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Effect of Partial Replacement of Crushed Aggregate with Natural Sand on Mechanical and Rheological Properties of Self-Compacting Concrete

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Abstract

This paper presents the results of an experimental study on the effect of crushed sand on the properties of fresh and hardened self-compacting concrete. Mixtures of self-compacting concrete have been produced with the replacement of 0%, 25%, 50%, 75% and 100 % of natural sand with crushed sand (CSS). Same coarse aggregate with crushing percentage of 75 has been used in all mixtures. Concrete grade of 450 Kg/m^3 and water to cement ratio of 0.4 have been considered in the mixture designs. Workability properties of self-compacting concrete were investigated by empirical tests viz. slump flow test, $T_{500,}$ V-funnel and L-box height. Rheological properties of concrete mixtures do not change remarkably by replacing 25% and 50 % of natural sand with CSS but if the mixture includes more than 50 % of CSS, the rheological properties of self-compacting concrete will be influenced negatively and may endanger the applicability of the concrete. Strength tests included cube compressive strength test, flexural strength and Splitting Tensile Strength test. The hardened self-compacting concrete exhibits excellent short term strength with 25% CSS content.

***Keywords*:**Self-Compacting Concrete, Natural River Sand, Crushed Sand, Rheology, Compressive Strength

1. Introduction

Conventional concrete is a mixture of cement, sand and aggregate. Properties of aggregate effect the durability and performance of concrete, so fine aggregate is an essential component of concrete. The most commonly used fine aggregate is natural river or pit sand. Fine and coarse aggregate constitute about 75% of total volume. It is therefore, important to obtain right type and good quality aggregate at site, because the aggregate form the main matrix of concrete or mortar [1, 2]. Among the constituent raw materials, the Natural River sand which forms around 35% of the concrete volume plays an important role in deciding the cost of concrete. Depleting sources of Natural River sand and strict environmental guidelines on mining has gradually shifted the attention of the concrete industry towards a suitable fine aggregate alternative that can replace the presently used Natural River sand. Crushed rock sand has surfaced as a viable alternative to Natural River sand and is being now used commonly throughout the world as fine aggregate in concrete. It is manufactured by crushing the quarried stone to a size that will completely pass through 4.75 mm sieve [3]. It is widely known that there are some great advantages while using aggregates from crushing processes or demolition recycled concrete. However, some problems that result from those aggregates need to be better understood, such as the fine particle content [4, 5] and the presence of angular grains [6] in crushed aggregates, and heterogeneity and high-water absorption [7] in the recycled concrete aggregate, although the manufactured and recycled aggregates can extend the

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life of the natural resources of aggregates. These characteristics are negative, and may strongly compromise the properties of the concrete at both fresh and hardened states.

Few studies are found which speak about the effect of these manufactured aggregates on the rheological behavior of concrete. Westerholm et al. [8] studied the influence of crushed aggregate on the rheological properties, using the Bingham model from rotational viscometer results. They showed that the properties of crushed aggregates, such as the particle shape and content of fine particles, strongly affected the rheology of mortars, with a significant increase in the yield stress and plastic viscosity. Cortes et al. [9] observed that the replacement of natural round sand, by crushed granite and limestone aggregates, increased the paste volume in mortars considerably. Raman et al. [10] reported some negative impact of crushed granite sand (ranged from 10% to 40%) on workability (slump test) and mechanical properties of concrete. In this respect, the negative outcomes were compensated by an adequate mix-design, and by using rice husk ash as a supplementary cementitious material. It is interesting to note that the shape and texture of crushed aggregates may increase the mechanical properties of concrete due to the interlocking effect between paste and aggregate particles [11]. Several studies have been conducted in the past to investigate the effect of partial replacement of Natural River sand with crushed rock sand. Researchers concluded that partial replacement up to 30% leads to decreasing slump value. However, a significant improvement in the compressive, flexural strength and impact resistance was observed [6]. It was observed that concrete made using crushed rock sand attained the comparable compressive strength, tensile strength and modulus of rupture as the control concrete [2]. It was concluded in a study that the compressive strength, split tensile strength and the durability properties of concrete made of quarry rock dust are nearly14% more than the conventional concrete [12].

Self-compacting concrete (SCC) is a kind of concrete with the capacity of filling the forms with no assistance during placing and no blockage by the reinforcement or segregation of the mix. These capabilities lead to such advantages as lower workforce, improved finishing quality and reduced working time. In order to achieve these characteristics, this composite material needs to be designed with a larger amount of fines that reduce the coarse aggregate interaction [13]. The obtained results are therefore significant both from the aspects of science and practical use. The effects of various amounts of crushed recycled concrete aggregates (CRCA) on some fresh and hardened properties of SCC were investigated previously [14] by introducing additional water into the mixtures due to the high water absorption characteristics of RCAs. The influence of various amounts of CRCAs on fresh and permeability properties of SCC was also investigated in the previous study [15] by using quasi-constant w/c ratio and gradually increasing superplasticizer dosage. A recent study investigated how the various amounts of FRCAs affect some hardened and fresh properties of SCC mixtures prepared with varying w/b ratios. Since the RCAs generally represent higher water absorption ratios, in the study [16] the additional water was added to the mixtures and RCAs were used in the air-dried condition.

The presented paper investigates how the various combinations of CSS utilization effect the rheological and mechanical behavior of SCC. Paper also represents the replacement percentage as the best and most optimized amount for CSS in self-compacting concrete to provide desired strength as well as workability.

2. Experimental Details and Methodology

2.1. Materials

The materials that were used in this study include Type 2 ordinary Portland cement (OPC), stone powder, natural fine and coarse aggregate, crushed standard sand, superplasticizer and water.

OPC which was used in this study complies with ASTM C109, C185, C188, C 191, C204 and C305. The typical chemical compositions and some physical properties of OPC are tabulated in Table 1.

Table 1
Chemical composition and physical properties of cement.

Composition (%)	
Ca O	64.8
C_3S	60.09
C_4AF	23.37
SiO_2	21.57
C_2S	13.7
C_3A	6.2
Al_2O_3	4.64
Fe_2O_3	3.63
MgO	1.96
SO_3	1.81
IR	0.28
Specific gravity (g/cm^3)	3.15
Blaine fineness (m^2/kg)	316.3

Polycarboxilicether type superplasticizer (SP) having specific gravity of 1.09 was used in this research.

Natural River and crushed sands with the maximum size of 4.75mm were used in this study. Specific gravity and water absorption were respectively 2.55 g/cm^3 and 2% for natural sand and 2.45 g/cm^{3}and 2.4% for crushed sand. Natural coarse aggregate with the maximum size of 19mm and with a specific gravity of 2.75 g/cm^3 and water absorption of 2.5% was also used. Particle size gradation and physical properties of these aggregates are according to INSO 302 (concrete aggregates – properties) [17]. Gradation details are presented in Table 2.Harmful materials must not exceed the following amounts in Table 3.

Table 2
Sieve analysis results of aggregates

Aggregates	Sieve size									
	19 mm	12.5 mm	9.5 mm	4.75 mm	2.36 mm	1.18 mm	600 µm	300 µm	150 µm	75 µm
	Percentage passing (%)									
Coarse Aggregate	100	31.91	0.63	-	-	-	-	-	-	-
Natural Sand	-	-	-	90.75	62.69	43.96	20.47	13.84	2	-
Crushed Sand	-	-	-	90.75	62.69	43.96	20.47	13.84	2	-
Fine Aggregate	-	-	-	-	-	-	82.34	36.08	4.66	-

Table 3
Harmful materials in fine aggregate (sand) for concrete

Material		Maximum allowable amount (Mass percentage)	Test Method
Clay clogs and flimsy particles		3.0	INSO 4978
Collier and lignite	Where the concrete surface is important	0.5	INSO 4984
	Other kinds of concrete	1	

Water soluble chlorides (for reinforced concrete aggregates)	$Cl_{0.02}$		0.02	INSO 19038-1[20]
	$Cl_{0.04}$		0.04	
Sulfur-containing combinations	Acid soluble sulfate	Forge aggregate	1.0	
		Other aggregates	0.8	
	General sulfur	Forge aggregate	2.0	
		Other aggregates	1.0	

Organic impurities of fine aggregates must be tested according to INSO 4979[18] and meet its requirements. There are some health requirements in INSO 449 [19] which fine aggregates in concrete must meet them.

2.2. Details of Mixes and Preparation

SCC mixtures were produced with the water to cement ratio of 0.4 and the concrete grade (cement dosage) of 450 Kg/m^3. Five individual gradations were assumed primarily to get to the satisfying self-compacting concrete mixture. For each primary mixture, L-Box, V-funnel and Slump flow tests were performed to test SCC minimum requirements. The best primary mixture was chosen as the base mixture. All SCCs were mixed in accordance with ASTM C192 [21] standard in a power driven rotating mixer with a 30L capacity. All parameters were kept constant in all mixtures and just sands were replaced in each mixture. Five different concrete mixtures were produced containing 0%, 25%, 50%, 75% and 100% CSS content. Table 4 shows the detail composition of five different concrete mixtures prepared in this study.

Table 4
The proportions of SCCs (kg/m^3)

Mix No.	Mix description	W/C	Cement	Water	SP	Natural Sand	Crushed Sand	Coarse aggregate	Fine aggregate	Air (%)
1	SCC-CSS-0	0.4	450	218	4.5	920	-	540	260	5
2	SCC-CSS-25	0.4	450	218	4.5	690	230	540	260	5
3	SCC-CSS-50	0.4	450	218	4.5	460	460	540	260	5
4	SCC-CSS-75	0.4	450	218	4.5	230	690	540	260	5
5	SCC-CSS-100	0.4	450	218	4.5	-	925	540	260	5

2.3.Testing

The testing programs were designed to determine how the considered CSS replacement ratios influence the properties of SCCs, which determines flow ability, filling ability and passing ability. The flow ability and flow rate of SCCs were tested by slump-flow test in accordance with EFNARC 2002. [22]

The T_{500} time is a measure for the speed of flow and it therefore represents the viscosity of SCC [13]. In this test, the fresh concrete is poured into a cone for the slump test. When the cone is pulled upwards, the time from commencing upward movement of the cone to when the concrete has flowed to a diameter of 500 mm is measured. This is named as the T_{500} time. The largest diameter of flow spread of concrete and the diameter of spread in the longitudinally perpendicular dimension are then measured and the mean is taken as the slump-flow. The filling ability of SCCs was tested by V-funnel test. In this test, the fresh concrete is filled into the V shaped funnel and the time taken for concrete to flow out of the funnel is measured and recorded as the V-funnel flow time. The L-box test and the J-ring test were used for testing the passing ability of SCC. In L-box test, the fresh concrete flows through tight openings between reinforcing bars without segregation or blockage. The L-box is supported on a level horizontal base and the gate between the vertical and horizontal sections is closed. The concrete from the mixer is poured into the filling hopper of the L-box. The gate is raised within 1 min so that the concrete can flow into the horizontal section of the box. When movement is ceased, the depths of concrete that are immediately behind the gate (H_1) and at the end of the horizontal section of the box (H_2) are measured and the ratio of H_2/H_1 is calculated. J-ring test is also used for testing passing ability. This test is basically similar to slump flow test which the same cone is filled with concrete and then the concrete flows on the surface but this time it should pass through a ring of vertical rebar trying to block the flow from spreading. After the concrete was spread completely and the flow stopped, the average diameter of two perpendicular diameters and the average concrete height difference between the inner and outer side of the rebar were measured. [24]

3. Experimental Results and Discussion

3.1. Fresh-state results

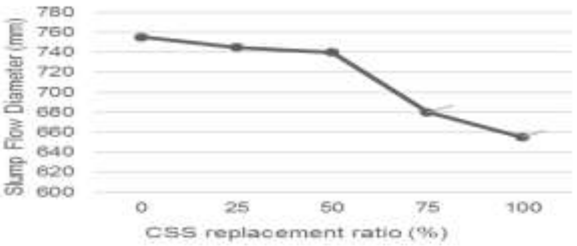
The results of the fresh-state self compacting concrete behavior with empirical onsite tests are shown in this section. As the replacement ratio of CSS increases, the flow ability and passability of the concrete with CSS content reduces and as time goes by it becomes noteworthy. The results of the slump-flow test based on the European Federation Standards show an obvious decreasing trend of the spread as the CSS replacement increases. It’s noticeable that the 25% and 50% mixes show a similar behavior as the natural sand mix does, whereas the 75% and 100% mixes show severe reduction of spread (Fig. 1-a). They are going toward losing SCC characteristics fast.

But they are still appropriate for common usages of SCC and lightly reinforced concrete members. This trend is similar to the results of T_{500} time (Fig. 1-b): 25% and 50% mixes behave similarly and properties reduction is more noticeable for higher replacement ratios.

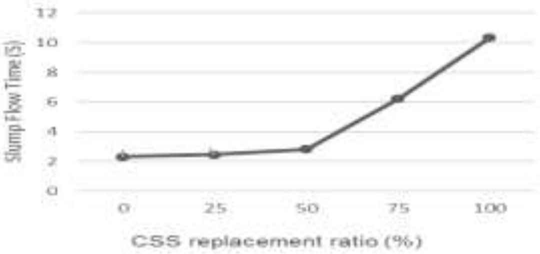
Fig. 1-c shows the results of the V-funnel test. Some of the mixes tended to pass too slowly through the neck of the device and this lead to a loss of flow ability property. This behavior could be related to a latent tendency of concrete to segregate. As were shown in slump-flow results, the general trend is a flow ability loss over CSS replacement increase. As the desirable time range for passing is between 6 and 12 seconds, the 100% CSS content mix shows high plastic viscosity which could lead to a performance issue and blockage.

The results of L-Box test agree with previous results as the 25% and 50% mixes showed similar behaviors as they deviate the natural sand mix result respectively 0.35% and 0.36% .(Fig. 1-d) In the 100% CSS content mix ,blockage occurred which makes it an inappropriate SCC for common and heavily reinforced areas.

The results of the J-ring test are displayed in Fig. 1-e and Fig. 1-f there are no substantial differences between results of spread in the J-ring and slump-flow test results as they follow the same trends. Height difference in all mixes was in the desirable range (less than 10mm). The 100% replacement mix result is close to the upper limit of the range which makes it a probable candidate for blockage.



a)



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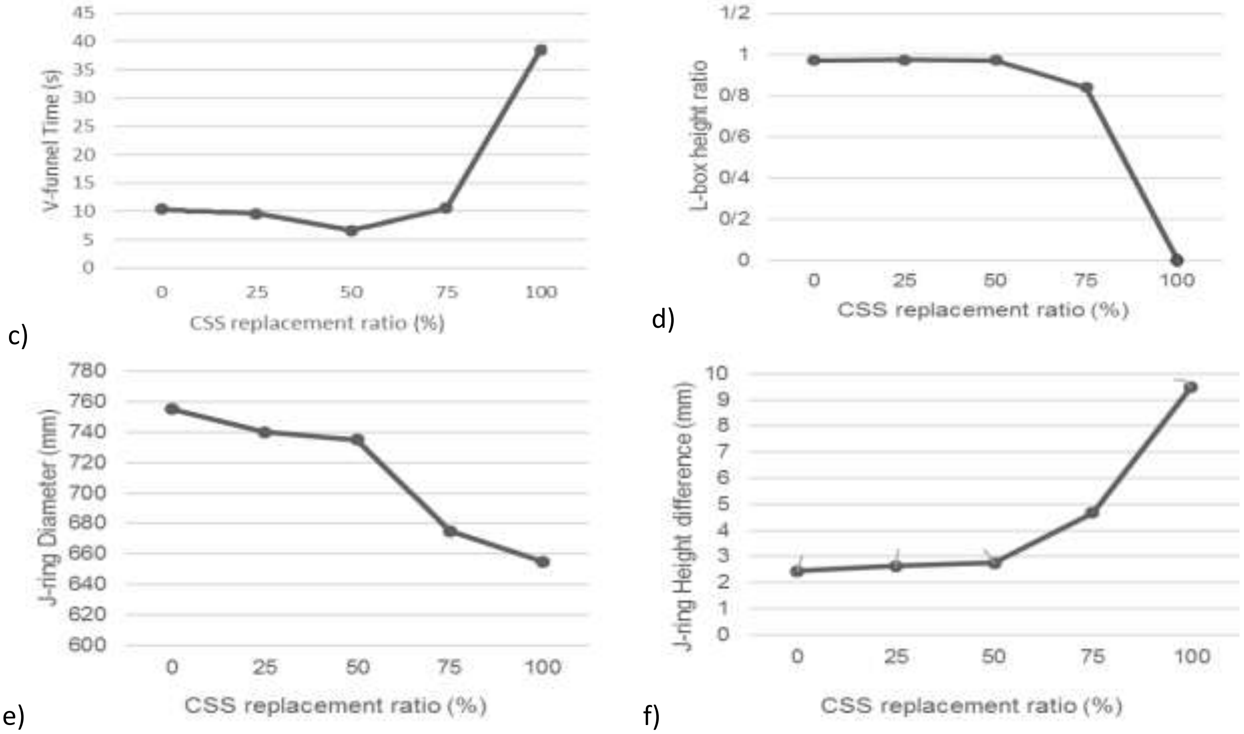

Fig.1 (a) Slump flow diameter, (b) T_{500} slump flow time, (c) V-funnel time, (d) L-box height ratio, (e) J-ring diameter and (f) J-ring height difference variations in terms of crushed standard sand contents

3.2. Mechanical Properties

Fig. 2 displays the compressive strength of the five mixes tested. The results are shown for 7, 28 and 90 days concrete cubic samples according to. In 7-day concrete tests, all CSS replaced mixes have less compressive strength than the natural sand mix. As the time goes by and in 90-day tests, with the increase of CSS replacement ratio, compressive strength increases. It could be linked to the more involvement of particles to each other and higher inner friction between including materials.

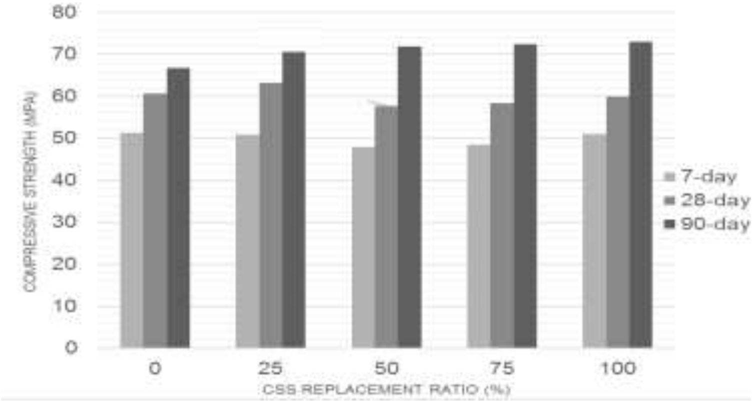

Fig 2. Compressive Strength at 7, 28 and 90 days

Splitting Tensile Strength test results are shown in Fig. 3(a) this test has been performed on 28-day cylindrical concrete specimens. Generally, the tensile strength increases as the CSS content percentage rises and in 100% CSS content it reveals the best tensile performance. As it is displayed in Fig. 3-b, same trend can be stated for flexural strength of the specimens. The strength differences between different CSS content specimens are in acceptable range which makes all mixes applicable on site based on the strength point of view.

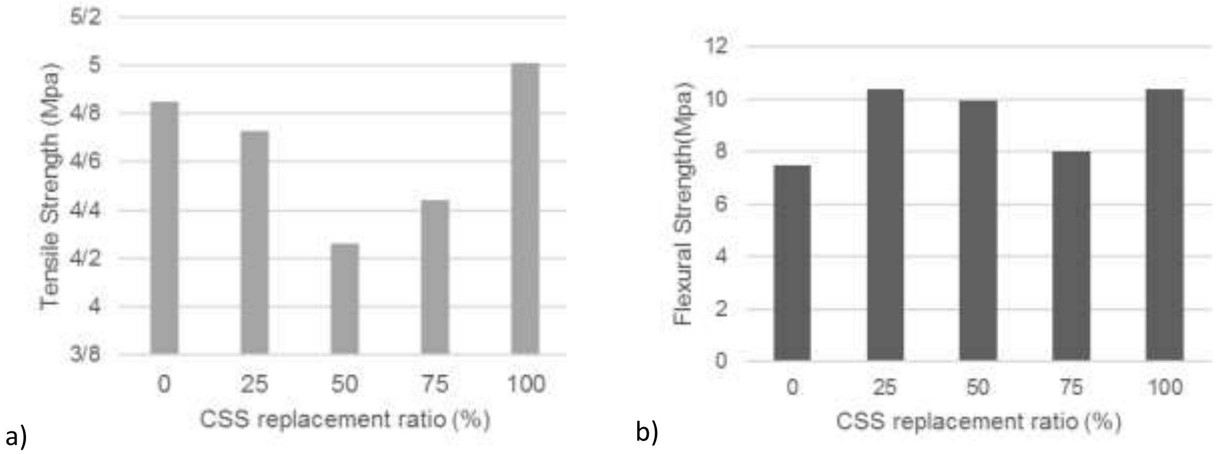

Fig.3 Splitting Tensile Strength Test and Flexural Strength Test results

4. Conclusion

The following conclusions are drawn from the test results and discussion:

- Yield stress of all concrete samples were in the permitted range for self-compacting concrete and samples with 0, 25 and 50% CSS content are practical for common and areas with overcrowded reinforcement.
- Concrete sample with 75% CSS content can be used in lightly reinforced areas. All test results prove this claim.
- It’s not recommended using the concrete with 100% CSS content. This sample has insufficient filling ability and flow ability properties and according to L-Box test results, it will probably face blockage.
- Concrete sample produced with 25% CSS content has the best rheological performance among all. Investigating test results of L-box and V-funnel tests show that the concrete with replacing a quarter of its sand with crushed sand will have better filling ability and passing ability comparing to the other samples.
- Concrete sample produced with natural sand has the best compressive performance in short-term age (7 and 28 days).
- In long-term compressive performance of concrete (90 days), using more CSS content improves compressive performance.
- Between 25 and 50% CSS content results in the best flexural and tensile strength.
- Totally, 25% CSS content seems to be the best and the most optimized amount of crushed standard sand to be used in concrete mixtures to provide both required rheological and compressive properties.

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