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STRENGTH AND DURABILITY ASSESSMENTS OF INDUCTION FURNACE SLAG - QUARRY DUST - BASED HIGH PERFORMANCE SELF - COMPACTING CONCRETE

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Abstract

Induction furnace slag (IFS) and quarry dust (QD) were reported as good materials in making ordinary concrete. Studies were not done on utilizing IFS and QD as constituents of high-performance-self-compacting-concrete (HPSCC). This study aims at assessing the effects of induction furnace slag and quarry dust on the strength and durability of high-performance self-compacting concrete. Strength tests including compressive, flexural, split tensile, rebound hammer tests were conducted on HPSCC. Likewise, durability tests including water absorption, total porosity and electrical resistivity tests were conducted. IFS at 0 % to 50 % (at 10 % intervals) replacement with Portland cement was used. Also, the optimum IFS content was combined with QD at 0 % to 50 % (at 10 % intervals) replacement with river sand. The results revealed an increment in strength up to 20 % IFS, 50 % QD with a rise of 15.34 % compressive strength over the control. The durability improved up to 20 % IFS, 60 % QD with a rise of 16.86 % electrical resistivity over the control. These showed that IFS and QD can be used for the production of HPSCC.

Keywords:

High-performance self-compacting concrete;
Strength;
Durability;
Induction furnace slag;
Quarry dust.

1 Introduction

In the construction industry, concrete remains very important and unique. For this reason, as modernization continues, concrete dominates. Nonetheless, recent concrete production poses several challenges which include environmental contamination, by product disposal, release of harmful carbon dioxide, exhaustion of raw materials and so on. Therefore, in making concrete unique in the construction industry, there is need for sustainability. For concrete to be sustainable, effort must be geared towards the effective utilization of industrial waste products such as induction furnace slag and quarry dust in concrete making. In India, about 5000 foundries are operating and about 1.7 million tons of induction furnace slag wastes emanate per annum. Ghana produces over fifty thousand tons of slags every year. As more foundries are located in the country, slag generation will be on a rise. Unfortunately, these slags are dumped on the foundry site as wastes. Also, many countries are prone to frequent building collapse and most of this collapse is fragile collapse, which points to weak concrete strength. Therefore, the development of cheap, environmentally friendly high-performance-self-compacting-concrete will benefit the construction industry [1-3].

High-performance-concrete is a unique type of concrete in concrete technology. Before now, it was regarded as high-strength-concrete. Later, it was discovered that strength is not the only characteristics peculiar to concrete. Therefore, high-performance-concrete is generally referred to as durable concrete. Self-compacting concrete (SCC) is also another concrete type which is different from normally compacted concrete because it has high range water reducer that helps to ease flow. SCC fills all parts of formwork at its own weight, with no form of vibration or compaction. SCC was first utilized in 1988, in Japan and was later adopted in 1990, in Europe, Sweden as well as Holland. SCC has been a very excellent alternative to normally-vibrated concrete in complex structures like curved as well as slender structures, where it is difficult in compacting normally-vibrated concrete, specifically where there are reinforcement congestions. Also, it is beneficial in the area of safety and health. Eliminating vibration results in eradication of vibration-related disease such as white finger disease, likewise making the site quieter. Another method in concrete technology is the combination of the essential properties of normally-vibrated high-performance concrete (HPC) with those of the self-compacting-concrete (SCC) in producing high-performance-self-compacting-concrete (HPSCC). Viscosity modifying admixture (VMA) or super plasticiser overcomes the drawback of high-performance concrete which is poor flowability while supplementary cementitious material (SCM) overcomes the disadvantages of the self-compacting concrete which are poor strength as well as poor durability [4,5].

Safiuddin and Zain [4] worked on the influence of fly ash (FA) as well as silica fume (SF) on un-hardened HPSCC characteristics as well as on its strength characteristics. They discovered that using silica fume only or fly ash only did not give a result as satisfactory as when then they are combined as binary mix in an HPSCC.

Abdullah et al. [5] studied the properties of the fresh and hardened HPSCC by incorporating fly ash (FA) in the concrete and was found that the result with least fly ash content gained more strength than the control.

Slags can be referred to as metallic and non-metallic oxides that are chemically combined together and which also contain some amount of minerals, metallic sulphides as well as gases. Foundry workers dispose the slags from the foundry sites and as a result, contaminating the land thereby, reducing the soil fertility. Induction furnace slag (IFS) has between 10 and 15 % of these metals. Many foundries neglect these unique metals. When producing cast iron as well as ductile iron in an induction furnace in a foundry, waste is generated. This waste is called induction furnace slag. Induction furnace slag which is a supplementary cementitious material is obtained as a waste product of cast iron which generates from an induction furnace that operates by the principle of electromagnetic induction. Induction furnace slag is a basic slag, different from blast furnace slag (acidic slag and a combustion furnace slag). This material is regarded as a useful waste disposed of the foundry site. However, induction furnace slag powder is obtained by pulverizing, milling, and sieving induction furnace slag to cement size. Using a cheaper SCM like induction furnace slag (IFS) reduces HPSCC production cost. Also, utilizing a low-cost IFS also reduces the environmental stress generated through the problem of disposal of wastes. Likewise, usage of IFS minimizes the need for cement in the construction industry, and as a result, lowers the cost of production of concrete and reduces the pollution of the environment evolving from cement manufacturing industries [6, 7]. Therefore, IFS does not just improve HPSCC properties but it also provides environmental and economic advantages. Till present, little work has been done in assessing the effects of induction furnace slag on the characteristics of HPSCC.

Qurishee et al. [6] replaced natural coarse aggregates with induction furnace slag and tested the strength characteristics. They discovered that the strength increased up to 40 %.

Netinger et al. [7] investigated the effects of high temperature up to 800 ^{0}C on concrete containing 60 % IFS and 40 % sand. They found very impressive crushing strength and elastic modulus of concrete up to 550 ^{0}C temperature.

Investigation on the effect of partially replacing induction furnace slag with river sand on the crushing strength of concrete revealed a very high strength at 30 % induction furnace slag content [8]

Syed and Shafiqur [9] replaced recycled coarse aggregate with IFS and studied the effects on the strength and durability of the concrete. They discovered that up to 50 % of IFS, there was increase in the strength and durability of the concrete.

Quarry dust (QD) is a waste obtained by crushing granite. It is mostly used as fine aggregate in concrete making. During quarrying crush rock into various sizes, dust is generated. The dust generated is called quarry dust in size range of 0 – 4.75 mm, which forms a waste material as well as air pollutant. As a result, quarry dust is recommended for construction works to reduce construction cost. Developing nations are faced with the challenges of alternatively replacing fine aggregates in concrete without affecting the concrete quality negatively. Quarry dust is recently used as structural and highway materials [10, 11].

Muhit et al. [10] investigated the effect of using quarry dust as partial replacement of cement and sand on the crushing and tensile strengths of concrete. They found a positive improvement in these strength characteristics over the control mix.

Sukumar et al. [11] worked on replacing quarry dust with river sand and discovered a rise in the crushing strength of self-compacting concrete at an early age.

Total replacement of sand with quarry dust in generally-known concrete enhances its crushing strength [12].

Study showed that using quarry dust in high performance self-compacting concrete can assist in eradicating the challenge of alkali silica reaction [13].

Up till now, limited study has been done in assessing the effects of incorporating IFS and QD on the characteristics of HPSCC. This study aims to assess the strength and durability characteristics of HPSCC by incorporating IFS in partial replacement with Portland cement between 0 % and 50 %, at 10 % replacement intervals and combining the optimum percentage of the IFS content with another set of HPSCC containing quarry dust as partial replacement of river sand from 0 % to 60 %, at 10 % replacement intervals, in order to determine the optimum combination of IFS and QD for sustainable, eco-friendly, unique strength and durability characteristics of HPSCC. The physical as well the chemical properties of the materials used were obtained, the fresh, strength and durability characteristics were also done. All these were carried out in order to know if IFS and QD are suitable for producing a sustainable and eco-friendly HPSCC and also to determine the optimum combination of IFS and QD.in making a sustainable and eco-friendly HPSCC.

2 Materials and methods

2.1 Materials

42.5R Portland cement was utilized as the major binder, satisfying ASTM Type I cement specification [14]. The specific gravity was 3.06, the fineness was 6 %, its initial and final setting times were 38 and 410 minutes respectively and its standard consistency value was 30 %.

Induction furnace slag was sourced for locally and was grounded and sieved to cement size, according to BS EN 197-1 [15]. The specific gravity was 2.95, the fineness was 8 %, its initial and final setting times were 90 and 580 minutes respectively and its standard consistency value was 3 3 %.

Granite of 12.5 mm size was also sourced for locally. It had 0.09 % natural moisture content, 1671 kg/m^3 bulk density, 2.66 specific gravity, 0.75 % water absorption and 37.20 % void content.

River sand was likewise sourced for locally. It had 0.8 % natural moisture content, 1779 kg/m^3 bulk density, 2.64 specific gravity, 0.85 % water absorption and 32.60 % void content.

Quarry dust was also utilized as fine aggregate in partial replacement of river sand. It possessed 0.5 % natural moisture content, 1876 kg/m^3 bulk density, 2.59 specific gravity, 0.68 % water absorption and 27.70 % void content.

Potable water was used as the mixing water for preparing and curing the concrete.

Complast SP 430 super plasticizer was used to make the required flowing ability of concrete, in accordance with ASTM C494/C 494M [16]. It was available in dark brown liquid form.

2.2 Mixture proportioning of the HPSCC

In total, thirteen HPSCC mixtures were designed. The designation and description of the concrete mixtures are presented in Table1. The concrete mixes were designated based on the IFS and quarry dust contents. For example, the HPSCC0, 100 designation was used for a high-performance self-compacting concrete prepared with 0 % IFS content and 100 % cement content, HPSCC20,80,10 designation was used for a high-performance self-compacting concrete prepared with 20 % IFS content, 80 % cement content and 10 % quarry dust. The water/binder (W/B) ratio used was 0.36.

Table 1: Designed HPSCC mixes.

S/N	Concrete type	Cement [kg/m^3]	IFS [kg/m^3]	River sand [kg/m^3]	Granite [kg/m^3]	Water [kg/m^3]	Quarry dust [kg/m^3]	Super plasticizer [kg/m^3]
1	HPSCC0,100	733.0	0	747.66	696.35	263.88	0	14.66
2	HPSCC10,90	659.7	73.3	747.66	696.35	263.88	0	14.66
3	HPSCC20,80	586.4	146.6	747.66	696.35	263.88	0	14.66
4	HPSCC30,70	513.1	219.9	747.66	696.35	263.88	0	14.66
5	HPSCC40,60	439.8	293.2	747.66	696.35	263.88	0	14.66
6	HPSCC50,50	366.5	366.5	747.66	696.35	263.88	0	14.66
7	HPSCC20,80,0	586.4	146.6	747.66	696.35	263.88	0	14.66
8	HPSCC20,80,10	586.4	146.6	672.88	696.35	263.88	74.78	14.66
9	HPSCC20,80,20	586.4	146.6	598.13	696.35	263.88	149.53	14.66
10	HPSCC20,80,30	586.4	146.6	523.36	696.35	263.88	224.30	14.66
11	HPSCC20,80,40	586.4	146.6	448.60	696.35	263.88	299.06	14.66
12	HPSCC20,80,50	586.4	146.6	373.78	696.35	263.88	373.88	14.66
13	HPSCC20,80,60	586.4	146.6	299.06	696.35	263.88	448.60	14.66

2.3 Testing of fresh HPSCC mixes

2.3.1 Slump flow and T_{500} time tests

The slump flow was conducted to determine the filling ability of the fresh HPSCC concrete using an Abram's slump cone. Pouring of the fresh concrete into the cone in just a layer was done, with no form of compaction. After the fresh concrete has settled inside the cone for about five seconds, upright rising of the cone was done, allowing the deformation of the fresh concrete over the surface of the non-absorbing pan. Starting of stopwatch was done at the same time and time taken for fresh concrete to get to the 500 mm spread circle was recorded as the T_{500} time slump flow value. Measurement of the diameter of the concrete flow was done at four different points and was averaged. The averaged flow diameter was recorded as the concrete slump flow, according to EFNARC [17], as indicated in Fig. 1.

2.3.2 L-box test

Passing ability characteristics of the fresh HPSCC was determined by carrying out L-box test in accordance with EFNARC [17], as seen in Fig. 1. The L-box apparatus was placed on a levelled ground with the sliding gate closed. Filling of the vertical part of the apparatus with the fresh concrete was done, after which it was allowed to settle for one minute. Lifting of the gate was done, allowing the fresh concrete to pass to the horizontal part of the apparatus. After the fresh concrete has finished passing, the height of the concrete at the horizontal part, H_1 and the height of the fresh concrete at the vertical part, H_2 were measured and recorded. The blocking ratio of H_2/H_1 was calculated.

2.3.3 V-funnel at $T_{5minutes}$ test

V-funnel at $T_{5minutes}$ test was conducted in determining the resistance of the fresh HPSCC to aggregate segregation according to EFNARC [17], using a V-funnel apparatus as seen in Fig. 1. Setting of the apparatus was done on a firm ground while it was wetted inside with water. Closing of the trap door was done while a head pan was put under the apparatus to receive the concrete. Filling of the V-funnel with the fresh concrete was done in just a layer, with no form of consolidation. Opening of the trap door was done immediately the fresh concrete has settled in the apparatus for five (5) minutes as the fresh concrete was made to flow out by gravity. Simultaneously, starting of the stopwatch was done till the fresh concrete finally discharged and the time taken for the full discharge to be done was taken as the flow time at $T_{5minutes}$.

a) b) c)

Fig. 1: Tests conducted: a) slump flow and T_{500mm} slump flow time tests, b) L-box test, c) segregation resistance test.

2.4 Test procedures for strength characteristics of the hardened concrete

2.4.1 Compression test

Compression test was done in determining the concrete compressive strength at 7, 28 and 56 days. The compression machine, Model YES-2000 with 2000 kN maximum capacity used is presented in Fig. 2. Triplicate 150 mm x 150 mm x 150 mm cubes were tested at each age. A total of 108 concrete cubes were tested for compressive strength. The compression was applied and the maximum or ultimate load carried by the specimen was noted. Compressive strength was determined on the basis of the ultimate load and the cross-sectional area of the cube and averaged from the results of three specimens.

2.4.2 Split tensile strength test

Split tensile strength of the hardened HPSCC was determined by carrying out split tensile test as shown in Fig. 2, at 28 and 56 days of curing. Seventy two cylindrical concrete samples of 200 mm (length) x 100 mm (diameter) samples were tested. Each sample was placed longitudinally in the compression machine. Model YES-2000 with 2000 kN maximum capacity and load was applied perpendicularly till the sample failed. The maximum load at failure was noted and recorded. The split tensile strength value was calculated as the ratio of the maximum load applied to the cross-sectional area of the sample and averaged from the results of three specimens.

2.4.3 Flexural strength test

Flexural strength of the hardened HPSCC was determined via full automated transverse flexural testing machine, Model 2A8580, as shown in Fig. 2, at 28 and 56 days of curing. Test was carried out on triplicate samples of 100 mm (width) x 100 mm (depth) x 500 mm (length) concrete beams at each curing age. Seventy-two samples were tested. Each sample was well positioned in the flexural testing machine on two roller supports and load was applied perpendicularly at the middle of the beam till the sample failed. The maximum load at failure was noted and recorded. The flexural strength value was calculated as the ratio of the maximum load applied to the cross-sectional area of the sample and averaged from the results of three specimens.

2.4.4 Schmidt/rebound hammer test (non-destructive test method)

Schmidt/rebound number of the hardened HPSCC was determined via Schmidt/rebound hammer (NDT) test as shown in Fig. 2, at 28 and 56 days of curing. Test was carried out on triplicate samples of 150 x 150 x 150 mm concrete cubes at each curing age. Seventy-two samples were tested. Prior to testing the samples were dried in the air for twenty-four hours and at ambient temperature in order to get a good result. A steel hammer impacted, with a predetermined amount of energy, a steel plunger in contact with the surface of the concrete. The distance that the hammer rebounded was measured as the Schmidt/rebound number, which was read from a graduated scale to the nearest whole number. Ten readings were taken from each test area and the average rebound number was determined. High value of Schmidt/rebound number shows that the concrete is sufficiently hard and it is of good quality.

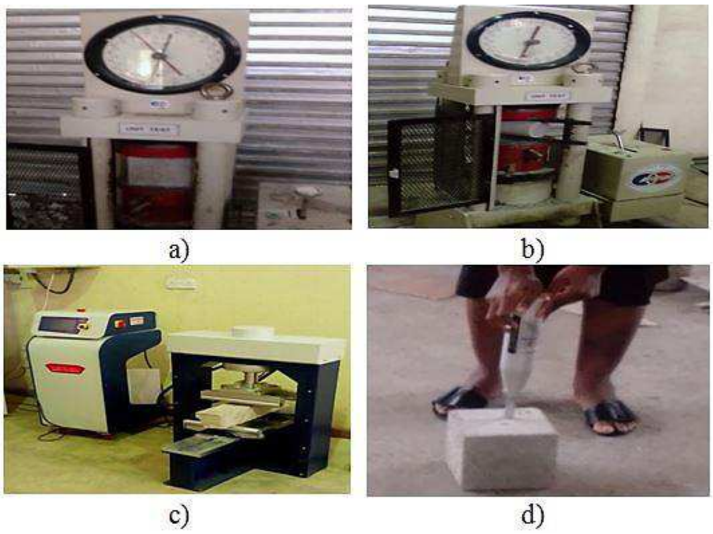

Fig. 2: Strength tests conducted on the hardened concrete a) compression strength, b) split tensile strength, c) flexural strength, d) schmidt/rebound hammer.

2.5 Test procedures for durability characteristics of the hardened concrete

2.5.1 Water absorption and total porosity tests

Water absorption and total porosity of the concrete were tested from saturated, suspended and oven-dry masses of the specimens. Water absorption as well as total porosity tests were done on a total of 72 concrete cubes. 150 mm (breadth) x 150 mm (depth) x 150 mm (length) concrete cube samples were cured for 28 days as well as 56 days. Triplicate specimens were used at each testing age. The specimens were dried in an oven, as seen in Fig. 3, for 24 hours and at 105 ± 5 ^{0}C and allowed to cool. Immediately upon cooling, the specimens were weighed to determine the oven-dry weight. The specimens were then immersed in water at 23 ± 2 ^{0}C for 24 hours. Specimens were removed, patted dry with a dry cloth. The saturated surface-dry and buoyant weights were measured using the buoyancy machine presented in Fig. 3. Finally, the water absorption as well as the total porosity of the concretes were determined by using Eq. (1) and Eq. (2).

$$W_a = \frac{M_s - M_d}{M_d} \text{ x } 100 \text{ \%} , \quad (1)$$

$$P_t = \frac{M_s - M_d}{M_s - M_b} \text{ x } 100 \text{ \%} , \quad (2)$$

where:
P_t - total porosity [volume %],
W_a - *w*ater absorption [mass %],
M_b - buoyant mass of the saturated specimen in water,
M_d - oven-dry mass of the specimen in air,
M_s - saturated surface-dry mass of the specimen in air.

2.5.2 Test for electrical resistivity

A circuit was set up, as seen in Fig. 3, using an Ammeter (0-10 uA), a voltmeter (0-15 V), a variable direct current (*d. c*) power supply (0 - 30 V) and connecting wires. The power supply was varied between 5 V and 10 V. The current was measured and the voltage across the concrete material was equally measured. Then, the electrical resistance was determined using Ohm's law (*V* = *IR*). The electrical resistivity, ρ (Ωm), was calculated using Equation 3. A total of 72 concrete cubes were tested for electrical resistivity. Triplicate specimens of 150 mm x 150 mm x 150 mm were used at each testing age.

$$\rho = \frac{RA}{L} , \quad (3)$$

where;
ρ - *e*lectrical resistivity of the concrete sample [kΩ-cm],
R - *e*lectrical resistance of the concrete sample [kΩ],
A - *c*ross-sectional area of the concrete sample [cm^2],
L - *l*ength of the concrete sample [cm].

a) b)

Fig. 3: Durability tests conducted on the hardened concrete: a) water absorption and total porosity tests, b) electrical resistivity test.

3 Results and discussion

3.1 Properties of the fresh high performance self-compacting concrete

Table 2 presents the fresh SCC results for slump flow, T_{500} slump flow time, L-box and V-funnel at $T_{5minutes}$. For the slump flow result, the values were between 620 mm to 687 mm, showing an excellent HPSCC filling ability. Usually, the slump flow of HPSCC varies from 550 to 850 mm [17]. The slump flow reduced considerably with higher IFS and quarry dust contents, as can be seen from the table. The reduction can be related to the high quantity of paste, reduced quantity of the aggregates in the concrete and increased fineness of the IFS and quarry dust content. The paste volume of the concretes was increased with higher IFS and quarry dust contents. In addition, the aggregate content was decreased at higher IFS and quarry dust contents. The slump flow decreases with increased paste volume, decreased aggregate content of the concrete and increased fineness of binder contents. The increased paste volume decreased aggregate content and increased fineness of binder requires more water to flow and as a result, reduces the concrete deformation. The slump flow results exhibited the relative differences in the filling ability of the concretes with some variation in the flow spread. Hence, the slump flow is recommended to assess the filling ability of HPSCC.

The T_{50cm} slump flow of different HPSCC mixtures varied in the range of 2.59 to 4.29 seconds, as seen in Table 2. The acceptable range for T_{500} slump flow is 2 - 5 seconds [17]. The T_{500} slump flow of concretes with higher IFS and quarry dust contents were above the control mix. It was understood that more kinetic energy was involved. The flow times increased with lower W/B ratio, lesser quantity of coarse aggregates, high volume of fines, increased content of pastes and greater IFS and quarry dust contents, therefore making the concrete more viscous.

The blocking ratio h_2/h_1 ranged between 0.80 and 0.95, as presented in Table 2. Normally, the HPSCC blocking ratio is between 0.8 and 1.0 [17]. The least blocking ratio h_2/h_1 was observed for HPSCC20 80, 60. But the highest ratio h_2/h_1 was attained for HPSCC0, 100. The reason was also as explained for the filling ability properties of the concrete. The blocking ratio h_2/h_1 showed an excellent HPSCC passing ability.

The V-funnel at $T_{5minutes}$ ranged between 1.88 and 3.16 seconds, as presented in Table 2. Normally, HPSCC V-funnel at $T_{5minutes}$ ranges between 0 and 3.5 seconds [17]. The highest value obtained was for HPSCC0, 100, while the lowest value obtained was for HPSCC20, 80, 60. The reason was also as explained for the filling ability properties of the concrete. The V-funnel at $T_{5minutes}$ showed adequate resistance to segregation.

Table 2: Fresh properties of HPSCC.

	Concrete type	**Slump flow [mm]**	**T_{50cm} slump flow [sec]**	**L-box (h_2/h_1)**	**V-funnel at $T_{5minutes}$ [sec]**
1	HPSCC0,100	687	2.59	0.95	1.88
2	HPSCC10,90	685	2.80	0.92	2.56
3	HPSCC20,80	680	3.72	0.90	3.00
4	HPSCC30,70	670	3.84	0.88	3.05
5	HPSCC40,60	657	3.93	0.83	3.08
6	HPSCC50,50	652	3.97	0.81	3.11
7	HPSCC20,80,0	680	3.72	0.90	3.00
8	HPSCC20,80,10	673	3.76	0.90	3.02
9	HPSCC20,80,20	660	3.85	0.89	3.05
10	HPSCC20,80,30	654	3,98	0.87	3.07
11	HPSCC20,80,40	641	4.14	0.84	3.10
12	HPSCC20,80,50	636	4.22	0.82	3.12
13	HPSCC20,80,60	620	4.29	0.80	3.16

3.2 Strength properties of high performance self-compacting concrete

3.2.1 Compressive strength

From the average compressive/crushing strength seen in Fig. 4 and Fig. 5, there was increase in the strength of the HPSCC from curing ages 7 days to 56 days as a result of cement hydration. Curing ages 7 days and 28 days had the highest strength increment. 28 days compressive/crushing strength was in the range of 38.67 to 66.79 MPa for different concretes. Also, 56 days compressive/crushing strength of the concrete varied from 55.25 to 78.89 MPa. The highest level of later-age compressive strength was achieved for HPSCC20, 80, 50, which contained 20 % IFS and 50 % QD. Conversely, the least compressive/crushing strength for all the curing days was obtained for HPSCC20, 80, 10, which was produced with 20 % IFS and 10 % QD. Nevertheless, the requirements for the early-age compressive strength (> 20 MPa) and later-age compressive strength (> 40 MPa at 28 days and 90 days) of high performance concrete [18] were fulfilled for all HPSCCs. The development of good compressive strength is due to the use of high-range water reducer (HRWR) that resulted in dense concretes with minimum voids. The increase in compressive strength relates to the fact that the porosity of the HPSCC was reduced. Also, there was increased binder volume due to low water/binder ratio as the quantity of water was not varied for all concretes. It was deduced that the binder volume increment made the fine aggregate as well as the coarse aggregate well packed as a result, leading to a higher compressive strength. The IFS and QD significantly increased the compressive strength of concretes at the ages of 7, 28 and 56 days. The improvement of compressive strength is mostly as a result of the fact that IFS is a pozzolan as well as due to the micro-filling nature of both the IFS and QD. With a smaller particle size, the IFS and QD is able to fill the concrete micro void. Likewise, IFS chemically combines with moisture as well as calcium hydroxide $Ca(OH_2)$ which is a product of hydration of cement to generate more calcium silicate hydrate. All concretes with only IFS, fulfilled the performance criteria for the tested compressive strengths. However, excellent compressive strengths were achieved for the concretes with 10 and 20 % IFS. Although, IFS content greater than 20 % caused mixing and handling difficulties due to excessive cohesiveness or stickiness, particularly at lower W/B ratios. Therefore, 20 % IFS content can be recommended as the optimum IFS content for HPSCC. Likewise, all concretes including IFS (optimum) and QD fulfilled the performance criteria for the tested compressive strengths. However, excellent compressive strengths were achieved for the concretes with 40 and 50 % QD. Therefore, HPSCC with 20 % IFS content and 50 % QD content (HPSCC20, 80, 50) can be recommended as the optimum HPSCC mix.

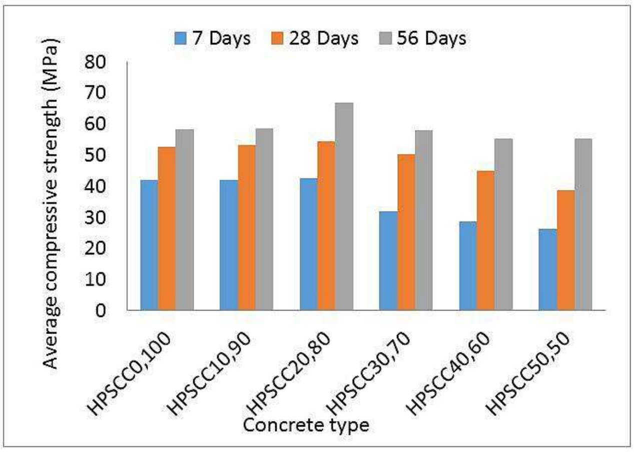

Fig. 4: Compressive strength of the tested HPSCC with induction furnace slag and no quarry dust.

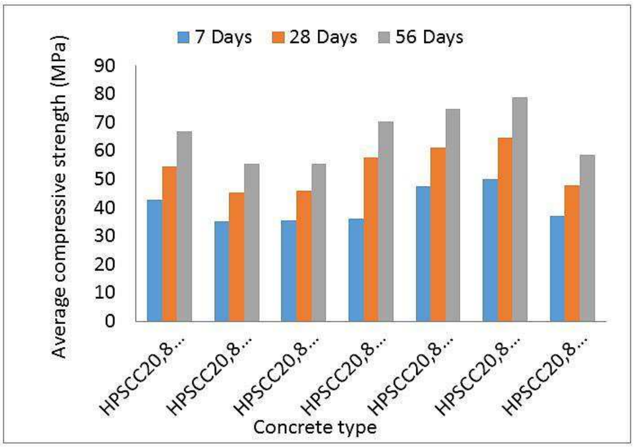

Fig. 5: Compressive strength of the tested HPSCC with induction furnace slag (optimum) and quarry dust.

3.2.2 Rebound number/Schmidt number

The rebound number varied in the range of 30 to 56, as seen from Fig. 6 and Fig. 7. This indicates a very good hard layer of the concretes. This is because a rebound number higher than 30 generally indicates an excellent quality of concrete [19]. The excellent rebound numbers attained was mostly due to the improved pore structure of concretes resulting from enhanced filling ability. Also, the rebound number of all concretes at 56 days was greater than that at 28 days, which is due to reduced porosity resulting from continued hydration of the cementing materials.

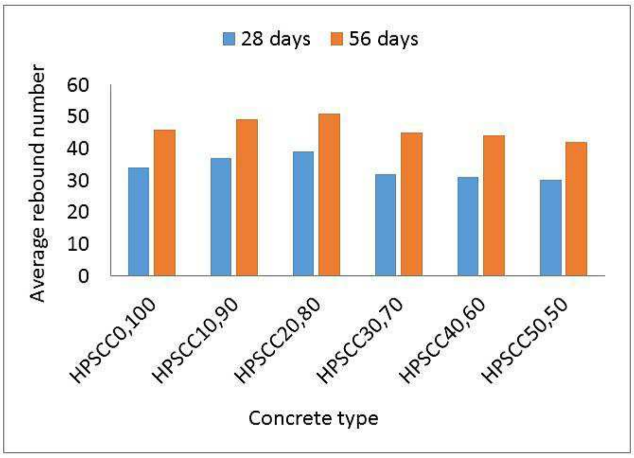

Fig. 6: Average rebound number of the tested HPSCC with induction furnace slag and no quarry dust.

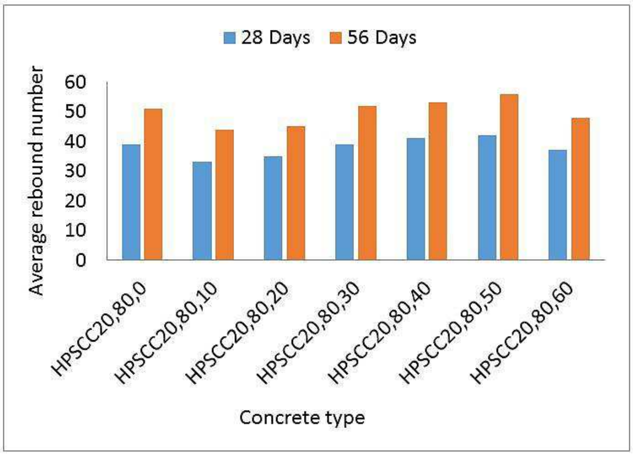

Fig.7: Average rebound number of the tested HPSCC with induction furnace slag (optimum) and quarry dust.

3.2.3 Split tensile strength

From the result obtained in Fig. 8 and Fig. 9, the splitting tensile strength increased as the curing age increased from 28 days to 56 days. Also, addition of IFS and QD increased the splitting tensile strength up to 20 % percentage replacement level for IFS and 50 % percentage replacement level for QD, for all curing ages. This was due to the improvement of the HPSCC porosity as a result of the micro-filling capability of IFS and QD as well as the pozzolanic nature of the IFS [20]. The highest value obtained at 28 days was 4.74 MPa, while the highest obtained at 56 days was 5.66 MPa.

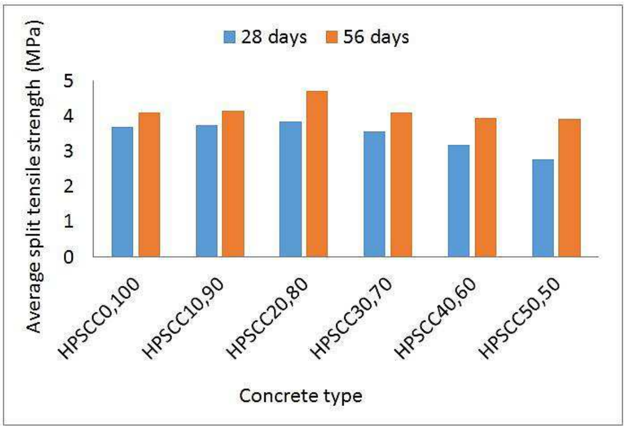

Fig. 8: Average split tensile strength of the tested HPSCC with induction furnace slag and no quarry dust.

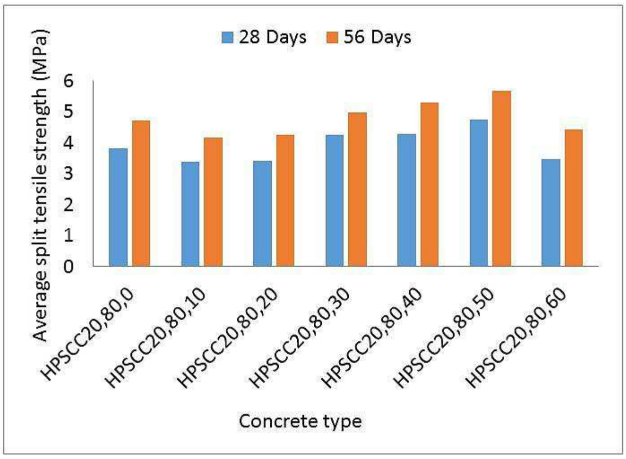

Fig. 9: Average split tensile strength of the tested HPSCC with induction furnace slag (optimum) and quarry dust.

3.2.4 Flexural strength

From the result obtained in Fig. 10 and Fig. 11, the flexural strength increased as the curing age increased from 28 days to 56 days. Also, addition of IFS and QD increased the flexural strength up to 20 % percentage replacement level for IFS and 50 % percentage replacement level for QD, for all curing ages. This was due to the improvement of the HPSCC porosity as a result of the micro-filling capability of IFS and QD as well as the pozzolanic nature of the IFS [20]. The highest value obtained at 28 days was 12.96 MPa, while the highest obtained at 56 days was 16.21 MPa.

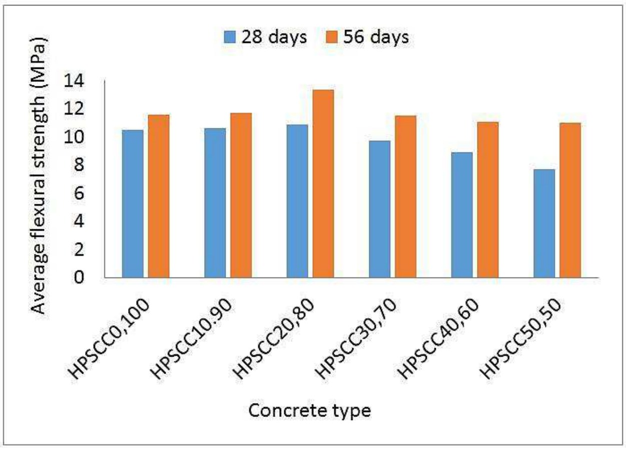

Fig. 10: Average flexural strength of the tested HPSCC with induction furnace slag and no quarry dust.

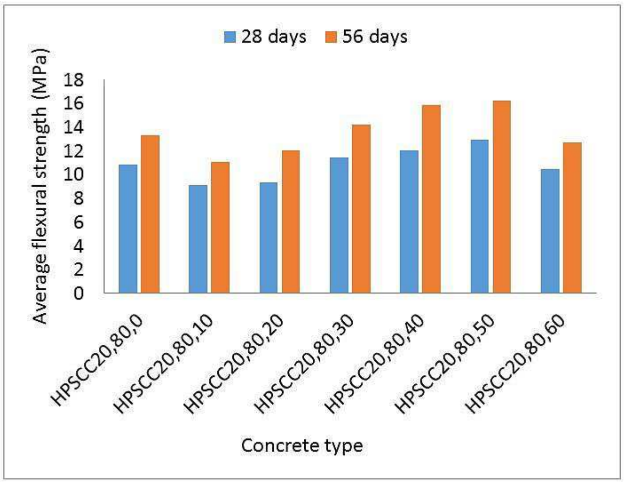

Fig. 11: Average flexural strength of the tested HPSCC with induction furnace slag (optimum) and quarry dust.

3.3 Durability properties of high performance self-compacting concrete

3.3.1 Water absorption

Lower water absorption was obtained at 56 days for all concretes, as seen in Fig. 12 and Fig. 13. Less porous concrete usually has low water absorption capacity. This research found out that the HPSCC total porosity is low. Also, there was increased volume of fines due to low water/binder ratio as the quantity of water was not varied for all concretes. It was deduced that the volume of fines increment made the fine aggregate as well as the coarse aggregate well packed as a result, produced an increased calcium-silicate-hydrate (CSH) leading to a reduced water absorption.

The IFS and QD significantly reduced the water absorption capacity of the concretes at 56 days. The reduction is mostly due to the micro filling ability of IFS and QD as well as the pozzolanic activity of IFS. With a smaller particle size, the IFS and QD is able to fill the concrete micro void. Likewise, IFS chemically combines with moisture as well as calcium hydroxide $Ca(OH_2)$ which is a product of hydration of cement to generate more calcium silicate hydrate. Likewise, this added calcium silicate hydrate causes reduction in the concrete pore structure as a result of the micro-filling of the capillary pores, thereby improving the concrete microstructures at the bulk paste matrix (BPM) as well as at the interfacial transition zone (ITZ) resulting in enhanced water absorption.

Nevertheless, the water absorption varied from 3.00 % to 4.49 %, which is relatively low. The water absorption of HPSCC generally varies in the range of 3 to 6 %. The concretes with 20 % content of IFS and 60 % QD content provided lowest water absorption. For example, HPSCC20, 80, 60 provided a water absorption of 3.0 % water absorption at 56 days. HPSCC0, 100 has the maximum water absorption value in this research which provided 4.49 % water absorption at the age of 28 days. The low range of water absorption (3.00 to 4.49 %) obtained was due to the limited pore connectivity and reduced HPSCC porosity. Concrete water absorption becomes low when the capillary porosity is less than 15 %, since most of the pores appear to be discontinuous and thus the flow channels for the water movement are reduced [21].

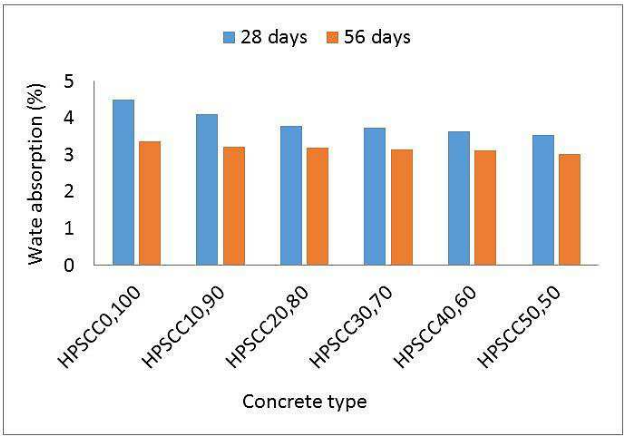

Fig. 12: Water absorption of the tested HPSCC with induction furnace slag and no quarry dust.

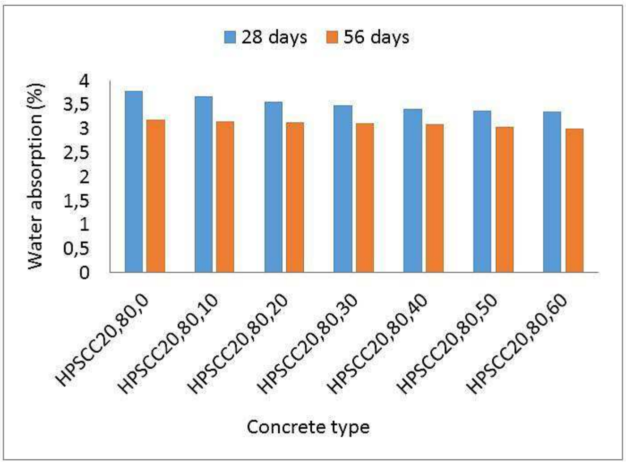

Fig. 13: Average water absorption of the tested HPSCC with induction furnace slag (optimum) and quarry dust.

3.3.2 Total porosity

The average test results for the total porosity of concretes are illustrated in Fig. 14 and Fig. 15. The total porosity ranged from 7.02 to 11.66 %. HPSCC20, 80, 60 gave the least total porosity, having a total porosity of 7.02 % at 56 days. On the contrary, HPSCC0, 100 gave the maximum value, which provided a total porosity of 11.66 % at 28 days. The total porosity results obtained in this study showed that the HPSCC quality was high, as written by Hearn [22] that concrete of high quality usually have a total porosity value of between 7 % and 15 %. Low values of total porosity were obtained for all concretes at the age of 56 days for the same reasons as discussed before. In addition, the pore structure of the concretes was improved due to the use of HRWR. The water reducers improve the fresh concrete fluidity, as a result, enhances the packing structures of the fine aggregates and the binders. Likewise, the water reducer improves the rate of hydration as a result of cement dispersion. Therefore, total porosity as well as the sizes of the pores are minimized in the concrete.

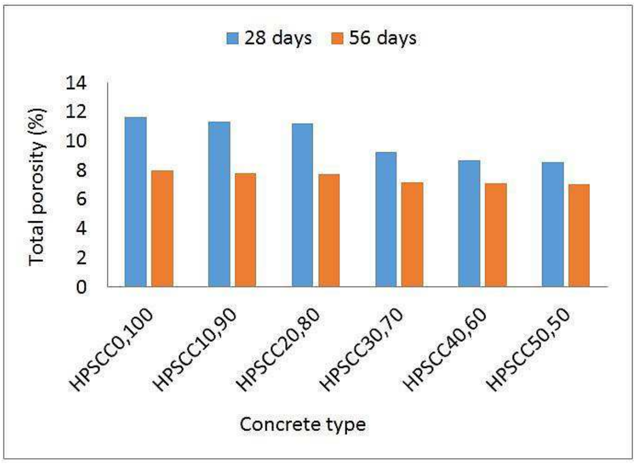

Fig. 14: Total Porosity of the tested HPSCC with induction furnace slag and no quarry dust.

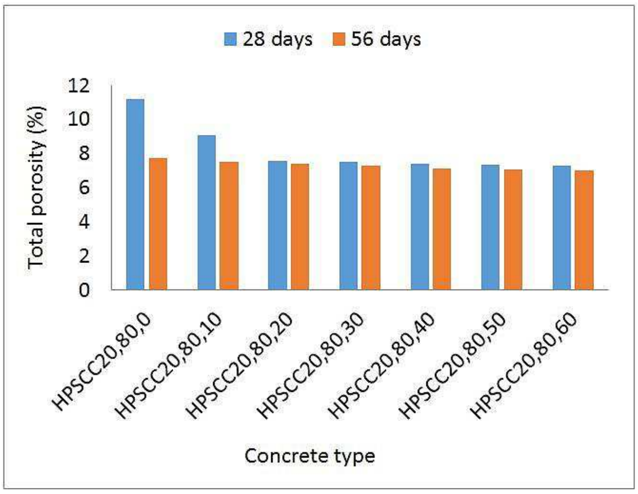

Fig. 15: Average total porosity of the tested HPSCC with induction furnace slag (optimum) and quarry dust.

3.3.3 Electrical resistivity

The electrical resistivity of the concretes varied in the range of 10.19 to 14.83 kΩ/cm for different types of concrete, as seen from Fig. 16 and Fig. 17. The resistivity of concretes must be greater than 5 kΩ/cm, since the corrosion rate can be high below this limit [22]. A concrete shows minimal resistance to corrosion with electrical resistivity value range of 5 kΩ/cm to 10 kΩ/cm while it shows an excellent resistance to corrosion with an electrical resistivity value of over 10 kΩ/cm [22]. All IFS and QD concretes provided electrical resistivity values greater than 10 kΩ/cm. Moreover, the true electrical resistivity of all concretes was higher at the age of 56 days. This is due to the reduced porosity at the later age. Also, the ionic concentration in pore solution decreases at later age due to enhanced micro filling and pozzolanic reaction and consequently the resistivity is increased.

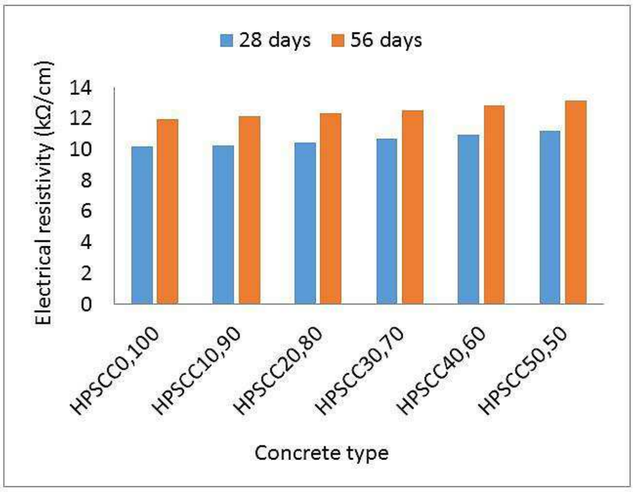

Fig. 16: Electrical resistivity of the tested HPSCC with induction furnace slag and no quarry dust.

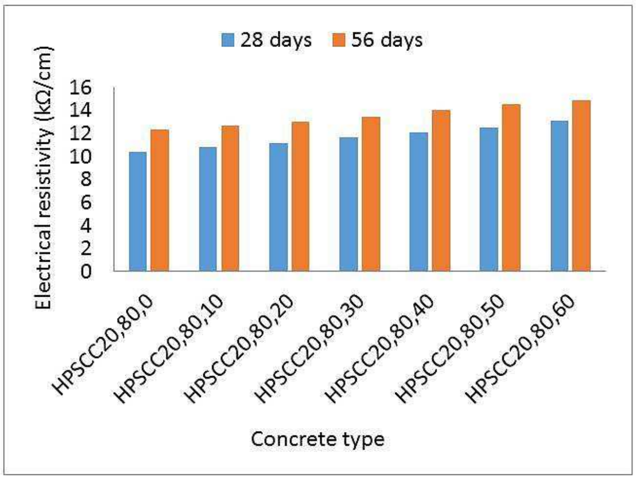

Fig. 17: Average electrical resistivity of the tested HPSCC with induction furnace slag (optimum) and quarry dust.

3.4 Concrete durability

The hardened properties determined indicated a good durability. The rebound hammer, compressive/crushing strength, split tensile strength as well as flexural strength results exhibited excellent physical condition or quality of the HPSCC with a reduced porosity and thus pointed to good durability. In addition, the low range of water absorption and total porosity as well as the high range of electrical resistivity obtained for most concretes suggested that they showed good durability. This is because the reduction in porosity enhances the freeze-thaw durability, decreases the water and gas permeability and increases the resistance to acid attack, carbonation and chloride penetration. A lower range of water absorption indicates the reduced penetration of chlorides and other deleterious agents into concretes. Also, the concretes with an electrical resistivity higher than 10 kΩ/cm exhibit low chloride ion permeability and reduced corrosion rate [23].

3.5 Optimum contents of induction furnace slag and quarry dust

The strength and durability properties of the concretes were improved gradually with the increased IFS and QD contents. All concretes including IFS and QD fulfilled the performance criteria for the tested strength and durability properties. However, excellent strength and durability properties were achieved for the concretes with 20 % IFS and 50 % QD. Therefore, HPSCC20, 80, 50 can be recommended as the optimum HPSCC mix.

4 Conclusions

Based on the experimental, the following conclusions are arrived at:

1) The constituent materials were suitable for producing the concrete mixtures, as they met the specified physical and chemical requirements.

2) The filling ability, passing ability and segregation resistance criteria were fulfilled for all HPSCCs.

3) The strength and durability properties of the HPSCCs were improved due to greater hydration of cement, enhanced micro filling and pozzolanic activity of IFS and QD.

4) The strength and durability properties of the HPSCCs were enhanced at low water/binder ratio as a result of improvement in paste densification resulting from greater hydration products in the presence of higher fines content.

5) The HPSCC strength and durability characteristics progressively enhanced as the IFS and QD contents increased. However, the performance criteria for all targeted strength and durability properties were fulfilled at 20 % IFS and 50 % QD, which was also suitable for the fresh properties of the HPSCC.

6) The production of high-performance self-compacting concrete incorporating IFS and QD is attainable. This research benefits future study and the technological advancement of HPSCC by focussing on two prospective solutions. Firstly, IFS and QD can be recycled, hence reducing its indiscriminate disposal, which portends serious environmental challenges. Secondly, IFS can be used as an alternative SCM, which is more eco-friendly than the PC.

References

[1] MOHANKUMAR, N. B.: High Quality Concrete Comprising of Several Mix of ACM's. Civil and Environmental Engineering, Vol. 16, Iss. 1, 2020, pp. 138-147.
[2] JOULAZADEH, M. H. - JOULAZADEH, F.: Slag, Value Added Steel Industry by Products. Archives of metallurgy and materials, Vol. 55, 2016, pp. 1137-1145.
[3] ANDREWS, A. - GIKUNOO, E. - OFOSU, M. - TOFAH, H.: Chemical and Mineralogical Characterization of Ghanaian Foundry Slags. Journal of Minerals and Materials Characterization and Engineering, Vol.11, 2017, pp. 183-191.
[4] SAFUDDIN, M, - ZAIN, M. F.: Effects of Silica Fume and Fly Ash on the Properties of High Performance Concrete. Proceedings of the Annual Conference on Canadian Society for Civil Engineering, Vol. 10, 2018, pp. 31 – 42.
[5] ABDULLAH, M. H. - ABUELGASIM, R. - RASHID, A. S. - MOHDYUNUS, Z.: Engineering Properties of Tanjung Bin Bottom Ash. SEPKA-ISEED, 01006, Vol.10, 2018, pp. 10-20.
[6] QURISHEE, M. A. - IQBAL, I. T. - ISLAM, M. S. - ISLAM, M.M.: Use of Slag as Coarse Aggregate and its Effect on Mechanical Properties of Concrete. In Proceedings of 3rd International Conference on Advances in Civil Engineering, CUET, Chittagong, Bangladesh, 2018.
[7] NETINGER, I. - RUKAVINA, M. J. - BJEGOVIC, D. - MLADENOVIC, A.: Concrete Containing Induction Furnace Slag Aggregate: Performance after High Temperature Exposure, 2016.
[8] JOHN, A. - JOHN, E.: Study on the Partial Replacement of Fine Aggregate using Induction Furnace Slag. American Journal of Engineering Research, Vol. 4, Iss. 1, 2019, pp. 1-5.
[9] SYED, I. A. - SHAFIQUR, M. R.: Mechanical and Durability Properties of Induction Furnace Slag Incorporated Recycled Aggregate Concrete. Advances in Civil and Structural Engineering Journal, Vol. 10, Iss. 4, 2018, pp. 1-11.
[10] MUHIT, I. B. - RAIHAN, M. T. - NURUZZAMAN, M.: Determination of Mortar Strength Using Stone Dust as a Partially Replaced Material for Cement and Sand. Advances in Concrete Construction, Vol. 2, Iss. 4, 2019, pp. 249–259.
[11] SUKUMAR, B. - NAGAMANI, K. - SRINIVASA RAGHAVAN, R.: Evaluation of Strength at Early Ages of Self-Compacting Concrete with High Volume Fly Ash. Construction and Building Materials, Vol. 22, Iss. 7, 2019, pp. 1394–1401.
[12] CHITLANGE, M. R. - PAJGADE, P. S.: Strength Appraisal of Artificial Sand as Fine Aggregate in SFRC. Journal of Engineering and Applied Sciences, Vol. 5, Iss. 10, 2019, pp. 34-38.
[13] HO, D. W. - SHEINN, A. M. - NG, C. C. - TAM, C. T.: The Use of Quarry Dust for HPSCC Applications. Cement and Concrete Research, Vol. 32, Iss. 5, 2018, pp. 505-511.
[14] AMERICAN SOCIETY FOR TESTING AND MATERIALS C 150: Standard Specification for Portland Cement. Annual Book of ASTM Standards. American Society for Testing and Materials, Philadelphia, USA. 2020.
[15] BRITISH STANDARD EN 196- 3: Method of Testing Cement: Physical Test. BSI, London, 2016.

[16] AMERICAN SOCIETY FOR TESTING AND MATERIALS C 494/ C494M: Standard Specification for Chemical Admixtures for Concrete. Annual Book of ASTM Standards, American Society for Testing and Materials, Philadelphia, USA, 2020.

[17] EUROPEAN FEDERATION OF NATIONAL ASSOCIATIONS REPRESENTING PRODUCERS AND APPLICATORS OF SPECIALIST BUILDING PRODUCTS FOR CONCRETE: Specifications and Guidelines for Self-Consolidating Concrete. European Federation of Suppliers of Specialist Construction Chemicals (EFNARC), Surrey, UK, 2002, pp. 1-32.

[18] BRAMESHUBER, W. - UEBACHS, S.: Practical Experience with the Application of Self-Compacting Concrete in Germany. Proceedings of the International Symposium on Self-Compacting Concrete, Tokyo, Japan. 2016, pp. 687-695.

[19] MISHRA, A.: Rebound Hammer Test on Concrete- Principle and Procedure. Journal of Civil Engineering Research, Vol. 7, 2016, pp 1-10.

[20] AMERICAN SOCIETY FOR TESTING AND MATERIALS C 618: Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete. Annual Book of ASTM Standards, American Society for Testing and Materials, Philadelphia, USA, 2020.

[21] BENTZ, D. P. - HAECKER, C. J.: An Argument for Using Coarse Cements in High-Performance Concretes. Cement and Concrete Research, Vol.29, 2019, pp. 615-618.

[22] HEARN, N.: Pore Structure and Permeability. Significance of Tests and Properties of Concrete and Concrete-Making Materials. ASTM STP 169C, American Society for Testing and Materials, Philadelphia, USA, 2016, pp. 240-262.

[23] SUGITA, S. - YU, Q. - SHOYA, M. - TSUKINAGA, Y. - ISOJIMA, Y.: The Resistance of Rice Husk Ash Concrete to Carbonation, Acid attack and Chloride Ion Penetration. Proceedings of the Third CANMET/ACI International Conference on High Performance Concrete: Design and Materials and Recent Advances in Concrete Technology, ACI SP-172, V.M. Malhotra, ed., American Concrete Institute, Farmington Hills, Michigan, USA, 2017, pp. 29-43.

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