microstructure of the composites. This observation corresponds with that of other studies where the use of BFS and/or SF was found to result in lower porosity of cementitious composites (Türkmen, Gül and Çelik, 2008; Chahal and Siddique, 2013; Awoyeru and Adesina, 2019b; Adesina and Das, 2020). It will also be noticed that in contrast to the fresh air content, the incorporation of SF resulted in lower porosity. This can be ascribed to the ability of the SF to refine the microstructure of cementitious composites after it has reacted with other components in the composite.
3.5 Absorption and Sorption

The permeability properties of cementitious composites reflect their overall durability as these properties are dependent on the ease of penetration and amount of water that can get into it. Figure 5 and Figure 6 present the absorption and sorption of the mixtures, respectively. It can be observed that the incorporation of BFS and SF as replacement of PC in the mixtures resulted in a significant decrease in the permeability (i.e. absorption and sorption) of the composites. These reductions in permeability can be associated with the ability of the BFS and SF to refine the microstructure limiting the ingress of moisture into the composites. The correlation between the absorption, sorption and permeable voids confirmed this as there is a strong correlation between these properties as shown in Figure 7.

In contrast to the effect of SF on the compressive strength, there is a decreasing trend observed in the reduction in the absorption and sorption of the mixtures with increasing SF content. This shows that the more refinement capability of the SF plays a more significant role in the refinement of the microstructure compared to the effect of the products formed.
Figure 5. Absorption of mixtures

Figure 6. Sorption of mixtures
4. Conclusions

In the current paper, the performance of high strength cementitious composites made with high volume supplementary cementitious material (i.e. slag and silica fume) was evaluated experimentally. The performance of the composites in terms of the fresh and hardened properties of the composites was investigated. The following conclusions can be made based on the results of this study:

1. Supplementary cementitious materials such as slag and silica fume can be used to replace Portland cement in cementitious composites without any significant effect on the corresponding performance.

2. The incorporation of blast furnace slag and silica fume resulted in a decrease in the density of the composites due to their lower specific gravity. Hence, in addition to the sustainability advantage with the use of these SCMs as replacement of Portland cement; they can be incorporated to reduce the weight of cementitious composites.

3. The incorporation of blast furnace slag and silica fume as replacement of Portland cement improved the performance of the composites in terms of increasing the compressive strength and reducing the permeability of the composites. Hence, these SCMs are sustainable alternatives to PC to produce high strength cementitious composites.

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