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Effect of coarse recycled concrete aggregate on the properties of a self-compacting concrete

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In this paper, the possibility of utilizing coarse recycled concrete (CRCA) aggregate obtained from a Construction and Demolition Waste (CDW) Plant in Delhi for making a 40 MPa Self compacted concrete (SCC) was evaluated. The CRCA was used in as-collected condition and was not processed any further. Aggregate Packing (bulk) Density (APD) method was adopted to obtain an aggregate mixture exhibiting maximum bulk density/least void content (45%) with which the SCC-CRCA mixture was prepared. In addition, SCC was also made using aggregate mixtures in which the NCA was replaced with CRCA at 0% and 100 % (of the total coarse aggregate content) by weight. The cement, fly ash and water were kept constant for all SCC mixtures. The effect of CRCA on the fresh concrete and the mechanical properties of SCC mixtures were evaluated. The test results indicated that the SCC mixtures made with CRCA up to 45% replacement can be used for structural concrete which is higher than that recommended in Indian (20 %) and International specifications (35 %) for traditionally vibrated (conventional) concrete.

Keywords: Self Compacting Concrete, Fly ash, Coarse Recycled Concrete Aggregate, Aggregate Packing Density, Fresh and Mechanical properties.

1 Introduction

The primary ingredients of SCC are same like those of Normal Aggregate Concrete (NAC). SCC is known for its excellent deformability, segregation resistance, ability to fill the formwork even within congested reinforcement and ability to fill formwork under its own weight, a superior level of finishing and, resulting in durable structure.

In the recent decade, much of the research has been carried out on the usage of Recycled Aggregate (RA) in normal concrete manifesting its technological advancement[1]. Indian specification IS 383 recommends[2] use of CRCA in different proportions in various types of concrete and, up to a maximum of 20 % in conventional Reinforced Concrete (RC). In this respect, the utilization of CRCA in SCC will manifest further technological advancements fulfilling the sustainability goals and contributing towards circular economy strategy. It is expected that the utilization of CRCA in SCC could be a promising thrust area for its usage in large scale, keeping in view the growing shortage of NCA[3].

SCC mixtures are generally produced with higher quantity of powder / paste content to provide the required flowability[4]. While the paste content in conventional concrete varies between 23-32 %[5], the same in SCC-NCA mixtures varies between 30-42 %[6]. Replacing NCA with CRCA would further require higher quantities of binder. However, proportioning of aggregate mixtures based on APD method with least void ratio/void content would optimize the binder content and would contribute to sustainability, by reducing the total binder content which primarily consists of Portland cement.

Grdic *et al.*,[7] and Pereira-De-Oliveira *et al.*,[8] evaluated the effect of CRCA on the properties of SCC and observed that slightly decreased the workability and strength with the increase in CRCA content. It was also observed that slump flow value increased with the increase in CRCA upto 60%, after which it decrease due to water absorption by smaller fine particles that formed due to partial breaking of CRCA. On the other hand, the V-funnel flow time increased with increase in CRCA due to their rougher surface as compared to NCA[3]. However, Uygunoglu *et al.*,[9] found that lower flow time of SCC-CRCA mixtures. Kapoor *et al.*,[10] (2016) reported a

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reduction by 4.5% in compressive strength of SCC mix containing CRCA at 50% with 30% fly ash, which is insignificant. However, Singh *et al.*,[11] found that with the addition of metakaolin (MK), the compressive strength of SCC mixtures made with CRCA at 50%, were improved with respect to SCC made with 100% NCA.

As may be observed the fresh and mechanical investigations on SCC-CRCA mixtures made with CRCA are scarce and randon. However, it is necessary to carry out a comprehensive investigation on its mechanical and durability properties for its effective use in structures. Direct use of CRCA would save immense amounts of energy needed for processing, if it is to be used in large quantities for field works. Therefore, an attempt has been made in this study to investigate the fresh (slump flow, T_{50cm}, V-funnel, L-box, and sieve segregation test), mechanical (compressive strength test, split tensile test, flexural test and modulus of elasticity) and time dependent (drying shrinkage) properties of SCC made with CRCA for a designed characteristic compressive strength of 40 MPa, and the findings of this experimental study are presented in this paper. It is expected that these results would be helpful to understand the influence of CRCA proportion in SCC mixtures and encourage its application in the pavement and structural construction.

2 Materials and Methods

2.1 Materials used

Ordinary Portland Cement (OPC) of grade 43 conforming to IS 269[12], and Class F fly ash conforming to IS 3812 (Part 1)[13] were used. The fineness of cement and fly ash used are 323 kg/m^3 and 329 kg/m^3 respectively. The NCA of 20 mm size and 10 mm size available in Delhi region were used. The CRCA of 20 mm and 10 mm was obtained from a CDW plant, near Burari in Delhi, India. The gradation curve for NCA and CRCA are given in Fig. 1. The properties of coarse aggregates are presented in Table 1. Class F fly ash was used in this study to improve the properties of CRCA and reduce detrimental effects of porous residual mortar. Natural fine aggregate (NFA) of specific gravity 2.64 and water absorption 0.8% conforming to Zone II of IS 383[2], available in Delhi region was used as fine aggregate. A superplasticizer based on second-generation polycarboxylic ether was used. It was a light brown liquid with a relative density of 1.08.

2.2 Mixing, Casting and Curing

APD method[18] was adopted and an aggregate mixture of maximum bulk density / least void content was obtained in which the proportion of CRCA was 45% in the total coarse aggregate and the same was used to prepare SCC-CRCA mixtures of characteristic compressive strength of 40 MPa. The optimum coarse to fine aggregate (CA: FA) proportions in the aggregate mixture was of 50: 50 (Mix A). Also, SCC mixtures with two other aggregate mixtures containing 0% and 100% of CRCA were also prepared. The binder content was fixed as 1.1 V_c, where V_c is the total void content in

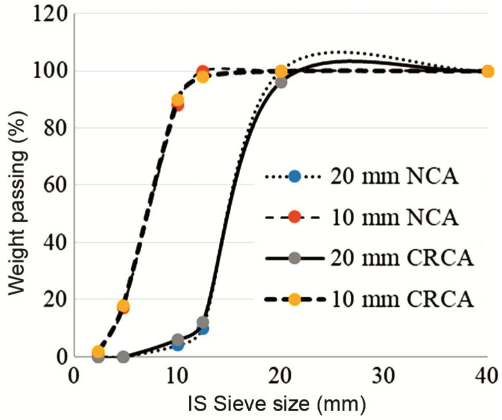

Fig. 1 — Gradation curve of NCA and CRCA.

Table 1 — Properties of aggregates used in the present study

Property (%)	NCA 20 mm	NCA 10 mm	CRCA 20 mm	CRCA 10 mm	Test Method (IS 2386:1963)
Water absorption	0.30	0.30	4.51	5.36	Part III[14]
Specific gravity	2.83	2.81	2.36	2.35	
Abrasion Value	22	29	24	26	Part IV[15]
Crushing Value	23	26	24	27	
Impact Value	14	16	20	22	
Flakiness	9.0	20	3.0	6.0	Part I[16]
Elongation	15	8.0	14	15	
Soundness	0.97	0.67	11	12	Part V[17]
Adhered mortar	-	-	29	51.67	Thermal Treatment

Table 2 — Mix Proportion of the SCC mixtures studied

Mixtures	% CRCA	Packing density of mixtures	Cementitious Materials		Water	Mix Proportions				NFA	SP
			C	FA		NCA		CRCA			
						20 mm	10 mm	20 mm	10 mm		
Mix A (50:50) Mix Proportions (kg/m^3)											
A-1	0	0.6607	350	102	181	435	435	0	0	870	2.70
A-2	45	0.7005	350	102	181	241	241	197	197	876	2.70
A-3	100	0.6722	350	102	181	0	0	441	441	882	2.70

Fig. 2 — Test setup for Modulus of Elasticity of SCC mixture.

Fig. 3 — Test setup for drying shrinkage of SCC mixture.

the aggregate mixture[20]. The extra paste content was added to facilitate the flow properties of SCC mixtures. The binder content thus used was 32.44 % (452 kg/m^3) in the total mix, and the same was kept un-changed in all the SCC mixtures. It may be noted that the paste content is on the lower side of the range often chosen for the SCC-NCA mixtures[6]. The mix proportions of all the mixtures along with their designation are given in Table 2. To counteract the effect of higher water absorption of CRCA, all the aggregates were immersed in water for 24 hours and surface dried before use. The flow properties of SCC mixtures (Slump flow, L-box, V-funnel and sieve segregation resistance test) were evaluated as per EFNARC guidelines[19]. The concrete specimen's cubes, prisms and cylinders were cast and specimens were covered with plastic sheets for 24 hours.

After 24 hours, the specimens were demoulded and placed in a water tank for curing. A compressive strength testing machine of 3000 KN capacity was used to determine the compressive and split tensile strength. A flexural strength testing machine with 100 KN capacity was used to determine the flexural strength of the prisms. The modulus of elasticity is determined on cylindrical samples as per IS 516[20]. The concrete specimens are tested in a strain controlled compression testing machine with 3000 KN capacity at room temperature of 27 ± 2 °C and relative humidity 65% or more are given in Figure 2. Two extensometers at the middle half of the height are used to get strain and average of two strains is taken. The drying shrinkage of all concrete mixtures was determined using a Length Comparator as per IS 516[21] as shown in Figure 3. Twenty-seven 150 x 150 x 150 mm cubes, twenty-seven 150 x 300 mm cylinders, eighteen 100 x 100 x 500 mm prisms and nine 75 x 75 x 300 mm prisms were cast and investigations were conducted to study the mechanical behaviour, drying shrinkage and microstructure of all SCC mixtures.

3 Results and Discussion

3.1 Flow properties

3.1.1 Flowability and Viscosity

The slump flow and T_{50cm} slump flow time results of all the mixtures are presented in Table 3. The SCC mixtures have exhibited slump in the range of 760-795 mm, conformed to class SF3 as per

Table 3 — Fresh Properties of SCC mixtures

Mix ID	Slump flow (mm)		T_{50cm} slump flow time (s)		V-funnel (s)		L-box (H_2/H_1)		Segregation resistance (%)	
	0 min	90 min	0 min	90 min	0 min	90 min	0 min	90 min	0 min	90 min
A-1	760 [SF3]	705 [SF2]	3.05 [VS2]	3.60 [VS2]	6 [VF1]	9 [VF2]	0.92 [PA2]	0.86 [PA2]	8.3 [SR2]	10.3 [SR2]
A-2	780 [SF3]	670 [SF2]	2.60 [VS2]	4.05 [VS2]	5 [VF1]	14 [VF2]	0.93 [PA2]	0.85 [PA2]	7.8 [SR2]	12.7 [SR2]
A-3	795 [SF3]	650 [SF2]	2.10 [VS2]	6.23 [VS2]	4 [VF1]	20 [VF2]	0.96 [PA2]	0.80 [PA2]	6.3 [SR2]	14.2 [SR2]

EFNARC guidelines[19]. The slump flow diameter increased and, T_{50cm} slump flow-time decreased at initial mixing time, for all the mixtures, as the CRCA content increased. This may be due to availability of excess water in the concrete mix, which could not be absorbed by CRCA at initial mixing time and the same trend is also reported by Martinez *et al.*,[22] and Singh *et al.*,[11]. It may be noted that the CRCA was not soaked in water in these studies, but SP content was increased, with reference to 0 % CRCA concrete, to obtain the increased flow. On the other hand, the CRCA was soaked in water in the present study, and no increase in SP content was made. However, Sherif A. Khafaga[23] reported lower slump flow immediately after mixing with increase in CRCA content, which is in contradiction to the results reported in the present study. This may be due to non-presoaking of CRCA in water for 24 hours by Sherif A. Khafaga[23].

3.1.2 Slump loss behavior

Table 3 presents the slump flow diameter measurements taken up to 90 minutes, which shows that there is a significant decrease in slump flow with time and with the increase in CRCA content. However, the mixtures with CRCA at 100% exhibited a faster loss of slump flow with time, and the flow decreased significantly after 90 minutes and similar observation was also made by Tang *et al.*,[24].

3.1.3 Filling ability

The results of the V-funnel time of SCC mixtures are presented in Table 3. The mixtures A-1 to A-3 initially exhibited a V-funnel time in the range of 6-4 s, and conformed to class VF1. It may be noted that V-funnel time of all the mixtures was less than 10 s, indicating excellent filling ability and no sign of blocking. When the mixing time increased, the V-funnel time increased with increase in CRCA content. The SCC mixtures A-1 to A-3 conformed to class VF2 at 90 minutes. Kapoor *et al.*,[10] and Singh *et al.*,[11] also reported a similar trend in variation of filling ability results, at the time of mixing.

3.1.4 Passing ability

The passing ability test results of the SCC mixtures are presented in Table 3. All the mixtures A-1 to A-3 exhibited a value in the range of 0.92-0.96 at initial mixing time, and conformed to the class PA2 as per EFNARC guideline[19]. When the mixing time increased, the passing ability decreased with increase in CRCA content. At 90 minutes after the mixing time, the passing ability of mixtures A-1 to A-3 varied in the range of 0.86-0.80 and conformed to class PA2. Singh and his team[11] also reported increase in passing ability with increase in CRCA content in the SCC mixtures due to the gradual increase in SP content. However, Kapoor *et al.*,[10] reported decrease in passing ability with increase in CRCA content.

3.1.5 Segregation Resistance

The segregation resistance of all SCC mixtures in terms of segregation ratio is presented in Table 3. The segregation ratio of Mix A varied in the ranges of 8.3-6.30% indicating that Mix A is more cohesive. These mixtures conformed to segregation class SR2. Grdic *et al.*, [7] also reported a decrease in segregation ratio of the SCC mixtures, made with fillers, with increase in CRCA content and the same could be due to the higher water absorption of CRCA compared to NCA. However, Safiuddin *et al.*, [3] reported the segregation ratio increased with the increase in CRCA content. It was attributed to increase of the fine fraction resulting from the fracture of the CRCA during mixing, at higher proportions of CRCA.

3.2 Mechanical properties

3.2.1 Compressive strength

The compressive strength of the SCC mixtures at various ages was investigated and the results are summarized in Fig. 4. It may be noted that all the mixtures achieved higher compressive strength than the characteristic strength of 40 MPa. The 28 day compressive strength of all the mixtures ranged from 54.58 to 44.50 MPa. It is clear from the results that the compressive strength increased with the increase in CRCA content up to 45 %, and beyond 45 % of CRCA content, the compressive strength decreased. This may be due to the mixture A-2 had higher aggregate packing density and lower void content than those of mixtures A-1 and A-3 as given in Table 2. When NCA was replaced with CRCA at 100%, the strength of mixtures A-3 had decreased by only 12.84 %, at 28 days, 11.79%, at 56 days, and 15.29% at 90 days. However, Kapoor *et al.*,[10] and Singh *et al.*,[11] also reported decrease in compressive strength with increase in CRCA content in SCC mixtures made with fly ash.

Furthermore, during a physical observation it was noted that the failure pattern of concrete specimens of all SCC-CRCA mixtures was similar to control mix (SCC-NCA) as shown in Fig. 5.

3.2.2 Split Tensile Strength

Figure 6 present split tensile strength test results of SCC mixtures under study. It may be seen that the split tensile strength of SCC mixtures increased with the increase in CRCA content up to 45% at 28 and 56 days, and then decreased with further increase in CRCA content. The increase, with reference to that of mixture A-1, was observed to be 2.13%, 4.25% for A-2 and A-3 mixtures at 28 days and 1.96 %, 5.88% at 56 days. The higher split tensile strength could be because of the rough surface texture in CRCA which provides better intermeshing between the CRCA and cement mortar as compared to NCA. However, Madduru *et al.*,[26] reported higher split tensile strength (4.15 MPa) of SCC mixtures (M40) containing 100% CRCA made with fly ash than that obtained in this study (2.90 MPa), despite a higher total binder content used by them (560 kg/m^3) as compared to 452 kg/m^3 used in the present study. It is widely known that the strength and other properties of concrete depend on binder content and its composition.

3.2.3 Flexural strength

Figure 7 present the flexural strength results of various SCC mixtures at an age of 28 and 56 days. The flexural strength of the SCC mixtures, exhibited a similar trend as the split tensile strength. It may be seen that the flexural strength of SCC mixtures

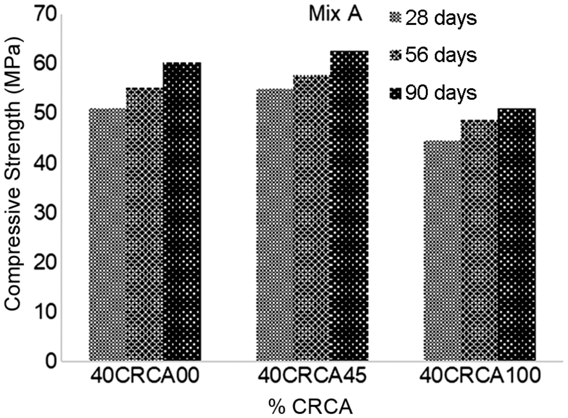

Fig. 4 — Compressive strength of SCC mixtures.

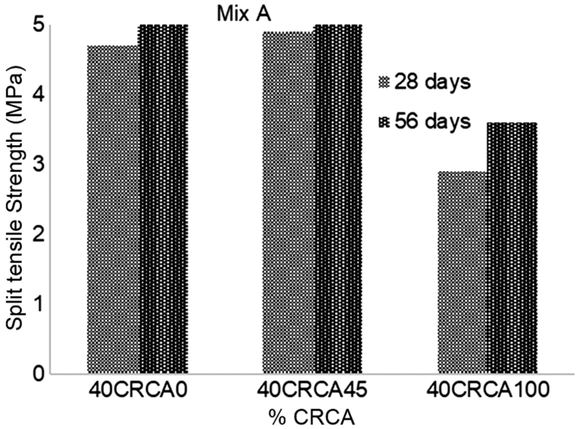

Fig. 6 — Split tensile strength of SCC mixtures.

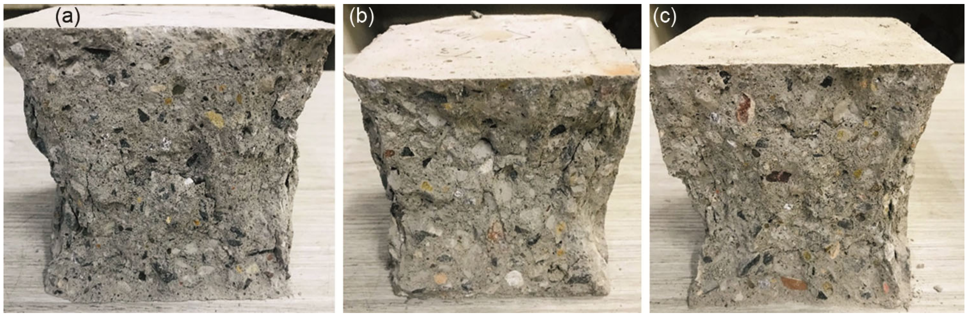

Fig. 5 — Failure patterns of various SCC mixtures under compression.

increased with the increase in CRCA content up to 45% at 28 and 56 days, and then decreased. The increase was observed to be 1.56%, 3.12% for A-2 and A-3 mixtures at 28 days and 0.52%, 2.26% at 56 days. The higher flexural strength of SCC-CRCA mixtures upto 45% could be due to the similar reasons as those attributed for its higher split tensile strength. It may be observed that the flexural strength of A-3 mixture is comparable with that of the respective control mixture A-1. While Madduru *et al.*,[26] reported lower flexural strength (4.36 MPa) of SCC mixtures (M40) containing 100% CRCA made with fly ash than that obtained in this study (4.75 MPa).

3.2.4 Modulus of elasticity

The modulus of elasticity of the SCC mixtures is presented in Fig. 8. At the age of 28 days, the control mixture A-1 and the mixtures A-3 exhibited the highest and lowest modulus of elasticity of 35.92 GPa and 31.74 GPa, respectively. The modulus of elasticity decreased with increase in the proportion of CRCA as seen in Fig. 8, unlike the trend the observed with the compressive strength. This may be due to micro cracks and fissure which could have formed in the aggregate during the manufacturing process of CRCA, leading to higher deformation during loading. It is well known that aggregates porosity and density influence the dimensional stability and modulus of elasticity of concrete the most than the compressive strength[27]. Thus, deformation of adhered mortar, which is generally porous in nature and hence undergoes crushing, during the initial stages of load application, results in higher strain and lower modulus of elasticity. The crushed adhered mortar could be resisting further deformation due to the applied load and hence exhibiting a higher compressive strength. The effect of quantity of adhered mortar and the extent of modification of the same by the cementitious admixture on the modulus of elasticity of SCC-CRCA needs further study. Pereira-de-Oliveira *et al.*,[8] reported higher modulus of elasticity results than those obtained in this study. However, the binder used by Pereira-de-Oliveira *et al.*,[8] comprised of lime filler in addition to cement and the total binder content (655 Kg/m^3) was higher than that used in this study (452 Kg/m^3).

3.3 Drying shrinkage

The effect of CRCA content on the drying shrinkage after 28 days of curing of testing is presented in Fig. 9. It was observed that the rate of increase of drying shrinkage constant after 56 days (from date of casting). The shrinkage strain measured, 120 days after mixing, for specimen of SCC mixes varied between 168 – 200 µm, indicating that the drying shrinkage of the SCC-CRCA mixes was within the range as per both Neville[27] and IS 456[28] recommendations. It is seen that, the shrinkage strain

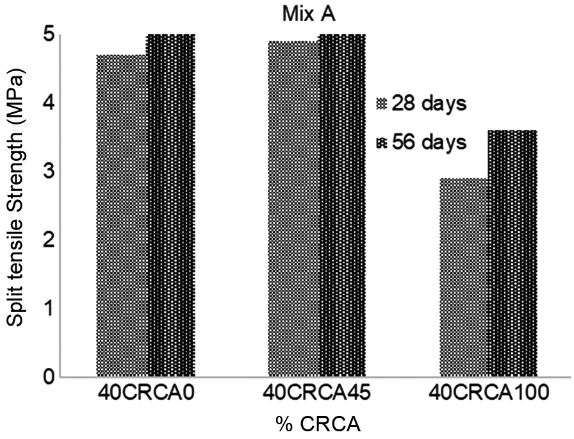

Fig. 7 — Flexural strength of SCC mixtures.

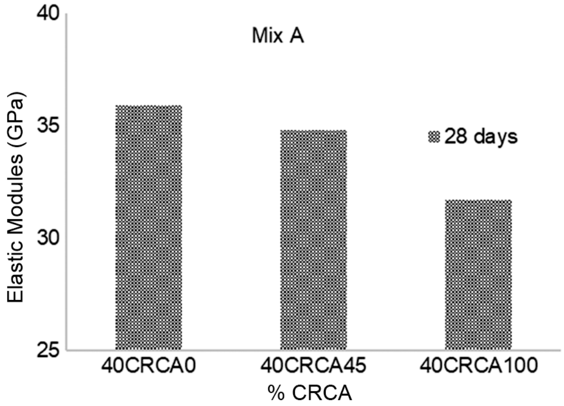

Fig. 8 — Modulus of elasticity of SCC mixtures.

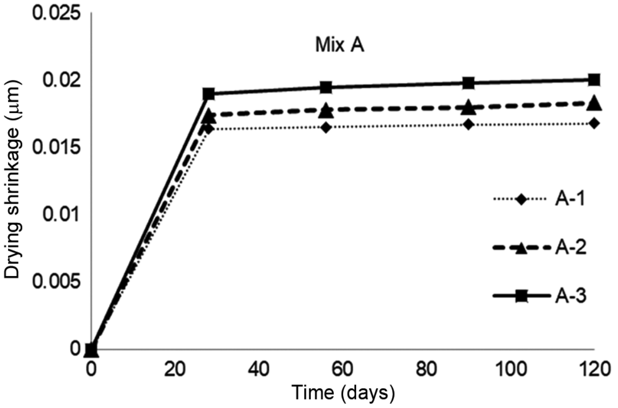

Fig. 9 — Dry shrinkage of SCC mixtures.

Fig. 10 — Test setup for Mercury intrusion porosimetry of SCC mixture.

of all SCC-CRCA mixtures increased linearly with increase in CRCA content up to about 28 days (56 days from day of casting). The higher shrinkage of SCC-CRCA specimens may be due to higher volume of mortar in the mixture, which includes both new mortar and residual adhered mortar[29], and higher-porosity CRCA, which could hold higher water content. Other researchers[30,31] also reported similar trend in their results.

3.4 Microstructural Characteristics of SCC mixtures

3.4.1 Mercury Intrusion Porosimetry

Mercury Intrusion Porosimetry (MIP) test was used to investigate the pore characteristics of SCC mixtures. MIP test setup is shown in Fig. 10. The pore size distribution curves of SCC mixtures A-1, A-2 and A-3 are shown in Fig. 11. It well known that a lower amount of mercury is needed to fill the larger size pores whereas higher amount of mercury is required to fill the smaller size pores. Fig. 11 indicates that the mercury intrusion process increased through a pore size range and then decreased indicating that the volume of pores was high in that size range and lower in the other higher size range of pores.

The total cumulative pore volumes of A-1, A-2 and A-3 SCC mixtures were 3.2 mm^3/g, 16 mm^3/g and 40 mm^3/g, respectively. The mercury intrusion for A-2 and A-3 mixtures varied in the pore size range from 4.5 nm to 90,000 nm, while the same for the SCC-NCA mixture A-1 varied in the range from 120 nm to 90,000 nm. It indicates that the larger size pores were filled with the fine material generated during mixing process of CRCA and contributing to the small size

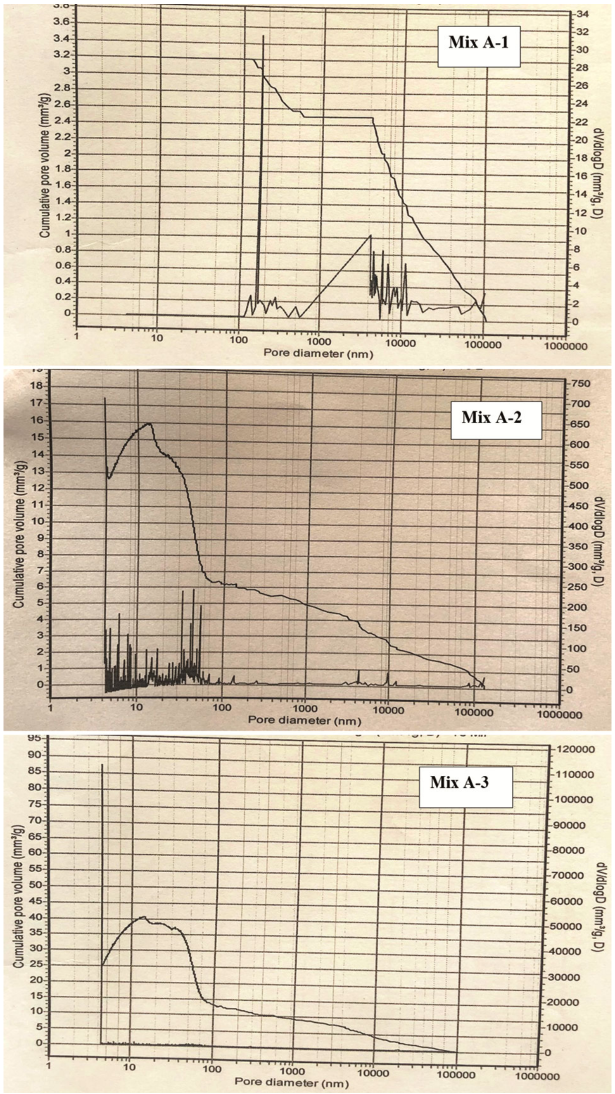

Fig. 11 — Pore Size Distribution curves of SCC mixtures.

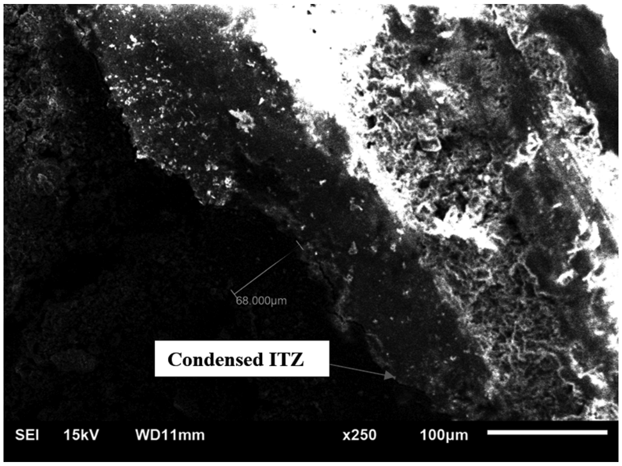

Fig. 12 — SEM image of SCC mixture A-1.

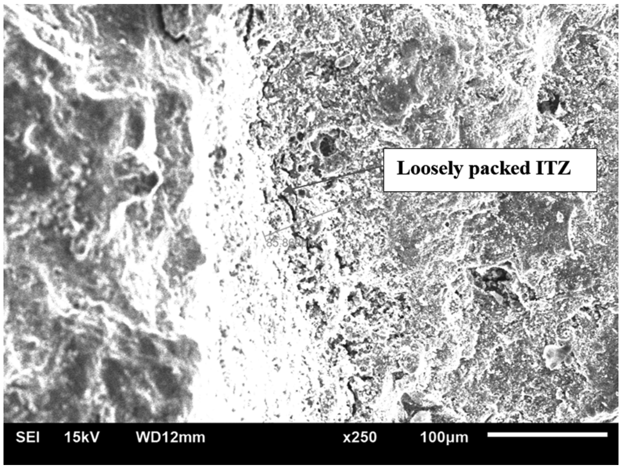

Fig. 13 — SEM image of SCC mixture A-2.

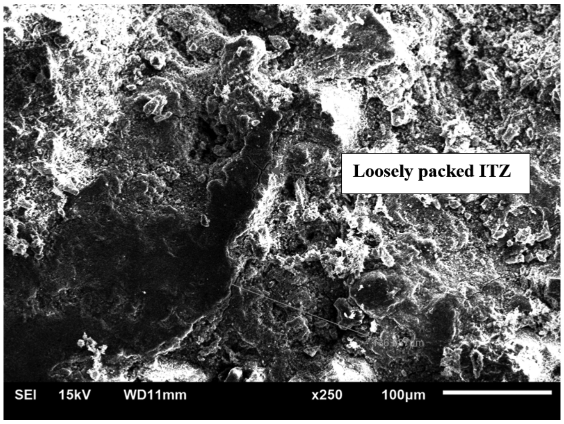

Fig. 14 — SEM image of SCC mixture A-3.

pores, which did not happen in the A-1 mixture, as it was made with all NCA. The maximum intrusion of mercury in to the SCC mix A-2 and A-3 mixtures was in the pore size range of 4.5–20 nm in comparison to that of mixture A-1 which is in the size range of 120 – 5000 nm.

3.4.2 Scanning Electron Microscopy

The ITZ microstructure of RAC is known to have a very complex structure as it is composed of more than one ITZ[32]. It may have numerous narrow ITZs surrounded by the newly formed ITZ as the CRCA is surrounded by the old cement paste. Thus, it contributes towards the widening of the new ITZ and will affect the resulting hardened properties of the concrete. The SEM images of the SCC mixtures A-1, A-2 and A-3 are presented in Figs. 12, 13 and 14, respectively. The ITZ of control SCC mixture A-1 was found to be densely packed and was with compact microstructure with finer hydration products as shown in Fig. 12. However, the SCC mixtures A-2 and A-3 exhibited a relatively loosely packed ITZ with a clear gap between the matrix, and the aggregate zone across the ITZ as shown in Figures 13 and 14. Similar observations were reported on the SEM of normal concrete[32], and SCC-fine recycled aggregate mixtures[33].

4 Conclusions

From this experimental research, the following conclusion can be inferred.

- The flow test result revealed that all SCC-CRCA mixtures fulfilled the workability parameters as per EFNARC. Therefore, SCC-CRCA mixtures can be used for site applications with a transit time of up to 90 minutes.
- It was observed that all the SCC-CRCA mixtures achieved the compressive strength of more than 40 MPa. The experimental results indicated that there was no significant variation in mechanical properties of SCC-CRCA vis-à-vis the SCC-NCA upto replacement of 45%, suggesting that higher quantities of CRCA, than that was recommended by various specifications, can be used in cement concrete and RC.
- The higher compressive, split and flexural strength at relatively lower binder contents were attributed to use of aggregate packing mixture with higher bulk density.
- The drying shrinkage values increased with increase in CRCA, however the same was within the recommended / accepted range.
- The ITZ of control SCC mixture A-1 was found to be densely packed with more compact microstructure and finer hydration product, while the SCC mixtures A-2 and A-3 exhibited loosely packed ITZ with open spaces (gaps) between the

matrixes. Also, the porosity of the SCC mixes A-2 and A-3 was significantly higher than that of SCC mixture A-1.

- Novelty of this study is (a) evaluation of flow properties of SCC-CRCA mixes upto 90 minutes after mixing out so that it could be helpful to understand the behavior of SCC-CRCA mixes during transit when using in large construction, (b) the results of the study revealed that replacement upto 45% of CRCA in total coarse aggregate can be used in structural concrete with satisfactory flow and mechanical properties.

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