Fresh Characteristics of High-Performance Self-Compacting Concrete using Induction Furnace Slag as Supplementary Cementitious Material

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Abstract. Using wastes products in concrete contributes towards sustainability in civil engineering construction. Producing high-performance-self-compacting concrete (HPSCC), using induction furnace slag (IFS) contributes positively to the sustainability of concrete technology. Many researchers have developed self-compacting concrete (SCC), but there are minimal investigations reported considering the high-performance in the development of SCC. The aim of this paper is to determine the fresh characteristics of HPSCC, using IFS as a supplementary cementitious material. Tests were conducted on filling ability, passing ability, as well as resistance to segregation of the fresh HPSCCs, containing IFS at percentage replacement of 0%, 10%, 20%, 30%, 40% and 50%. Slump flow and $T_{50cm}$ slump flow tests were conducted to determine the filling ability. L-Box test was used to determine the passing ability. V-funnel at $T_{5\text{minutes}}$ test was conducted to determine the resistance to segregation. The results showed that the slump flow ranged between 652 and 687 mm, the $T_{50cm}$ slump flow ranged between 2.59 and 3.97 seconds, the L-box value ranged between 0.81 and 0.95, while V-funnel at $T_{5\text{minutes}}$ ranged between 1.88 and 3.11. The fresh properties criteria, according to EFNARC were fulfilled, except for few concretes with IFS content greater than 20%. It is therefore recommended that induction furnace slag be incorporated as a supplementary cementitious material (SCM) when producing HPSCC.

Keywords: High-performance-self-compacting concrete, induction furnace slag, supplementary cementitious materials, filling ability, passing ability, resistance to segregation.

1. Introduction

Concrete, mostly limestone Portland cement concrete is a blended substance, which contains coarse and fine aggregates, blended with cement. It is sometimes combined with other hydraulic cements, such as supplementary cementitious materials [1].
Currently, limestone Portland cement, as well as SCMs are the least expensive binding agents that keep the concrete production. Nevertheless, limestone Portland cement manufacture consumes more energy. Each limestone Portland cement (PC) production tonne generates about 1 tonne of carbon dioxide (CO₂). As a result, manufacture of limestone Portland cement cement production causes close to 5% for every carbon dioxide discharge [2].

The principle of high-performance concrete developed recently. At first, it was taken as high-strength concrete. This possesses certain advantages, unfortunately, it is not complete in its sense. It is needful to look into several concrete parameters also, which oftentimes are more important than strength parameter.

High-Performance concrete can be defined as a concrete containing suitable constituents, mixed in accordance to a chose design mix; adequately blended, moved, deposited, compacted and moistened in such a way that concrete produced exhibits an outstanding characteristics in the structure been positioned, in the environmental conditions been subjected to, as well as the loadings it will carry when designed. Therefore, high-performance concrete can be regarded as durable concrete.

Self-compacting concrete can be defined as that unique concrete which has the potential to pass across densely-packed steel bars, fill all parts formwork, as well as compact well without a compactor. It exhibits good passing ability, outstanding filling ability, as well as excellent resistance to segregation [3], [4].

Combining the durability characteristic, as well as the high-strength property of high-performance concrete (HPC) with self-compacting concrete (SCC) and at a lower water-binder proportion, high-performance self-compacting concrete (HPSCC). High-performance self-compacting concrete can be defined as a type of concrete that produces outstanding characteristics, in terms of strength, flowability, transportability, as well as durability in line with the specifications for conditions of service at a specified loading, constituent materials, as well as environmental exposure.

The fundamental HPSCC fresh characteristics are the resistance to segregation, passing ability, as well as filling ability.

The filling ability property of HPSCC can be defined as the potential of HPSCC, in its fresh state to fill all parts of the concrete formwork at its self-weight, without a vibrator [5], [6]. The filling ability property of HPSCC has an important effect on the placing of concrete and its ability to consolidate at its own weight [7]. The passing ability of HPSCC generally refers to the capacity of HPSCC to pass across densely packed reinforcing rods [5], [6]. For densely reinforced structures, the excellent HPSCC passing ability allows for easy placing of the concrete, as well as self-compaction across the heavily reinforced steel rods [7]. The HPSCC’s resistance to segregation means the ability of the concrete to continue to be stable without any form of bleeding, settling of the coarse aggregates, as well as disconnection of the concrete paste [6]. Particularly, when HPSCC does not satisfy the adequate resistance to segregation property, there is non-uniformity in the concrete mix.

Supplementary cementitious materials can be defined as those finely grounded materials that add to the characteristics of concrete by their hydraulic and/or pozzolanic behaviour [8]. Mark et al [9] in their review paper found out that SCMs have positive influence on the properties of normally-compacted concrete. Arum and Mark [10] in their study concluded that cupola furnace slag (the old form of induction furnace slag), which is an SCM, has a positive influence on concrete.

In producing cast iron in the modern way, secondary by-products are formed. The most abundant by-product obtained in this modern way is induction furnace slag. When an induction furnace slag is crushed, pulverized, milled and sieved to cement size, it is referred to as ground granulated induction furnace slag (GGIFS). Induction furnace slag is such material that can be used as cement replacement [11]. This material considers being a potential waste material which is dumped near the industrial area. Using a cheaper SCM like induction furnace slag (IFS) will reduce the total cost of producing HPSCC. Likewise, usage of IFS minimizes the cement usage, as a result, lowers the expenses incurred in manufacturing cement as well as reduces the emission of harmful gases to the environment evolving from cement
manufacturing industries. Therefore, IFS does not just enhance the durability and properties of concrete. It also brings ample benefits environmentally and economically. Up till now, there is limited research carried out to investigate the capacity of IFS by exploring its influence on durability, fresh and hardened properties of HPSCC.

2. Materials and Methods

2.1. Materials

2.1.1. Induction Furnace Slag (IFS). Locally available induction furnace slag was obtained at Nigeria foundries limited, Sango, Ota, Ogun State, Nigeria. It was crushed, pulverized and milled to fine aggregate size using steel ball rolling mill at Highway/Transportation Laboratory of Covenant University, Ota, Ogun State, Nigeria. The fine aggregate-sized slag was sieved through 45 μm sieve so as to get the powdered IFS that was utilized as the SCM, conforming to cement grading requirement of BS EN 197-1 [12].

2.1.2. Portland Cement. Dangote 3X Portland cement was utilized, and was obtained at a retail outlet in Ota, Ogun State, Nigeria. The cement satisfied ASTM Type 1 specification [13].

2.1.3. Granite. Locally available granite was obtained at a quarry site in the form of a mixture of broken and spherical granite. The nominal size of the granite was 12.5 mm. The spherical granite took half of the whole portion of the granite content.

2.1.4. River Sand. Indigenous river sand was utilized as the fine aggregate. This river sand was obtained as soil deposition.

2.1.5. Potable Water. Drinkable water was utilized for mixing the concrete. The quality of the water was such that it was free from impurities and potable enough for drinking.

2.1.6. Superplasticizer. Polycarboxylate-based HRWR, commercially known as Complast SP 430 superplasticizer was utilized in achieving the expected concrete flow, in accordance to ASTM standard [14].

2.2 Methods

2.2.1. Mixture proportioning of the various types of concrete mixture. A total of six (6) different types of HPSCC mixtures were designed, as shown in Table 1. The concrete mixtures were designated based on the GGIFIS content. The mixing ratio of the aggregate contents obtained was based on saturated surface-dry condition. However, the dried aggregates were utilized for the concrete production. Therefore, the aggregates took in substantial quantity of the water for during concrete batching. Also, superplasticizer added to the fluidity of the concrete. Thus, the taking in of water by the aggregates, as well as the addition of fluidity by superplasticizer was considered when determining the water for mixing. Moreover, the aggregate contents were determined based on their absorption and moisture content.
Table 1. Details of concrete mixture proportions.

| S/N | Concrete Type     | Cement (kg/m³) | GGIFS (kg/m³) | River Sand (kg/m³) | Granite (kg/m³) | Water (kg/m³) | Superplasticizer (kg/m³) |
|-----|-------------------|----------------|---------------|-------------------|-----------------|--------------|--------------------------|
| 1   | HPSCC0,100        | 733.0          | 0             | 747.66            | 696.35          | 263.88       | 14.66                    |
| 2   | HPSCC10,90        | 659.7          | 73.3          | 747.66            | 696.35          | 263.88       | 14.66                    |
| 3   | HPSCC20,80        | 586.4          | 146.6         | 747.66            | 696.35          | 263.88       | 14.66                    |
| 4   | HPSCC30,70        | 513.1          | 219.9         | 747.66            | 696.35          | 263.88       | 14.66                    |
| 5   | HPSCC40,60        | 439.8          | 293.2         | 747.66            | 696.35          | 263.88       | 14.66                    |
| 6   | HPSCC50,50        | 366.5          | 366.5         | 747.66            | 696.35          | 263.88       | 14.66                    |

2.2.2. Fresh Concretes Production. Fresh HPSCC concretes were produced according to ASTM standard [15], and were done at the Structures Laboratory, Covenant University, Ota, Ogun State.

2.2.3. Batching procedure. The batch quantities of the fresh HPSCC were calculated before batching. The fresh HPSCC batch quantities taken were at the minimum of 15% higher, in order to cater for the losses at the time of test. The constituent materials were taken on weight basis.

2.2.4. Fresh HPSCC tests. The fresh HPSCC mixtures were tested for filling ability by carrying out slump flow test and T₅₀₀ slump flow test. It was also tested for passing ability by carrying out L-box test and finally tested for segregation resistance by carrying out V-funnel at T₅_minutes test. These were done at the Structures Laboratory of Covenant University, Ota, Ogun State.

2.2.4.1 Slump flow and T₅₀₀ time Tests. Conduction of slump flow test was done according to EFNARC standard [6], utilizing Abram’s slump cone, as seen in Figure 1. Concrete samples were poured inside the apparatus in a single one layer, with no form of compaction. The apparatus was removed uprightly, to make the concrete sample to distort on top of a non-absorbent pan. A stopwatch was started simultaneously while the time required for the flowing concrete to get to 500 mm diameter circle was taken to be the T₅₀₀ time slump flow value. The concrete flow diameter was taken as the slump flow, and was taken at the four (4) points dividing the spread to eight (8) parts.

Figure 1. Slump Flow Test.

2.2.4.2 L-box Test. Conduction of L-box test was done according to EFNARC [6], as seen in Figure 2. The apparatus (L-box) was positioned on a flat ground, while closing the sliding gate with the sliding gate closed. Fresh concrete was poured into the vertical part of the L-box, which was allowed to rest for about a minute. Afterwards, the fresh concrete was made to flow to the horizontal part of the L-box. The vertical
height $H_1$, as well as the horizontal height $H_2$ of the concrete in the apparatus was taken, immediately the fresh concrete did not flow again. The blocking ratio $H_1/H_2$ was determined.

![Figure 2. L-Box Test.](image)

2.2.4.3. V-funnel at $T_{5\text{minutes}}$ test. Conduction of V-funnel at $T_{5\text{minutes}}$ test was done according to EFNARC [6], as seen in plate 3. Water was poured into the apparatus (V-funnel), to wet it, and the apparatus was later placed on a flat ground. A container was put under the apparatus, while closing the flap. Filling of the L-box with fresh concrete was done once, without compacting or tapping it with compacting rod. After five minutes, opening of the flap was done, and the concrete was made to flow into the container, by its own weight. Concurrently, the time it took for the fresh concrete to pour into the container was measured as the time of flow at $T_{5\text{minutes}}$.

![Figure 3. V-funnel at $T_{5\text{minutes}}$ Test.](image)

3. Results and Discussion

3.1. Results

The HPSCC mixtures results for slump flow, $T_{500}$ slump flow test, L-box test and V-funnel at
$T_{\text{5min}}$ minutes test are presented in Figures 4 to 7.

**Figure 4.** Effect of Induction Furnace Slag on Filling Ability Property of HPSCC.

**Figure 5.** Effect of Induction Furnace Slag on Filling Ability Property of HPSCC.

**Figure 6.** Effect of Induction Furnace Slag on Passing Ability Property of HPSCC.
3.2. Discussion

3.2.1 Filling Ability of Concretes. The slump flow value of the fresh HPSCC ranged between 652 mm and 687 mm, indicating an outstanding filling ability of the HPSCC. Usually, HPSCC slump flow values range between 550 and 850 mm [6], [16], [17]. From Figure 4, as IFS quantity increased, the slump flow value reduced considerably. This is caused by the higher contents of concrete paste, reduced quantities of aggregates, as well as higher IFS fineness. Increase in IFS content increased the volume of the fresh concrete paste, as well as reduced the quantities of the aggregates. Slump flow value usually reduces when the volume of concrete paste increases, quantity of aggregates reduce, as well as when the binders fineness increase [18], [19]. The high binders fineness, high volume of fresh concrete paste, as well as reduced quantities of aggregates need additional mixing water for flowability and hence, reduce the deformability of the concrete, as the collision between aggregates is greatly increased with lower inter-particle distance. Therefore, HPSCC filling ability can be assessed by slump flow test.

The $T_{50\text{cm}}$ slump flow of different HPSCC mixtures ranged between 2.59 and 3.97 seconds, as seen in Figure 5. The acceptable range is between 2 and 5 seconds [6]. The $T_{50\text{cm}}$ slump flow of concretes with higher IFS content was above the control mix. This was because there was increase in kinetic energy. The flow times increased with lower W/B ratio and greater IFS content, thus indicating an increase in the plastic viscosity of the concretes. The volume fraction and surface area of binder were increased with higher IFS content. The increased volume fraction and surface area of the binder increase the viscosity of concretes, and hence increase the flow time of concretes [20]. However, the aggregate content of concretes was reduced and the paste volume was increased simultaneously with the greater IFS content. The reduced aggregate content and the increased paste volume increased the plastic viscosity of the concretes [21], [6].

3.2.2. Passing Ability of Concretes. The ratio $h_2/h_1$ varied in the range of 0.81 to 0.95 as can be seen from figure 3. Usually, the ratio of $h_2/h_1$ for HPSCC varies from 0.8 to 1.0 [6]. The minimum ratio $h_2/h_1$ was observed for the HPSCC with 50 % IFS. But the highest ratio $h_2/h_1$ was attained for the HPSCC with 0%
IFS. The trend was similar as observed in case of the filling ability properties of the concretes. The ratio \( h_2/h_1 \) exhibited a good passing ability of the concretes.

3.2.3. Segregation Resistance of Concretes. The V-funnel at \( T_{5\text{minutes}} \) varied in the range of 1.88 to 3.11 seconds as can be seen from figure 4. Usually, the V-funnel at \( T_{5\text{minutes}} \) for HPSCC varies from 0 to 3 seconds [6]. The minimum value was observed for the HPSCC with 0% IFS. But the highest value was attained for the HPSCC with 50% IFS. The trend was similar as observed in case of slump flow. The V-funnel at \( T_{5\text{minutes}} \) exhibited a good segregation resistance of the concretes.

4. Conclusions and Recommendations

a. The test results obtained for the fresh properties showed that the slump flow reduced with greater IFS content. In addition, the \( T_{50\text{cm}} \) slump flow increased considerably with greater IFS content. Also, the L-Box decreased with higher IFS content. Likewise, the V-funnel at \( T_{5\text{minutes}} \) increased considerably with greater IFS content.

b. The filling ability, passing ability and segregation resistance criteria were fulfilled for all HPSCCs except few concretes with IFS content greater than 20% that exhibited high viscosity mostly due to the excessive surface area of IFS.

c. It is recommended that induction furnace slag should be used as a supplementary cementitious material, since the fresh properties of the resulting IFS-based HPSCC were within the standard limits specified by EFNARC.

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