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Influence Of Sand To Aggregate Ratio On The Fresh And Mechanical Properties Of Self-Compacting High-Performance Concrete

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Abstract – Self-compacting high-performance concrete (SCHPC) combines the properties and advantages of self-compacting concrete and high-performance concrete in both fresh and hardened state. For the SCHPC mix design, sand to aggregate ratio is a crucial parameter and plays an important role in governing the properties of SCHPC mix. This paper presents the results of an experimental investigation on the flowability, passing ability and mechanical properties of SCHPC mixes for various sand to total aggregate (S/A) ratio and water to cementitious material (w/cm) ratio. Tests were conducted on specimens using four (w/cm) ratios: 0.26, 0.30, 0.35 and 0.40 and two (S/A) ratios: 48% and 53%. All the mixtures were tested using slump flow test, J-Ring test, and L-box test in the fresh state as well as compressive strength, splitting tensile strength, and unit weight in the hardened state. The test results revealed that a lower S/A ratio (0.48) enhanced the flowability where as the higher S/A ratio (0.53) enhanced the passing ability. The lower S/A ratio (0.48), containing greater proportion of coarse aggregate, generally improved the mechanical properties of SCHPC compared to the mixes with the higher S/A ratio (0.53).

***Keywords*:** Self-compacting concrete; high-performance concrete; sand to aggregate ratio, water to cementitious material ratio.

1. Introduction

Self-compacting concrete (SCC) is one of the greatest innovations in concrete technology and the production of SCC is increased rapidly due to its several merits in terms of improved properties and applications compared to conventional concrete. SCC can simply be placed into the framework and go through areas of congested reinforcements under its own weight without any external vibration [1]. High-performance concrete (HPC) is a special type of concrete with high strength and durability [2]. Self-compacting high-performance concrete (SCHPC) is produced by combining the characteristics of SCC and HPC which results in superior performance in terms of flow characteristics, strength, and durability. However, SCHPC is more sensitive to mix design and material qualities compared to conventional concrete. Due to variations in the water content, type and shape of aggregates, fineness modulus, grading and the admixture type, the quality of the produced concrete can significantly vary [3], [4].

Aggregates, which account for more than 60% of the total volume of SCC, have a major effect on both fresh and hardened properties of the mixtures of SCC [5]. The volume fraction of coarse aggregate and particle size should be controlled in a specific range to ensure the required flowability of SCC [3]. Many researchers have investigated coarse aggregates characteristics as well as their influence on the fresh and mechanical properties of SCC as the investigation of aggregate properties is highly crucial in the mix proportioning of SCC [6], [7].

The rheological and mechanical properties of concrete are significantly affected by the fine aggregate to the total aggregate ratio. The low sand to aggregate ratio (S/A ratio) negatively affects the flowability of concrete. This is attributed to the absence of sufficient mortar which fills voids among coarse aggregates. On the other hand, a high S/A ratio also reduces the flowability of concrete due to the high specific surface area of sand that minimises the cement layer thickness which lubricates solid particels and allows aggregate particles to flow more easily [8]. The European Guidelines for Self-Compacting Concrete [9] suggested that the typical range of fine aggregate is between 48% and 55% of the total aggregate by weight. The S/A ratios also affect the mechanical properties of concrete. The compressive strength, unit weight, tensile strength, modulus of elasticity and the fracture energy of SCC are influenced by the content of coarse aggregate which decreases inversely to the increase of S/A ratio [3], [7], [10]. The design of SCHPC and the performance of concrete structures mainly rely on these mechanical characteristics.

The objective of this study is to investigate the effects of the S/A ratio (0.48 and 0.53) on the performance SCHPC with different water to cementitious materials (w/cm) ratio and paste to solid (p/s) ratio including the fresh properties (slump flow test, J-ring test, L-box test) and mechanical properties (compressive strength, unit weight and splitting tensile strength).

2. Experimental Programme

2.1 Materials

Portland cement (type I 52.5) complying with EN 197-1[11], ground granulated blast furnace slag (GGBS) and fly ash with a specific gravity of 3.15, 2.4, and 2.4 respectively were used. The fineness of the Portland cement is 384 m^2/kg. A superplasticiser of Poly-Aryl-Ether based type (MasterGlenium ACE 499) with a specific gravity of 1.07 was used. Crushed limestone coarse aggregate with a specific gravity of 2.65 and a maximum size of 20 mm is used in this research. The fine aggregate is natural river sand with a specific gravity of 2.55 and a maximum size of 2 mm. The fine aggregate was replaced by an equivalent volume (30%) of the coarser fraction of limestone (limestone dust) with a specific gravity of 2.6 and the size ranging between 0.125 mm and 2 mm.

2.2 Mixture design

Four series of SCHPC mixes were designed based on the mix design method proposed by Karihaloo and Ghanbari [12] , and Abo Dhaheer et al. [13] with compressive strengths of 70, 80, 90 and 100 MPa and, w/cm ratios of 0.26, 0.30, 0.35 and 0.40 respectively. All mixtures were prepared with 40% (by weight) replacement of Portland cement with fly ash and GGBS. The SCHPC mixes contained two different S/A ratios, and the mixtures are designated A and B for 0.48 and 0.53 S/A ratios, respectively. Table 1 presents the compositions of all mixes.

Table 1. Mix proportions of SCC mixes, $\boldsymbol{kg/m^3}$

Mix designation	water	cm			SP	FA	CA	w/cm	SP/cm
		Cement	GGBS	Fly Ash					
70A	188.4	283	94	94	2.83	775	840	0.40	0.6%
70B	188.4	283	94	94	2.83	848	750	0.40	0.6%
80A	174.2	299	100	100	3.48	780	845	0.35	0.7%
80B	174.2	299	100	100	3.48	863	751	0.35	0.7%
90A	164.4	329	110	110	4.38	769	833	0.30	0.8%
90B	164.4	329	110	110	4.38	843	751	0.30	0.8%
100A	151.7	350	117	117	5.83	767	831	0.26	1.0%
100B	151.7	350	117	117	5.83	844	751	0.26	1.0%

2.3 Test methods

Self-compactibility characteristics of the mixes were evaluated with slump flow, J-ring, and L-box tests according to the EFNARC guidelines [9]. From each of the eight mixes (Table 1) five cubes (100×100×100 mm^3), and three cylinders (100 mm × 200 mm) were cast. After 1 day, the specimens were de-moulded and cured in water at a temperature of 22 (± 1) °C for 7 days and 28 days. Prior to the compression test, the unit weight was measured after 28 days of curing. The weight of cylindrical specimens was determined preceding compression testing and then the unit weight was computed by measuring the volume of the cylindrical specimen.

3. Results and Discussion

3.1. Fresh properties

All the above mixes were subjected to slump flow test (flowability) and J-ring test and L-box test (passing ability) to ensure that all mixtures satisfied the self-compacting criteria without any sign of segregation or bleeding. All SCC mixes passed the fresh state flow tests (Figures 2-4). The experimental results of fresh properties of all mixtures are summarised in Table 2 and Table 3.

Table 2. Slump flow tests of SCC mixes

Mix designation	Spread(mm)	t_{500}(s)
70A	750	1.27
70B	720	1.8
80A	770	1.9
80B	750	2
90A	800	3
90B	790	3.6
100A	840	4.2
100B	825	4

Table 3. J-ring and L-box tests of SCC mixes

Mix designation	J-ring* flow test		L-box** test		
	Spread(mm)	t_{500j} (s)	t_{200} (s)	t_{400} (s)	H_1/H_2
70A	710	2.1	0.65	1.73	0.93
70B	690	2.75	0.8	1.8	0.95
80A	730	3.5	0.93	2.23	0.95
80B	710	3.2	1.84	4.85	0.97
90A	770	4.3	1.24	3.4	0.97
90B	760	5	1.46	3.95	0.98
100A	790	5.3	3.1	5.8	0.98
100B	775	6.4	3	5.6	0.99

* J-ring apparatus with 12 steel rods

** L-box has two smooth steel bars of (12 ± 0,2) mm diameter

The results of the slump flow test are given in Figure 1 which illustrates that as the S/A ratio is increased from 0.48 to 0.53 (while keeping the volume fraction of total aggregate constant and maintaining the paste volume constant for each series), the slump flow diameter decreased. This result is in agreement with the experimental study presented in [14]. This could be attributed to the fact that the higher surface area to volume ratio of sand raises the effective aggregate volume. However, Yardimci et al. [10] reported contrasting results to the present study, the flowability increased when S/A ratio is increased from 0.484 to 0.715. However, the reason behind that observation was due to the increase in the amount of superplasticiser used with the increase of S/A ratios.

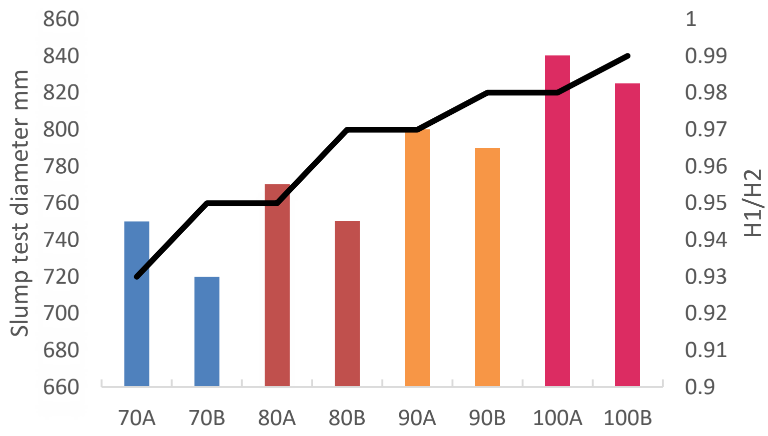

Figure 1. Diameters in slump tests and H_1/H_2 in L-box tests

J-Ring test can be used in conjunction with a slump flow test to evaluate the passing ability of the SCC mix according to the ASTM C 1621/C1621M [15]. If the difference in the final spread diameter between the slump flow and J-ring flow is less than 25mm, then there is no visible blocking. There is little to noticeable blockage if the difference is between 25mm to 50mm. The difference between the spread diameter in slump and J-ring tests observed are shown in Table 4 and the difference in spread diameter for all the mixes ranges between 25mm to 50mm.

Table 4. Difference between slump and J-ring spread

Mix designation	D_{slump}	D_{J-ring}	$D_{slump} - D_{J-ring}$
70A	750	710	40
70B	720	690	30
80A	770	730	40
80B	750	710	40
90A	800	770	30
90B	790	760	30
100A	840	790	50
100B	825	775	50

The effect of S/A ratio on the passing ability was assessed by the H_2/H_1 from L-box test (Table 3). This test is recommended for evaluating the passing ability of SCC mixtures. According to EFNARC, an increasing H_1/H_2 ratio indicates better passing ability [9]. The results of L-box test showed that increasing the S/A ratio from 0.48 to 0.53 slightly enhances the passing ability of all mixes. It can be concluded that increasing S/A ratio from 0.48 to 0.53 improved the passing ability while the slump flow diameter (flowability) slightly decreased as shown in Figure 1.


Figure 2. Slump cone test of SCC mixes


Figure 3. J-ring test of SCC mixes


Figure 4. L-box test of SCC mixes

3.2 Mechanical properties

3.2.1 Compressive strength

The compressive strength of four series of SCHPC specimens with 0.48 and 0.53 S/A ratios after 7 and 28 days is shown in Table 5. The mixes with 0.48 S/A ratio achieved higher compressive strength compared to mixes with 0.53 S/A ratio. However, the effect of S/A ratios on the compressive strength is insignificant within the ratio of S/A recommended by EFNARC guidelines. It is generally agreed that the compressive strength is mainly determined by the ratio of water to cementitious materials and the composition of the powder [16]. Nevertheless, compressive strength is also affected by the coarse aggregate, the fraction of which decreases as the S/A ratio increases. Hence, substituting coarse aggregate with an equivalent volume of sand resulted in a reduction in compressive strength [3]. Yardimci et al. reported that the increase of the S/A ratio from 0.48 to 0.71 resulted in a reduction of 13.7% of the compressive strength of SCC [10].

Table 5. Hardened properties tests for SCC mixe

Mix designation	Compressive strength (MPa)		Unit weight (kg/m^3)	Tensile strength (MPa)	Ratio of tensile strength / compressive strength
	7 days	28 days			
70A	48.25	74.22	2382.125	5.28	0.0711
70B	45.30	70.14	2376.396	5.65	0.0806
80A	63.48	80.10	2435.495	7.38	0.0921
80B	62.82	78.00	2413.001	7.52	0.0964
90A	70.50	93.20	2445.893	8.00	0.0858
90B	68.70	90.00	2430.933	7.81	0.0868
100A	80.40	100.10	2471.252	7.17	0.0716
100B	74.50	98.10	2462.127	6.57	0.0670

3.2.2 Unit weight

Several conventional equations indicate that coarse aggregate content affects the value of modulus of elasticity of concrete by affecting the value of its unit weight[17]. Tomosawa examined the unit weight of concrete specimens before the compression test [7]. As it can be seen from Table 5, all mixes A with lower S/A ratio (0.48), higher coarse aggregate content, have higher unit weight compared to mixes B. It can be seen that the higher compressive strength and lower S/A ratio have the higher unit weight. In other words, for a given concrete strength, the higher S/A ratio resulted in a decrease in the unit weight of concrete which would result in a reduction in the value of modulus of elasticity.

3.2.3 Splitting tensile strength

By adjusting the ratio of S/A, the distribution of fine and coarse aggregate, as well as the force among particles, could be changed. Table 5 shows the tensile strength and the ratio of compressive strength to tensile strength of SCC mixes after 28 days. These results show the ratios are in the range of 6% - 10%. According to the guideline from AIC 318 [18], the relationship between splitting tensile strength and compressive strength of concrete can be described by Equation 1 as,

$$f_{tsp} = 0.56 {f_c}^{0.5} \quad (1)$$

where, f_{tsp} is the tensile strength and f_c is the compressive strength.

The relationship between splitting tensile strength and compressive strength of SCHPC mixes (Figure 5) can be expressed by Equation 2 as,

$$f_{tsp} = 0.75074 {f_c}^{0.5} \quad (2)$$

It can be concluded that the ratio of tensile strength to compressive strength of SCHPC mixes were higher than that of normal concrete.

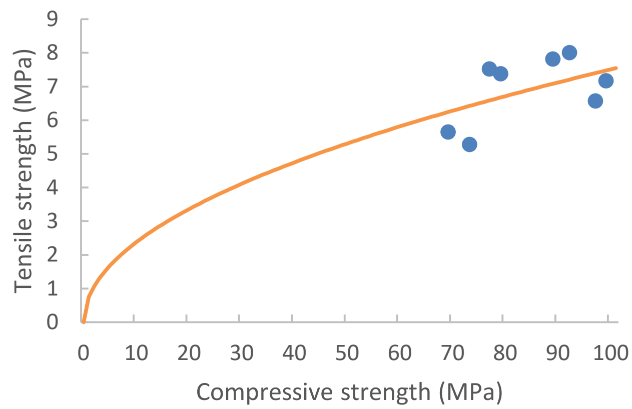

Figure 5. Relationship between splitting tensile strength and compressive strength of SCC mixes

4. Conclusion

Self compacting high performance concrete is a vastly used material in the industry and hence it always presents an opportunity for the researchers to innovate and improve this material. This study investigates the effects of mix proportions on self compacting high performance concrete by varying its consitutents. The proportion variables include sand to aggregate ratio, water to cementitious ratio and paste to solid ratio. The tests included slump flow test, J-ring test, L-box test and the evaluation of mechanicial properties (compressive strength, unit weight and splitting tensile strength). All of the mixes which were subjected to slump flow test, J-ring test and L-box test satisfied the self-compacting and flow state tests criteria without any signs of segregation. The slump flow test illustrated that sand to aggregate ratio is directly proportional to the slump flow diameter. The results revealed that the mixes with 0.48 sand to aggregate ratio yielded a higher compressive strength in comparison to a higher S/A ratio of 0.53. However, the effect can be considered insignificant and it was found that the compressive strength is mainly determined by the ratio of water to cementitious materials and the powder composition. It was also noted that the mixes with the lower sand to aggregate ratio resulted in a higher unit weight and the ratio of tensile strength to compressive strength of the SCHPC mix was higher than that of the normal concrete.

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