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Aggregate Packing Density Approach for Sustainable SCC using Un-Processed Coarse Recycled Concrete Aggregates

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ABSTRACT

The production of Self Compacting Concrete (SCC) needs a large amount of binder (cement) to fulfill its flow requirements. The production of cement is associated with high energy consumption and CO₂ emissions, which result in serious environmental pollution. Making SCC with Coarse Recycled Concrete Aggregate (CRCA) throws further challenges. Mix proportions of a 40 MPa SCC-CRCA were estimated using the aggregate proportions obtained by aggregate packing density method (APD), Indian Standard (IS 10262), and those based on Compressible Packing Method (CPM). It was observed that the APD method yielded an SCC-CRCA with reduced binder content by 5.40% and 26%, as compared to the other two methods. Also, in the SCC-CRCA mixes proportioned by using APD method, resulted in a reduction in total energy consumption by 5.10%, total emission of CO₂ by 9.23 % and material cost by 14.44 % at the prevailing rates in comparison to the IS 10262 design method. No significant variation in the flow and mechanical properties of SCC-CRCA was observed up to a replacement of 45 %, in the total coarse aggregate which is higher than that recommended in Indian (20 %) and International specifications (35 %) for traditionally vibrated (conventional) concrete.

1 Introduction

Growing urbanization worldwide is leading to rapid infrastructure development, requiring outsized quantity of construction materials, and land requirements. For giant constructions, cement concrete is preferred as it provides long life and low maintenance cost. On the other hand, the greenhouse gas emissions associated with the production of Portland cement and the overwhelming consumption of natural resources in concrete manufacture has raised concerns regarding the environmental impact of concrete. Often smaller structures are demolished to construct new ones. As the

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scarcity for natural aggregates is increasing due to environmental restrictions, usage of Recycled Aggregate (RA) processed from Construction and Demolition Waste (CDW) is growing in various civil engineering applications [1]. Utilization of CRCA is recognized as beneficial and is encouraged in construction through modification of existing codal provisions [2]. Various countries / organizations have issued guidelines specifying different proportions of CRCA, as replacement of Natural coarse aggregate (NCA), in natural aggregate concrete (NAC) containing NCA (NAC-NCA) mixes, on empirical basis. Indian specification IS 383-2016 [3] recommends use of CRCA in different proportions in various types of concrete and, up to a maximum of 20 % of NAC in Reinforced Cement Concrete (RCC). Specifications like DIN 4226-100 [4], CCAA 2008 [5], HKBD 2009 [6], BS 8500:2 [7] recommended use of CRCA, as replacement of NCA, in concrete / RCC in different proportions, but up to a maximum of 35%.

SCC usage in civil infrastructure development has increased remarkably during the past 10 years. The aggregates in SCC occupy 55-60% of its volume [8] and the coarse aggregates comprise 45-50% of the total volume of aggregate. Hitherto, only NCA has been employed for manufacture of SCC. The utilization of CRCA in SCC would further contribute to sustainability and towards circular economy approach. Research in this promising thrust area could enhance its usage and alleviate difficulties encountered because of the shortage of NCA [9].

2 Aggregate Proportions for SCC-CRCA

SCC is more sensitive to mix proportions than the traditionally vibrated concrete. The replacement of NCA with CRCA introduces new variables to the mix design process [10] such as ratio of coarse to fine aggregate (CA: FA), the size and shape of CRCA and the ratio of water to binder (w/b) materials [11]. A number of studies have revealed that replacement percentage of CRCA plays an important role [12] in properties of SCC-CRCA. Currently there are no guidelines on use of CRCA in SCC.

In the recent years, the sustainable development of concrete, which emphasizes on saving of energy, materials, protection of environment and conservation of non-renewable natural resources, has attracted widespread attention [13]. SCC mixes are generally produced with higher quantity of powder content to provide the required flowability [14]. Replacing NCA with CRCA would further require higher quantities of binder. However, proper proportioning of aggregate mixtures 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. However, the effect of adhered (residual) mortar on CRCA would play a significant role on the properties of the NAC and more so on SCC. Therefore, many a times the CRCA is processed to remove or reduce the quantity of adhered mortar. However, this method needs lots of quantity of energy and time, when CRCA is used in large scale. Supplementary Cementitious Materials (SCM) are often used in NAC when un-processed CRCA is used, to reduce the effect of adhered mortar.

Powers [15] in his study on aggregate mixtures demonstrated that the void ratio, defined as the ratio between the volume of voids (E) and the volume of solids (I-E), of binary particulate system, would be minimum at a particular combination of the binary components. APD method for proportioning of aggregate mixtures emanated from this concept. This method was employed for proportioning of SCC-NCA mixes [16-19], and SCC-CRCA mixes [20-21]. Wherever CRCA was used, it was used as part or full replacement of NCA. Nandanam et al. [21] prepared SCC mixes, with 100 % treated CRCA, for concrete of strength 75 MPa and with binder content 550 kg/m³. An optimum aggregate proportion was obtained through DIN 1045-1 [22], and the same was CA: FA= 52:48. Sumanth et al. [20] obtained optimum aggregate proportion of CA: FA = 50:50 for SCC of strength 30MPa, 50MPa and 70MPa. Un-treated CRCA was used in this study. It was concluded that CRCA content, in total coarse aggregate, of 25-30 % for medium strength grade SCC, and 20-25 % for high strength grade SCC can be used. They prepared SCC-CRCA mixes with total binder content of 426, 550, 661 kg/m³ and w/b ratio of 0.47, 0.35, 0.28, respectively for the three strength types of concrete.

CPM concept developed by De Larrard [23] was to obtain the optimum proportions of CA: FA for making dense concrete. Madduru et al. [24] prepared SCC mixes, with 100 % treated CRCA, with three w/b ratio i.e. 0.48, 0.38, 0.30, and different quantities of binder i.e. 420 (for M 20 concrete), 520 (for M 40 concrete), 640 (for M 60 concrete) kg/m³, using CPM method. The optimum aggregate proportion was CA: FA= 39:61.

IS 10262 [25] method was used for proportioning of SCC-CRCA [26-29] mixes. Panda et al. [26] prepared the SCC mixes, with 10%, 20%, 30% and 40% untreated CRCA (in total coarse aggregate) with a ratio of water to cement

(w/c) i.e. 0.47 while Ranjan kumar [28] prepared SCC mixes, with 60% and 100% treated CRCA, with w/c ratio i.e. 0.55 and, the binder comprised cement content 330 kg/m³, silica fume and fly ash. The aggregate proportion was CA: FA= 48:52. Ajith et al. [29] used an aggregate proportion of CA: FA = 51:49 for w/b ratio i.e. 0.27. SCC-CRCA mixes were prepared with 50%, 70% and 100% untreated CRCA and with a binder content of 550 kg/m³.

3 Objective of the Current Study

A review of existing studies revealed that no-comprehensive study (encompassing flow, mechanical and durability properties) was available on SCC-CRCA mixes using one particular aggregate mixture proportioning method, to understand their overall behavior. In this study, such an attempt has been made to prepare optimum aggregate mixtures based on maximum bulk density or minimum void ratio (APD method) and using NCA, un-processed CRCA and natural fine aggregate (NFA). The SCC mixes were made for a characteristic compressive strength of 40 MPa, and its flow, mechanical and durability properties have been investigated. The test results of flow behaviour and compressive strength are presented in this paper. A theoretical comparison of sustainability aspects of SCC mix proportions made with APD, CPM and IS 10262 methods has also been carried out and the results are presented. It is expected that these results would be helpful for the application of SCC with un-processed CRCA in the construction of infrastructure with congested of reinforcement, and in precast industry.

4 Experimental Study

4.1 Materials used

Ordinary Portland Cement (OPC) of grade 43 conforming to IS 269-2015 [30], and Class F fly ash conforming to IS 3812 (Part 1)-2013 [31] were used. Crushed granite NCA of 20 mm size and 10 mm size available in Delhi region were used. The CRCA of sizes 20 mm and 10 mm was obtained from a CDW processing plant, near Burari in Delhi, India and was used without any further processing. The particle size distribution of both NCA and CRCA were within the prescribed limits as specified in IS 383-2016 [3]. The physical and mechanical properties of coarse aggregates, along with the recommended specifications of CRCA, as per some of the International Standards, are presented in Table 1.

Table 1 - Properties of aggregates used in the present study

Property	CRCA		NCA	
	Experimental result	Acceptance criteria	Experimental result	Acceptance criteria
Specific Gravity	2.355	2.3 or more (JIS A 5022 – Class M) [32]	2.83	2.30 – 2.90 (ACI E1-07) [33]
Water Absorption (%)	4.58	5.0 or less (JIS A-5022 – Class M) [32]	0.30	2.0 (MORTH-2013) [34]
Abrasion loss (%)	24	40 or less (KS F 2573) [35]	23	< 30 (IS 383:2016) [3] <30 (MoRTH-(2013) [34]
Crushing value (%)	24	-	22	< 30 (IS 383-2016) [3] <30 MoRTH (2013) [34]
Impact value (%)	20	-	14	< 30 (IS 383-2016) [3] <24 (MoRTH-2013) [34]
Adhered residual mortar (%)	29.0	-	-	

Class F fly ash was used in this study to reduce detrimental effects of porous residual mortar on CRCA. The CRCA was immersed in water for 24 hours and surface dried before use to minimize the effect of higher water absorption. NFA available in Delhi region conforming to Zone II of IS 383-2016 [3] was used. A second-generation polycarboxylic ether based superplasticizer (SP) was used.

4.2 Mixing, Casting and Curing

SCC-CRCA mixes for a characteristic compressive strength of 40 MPa were prepared for which the aggregate proportions were arrived at by using the APD Method [36]. An optimum CA: FA proportion of 50: 50 (Mix A) was obtained for maximum bulk density/ minimum void ratio, with the proportion of CRCA as 45 % in the total coarse aggregate. This is higher than the CRCA content recommended for use in NCA. A total of four SCC-CRCA mixes namely, with CRCA content varying as 0%, 20 %, 45 % and 100% were prepared for reference and comparative study purpose. In addition to the above optimum proportion of aggregates, two more SCC-CRCA mixes with aggregate proportions of 55:45 (Mix B) and 45: 55 (Mix C) were prepared to study the effect of variability in the aggregate proportions. Thus a total 12 SCC-CRCA mixes were prepared as detailed in Tables 2 and 3. A total of 12 SCC mixes including 3 controls SCC mixes with 100% NCA (optimum mixture of 20 mm and 10 mm fractions) and 9 test mixes with CRCA.

The flow properties of the SCC-CRCA mixes at 30, 60 and 90 minutes, after the addition of mixing water, were evaluated as per EFNARC Guidelines [37]. The temperature and relative humidity during the mixing and casting processes were maintained at 27 ± 2 °C and $65 \pm 5\%$, respectively. Although the flow properties of mixes A, B, C were investigated, specimen of SCC mixes of Type A and C only were tested for mechanical properties as per IS 516-2013 [38] as they exhibited satisfactory flow properties fulfilling the requirements of SCC.

Table 2 Mix Proportions percentage wise

Mix Type (CA:FA)	Mix Classification	% CRCA in total CA	Aggregate proportions (%)				
			NCA		CRCA		NFA
			20 mm	10 mm	20 mm	10 mm	
A (50: 50)	A-1	0	25	25	-	-	50
	A-2	20	20	20	5.0	5.0	50
	A-3	45	13.75	13.75	11.25	11.25	50
	A-4	100	-	-	25	25	50
B (55: 45)	B-1	0	27.5	27.5	-	-	45
	B-2	20	22	22	5.5	5.5	45
	B-3	45	15.12	15.12	12.38	12.38	45
	B-4	100	-	-	27.5	27.5	45
C (45: 55)	C-1	0	22.5	22.5	-	-	55
	C-2	20	18	18	4.5	4.5	55
	C-3	45	12.38	12.38	10.12	10.12	55
	C-4	100	-	-	22.5	22.5	55

Table 3 Mix Proportions of the SCC mixes studied

Mix designation	% CRCA	Cementitious Materials		Water	Mix Proportions				NFA	SP
		Cement	Fly ash		NCA		CRCA			
					20mm	10mm	20mm	10mm		
Mix A (50:50) Mix Proportions (kg/m³)										
A-1	0	350	102	181	435	435	0	0	870	2.70
A-2	20	350	102	181	349	349	87	87	873	2.70
A-3	45	350	102	181	241	241	197	197	876	2.70
A-4	100	350	102	181	0	0	441	441	882	2.70
Mix B (55:45) Mix Proportions (kg/m³)										
B-1	0	350	102	181	482	482	0	0	788	2.70
B-2	20	350	102	181	386	386	97	97	790	2.70
B-3	45	350	102	181	266	266	219	219	793	2.70
B-4	100	350	102	181	0	0	489	489	799	2.70
Mix C (45:55) Mix Proportions (kg/m³)										
C-1	0	350	102	181	383	383	0	0	937	2.70
C-2	20	350	102	181	307	307	77	77	939	2.70
C-3	45	350	102	181	212	212	173	173	942	2.70
C-4	100	350	102	181	0	0	388	388	948	2.70

5 Results and Discussion

5.1 Flow Properties

5.1.1 Flowability and Viscosity

The slump flow and $T_{50\text{cm}}$ slump flow time results of all the mixes are presented in Figures 1 and 2. While Mix B and Mix C conformed to class SF2, Mix A conformed to class SF3. The slump flow diameter increased and, $T_{50\text{cm}}$ slump flow time decreased at initial mixing time, for all the mixes, 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. Martinez-Garcia et al. [39] and Singh et al. [40] also reported a noticeable increase in instant slump flow with increase in CRCA content. Sherif A. Khafaga [41] reported lower slump flow immediately after mixing with increase in CRCA content, which could be due to non-presorting of CRCA in water for 24 hours. It was also observed that the slump flow decreased and $T_{50\text{cm}}$ increased with time and with the increase in CRCA content as shown in Figures 1 and 2. The flowability retention of Mix A was better than that of Mix B and Mix C.

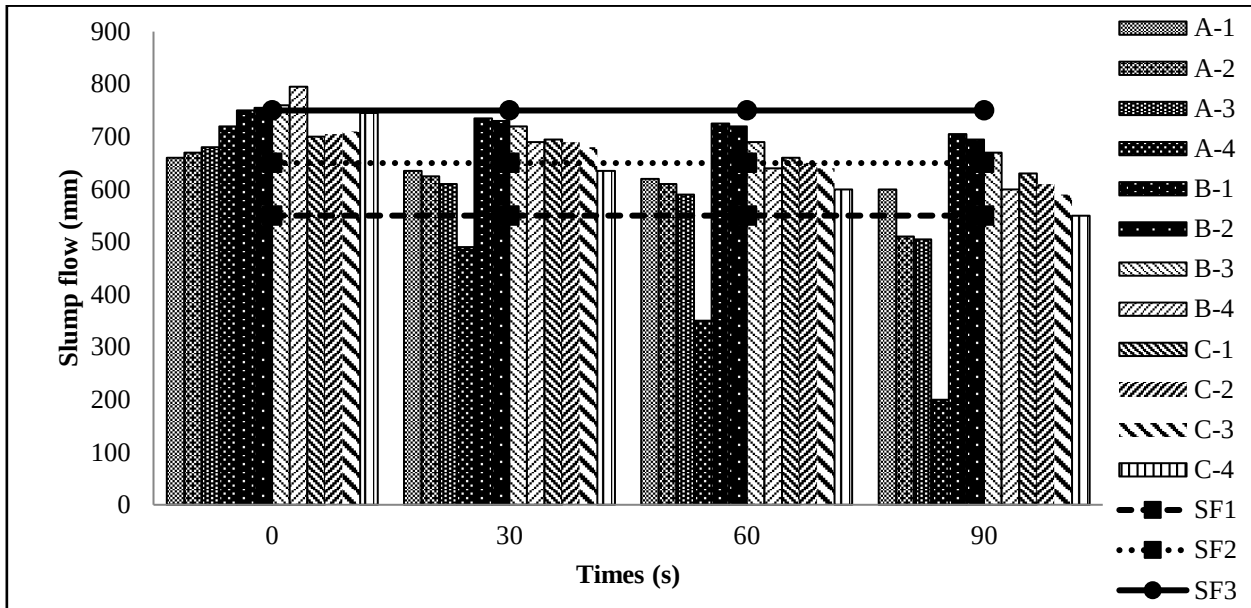


Figure 1 - Slump flow of SCC mixes of Type A, B and C

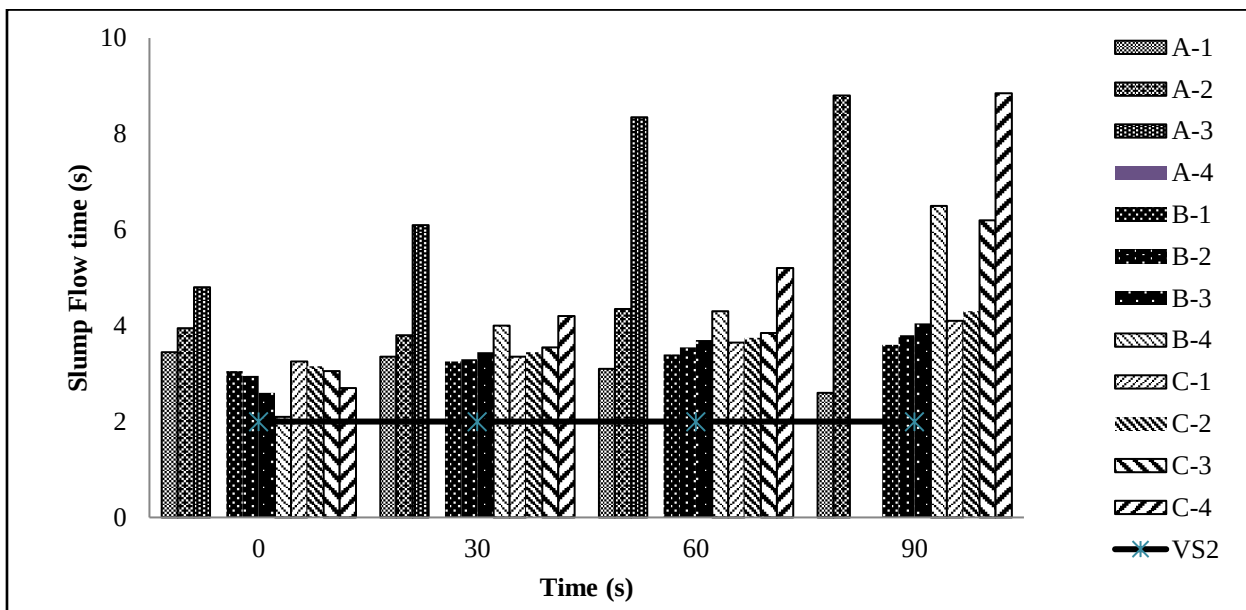


Figure 2 - Slump flow with time for different SCC mixes of Type A, B and C

5.1.2 Filling ability

The results of the V-funnel time of SCC mixes are presented in Figure 3. It may be noted that the initial V-funnel time of all the mixes was less than 10 s, indicating excellent filling ability and no sign of blocking. The mixes B-2, B-3 and B-4 initially conformed to class VF1 but the mix B-1 conformed to class VF2. Mixes A-1 to A-4 and C-1 to C-4 initially conformed to class VF1. Singh et al. [40] and Kapoor et al. [42] also reported a similar trend in variation of filling ability results, at the time of mixing, for SCC mixes made with fly ash and with increase in CRCA content. When the mixing time increased, the V-funnel time increased with increase in CRCA content. At 90 minutes after the mixing time, mixes B-1 to B-4 and C-4 exhibited a high flow time, indicating increased viscosity (due to continuous cement hydration), resulting in interruption of continuous flow of concrete through the opening of V-funnel. SCC mixes A-1 to A-4 conformed to class VF2 at 90 minutes.

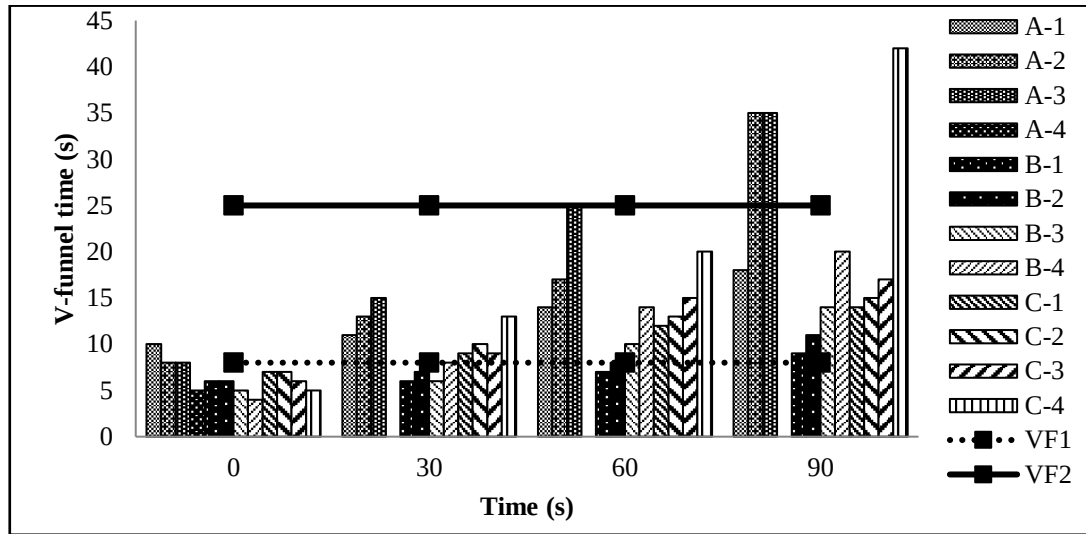


Figure 3 - V-funnel flow time of SCC mixes of Type A, B and C

5.1.3 Passing ability

The passing ability test results of the SCC mixes are presented in Figure 4. While all the mixes of Type B were getting blocked between the steel bars in the L-box test, the mixes of Type A and C conformed to the class PA2. When the mixing time increased, the passing ability decreased with increase in CRCA content, and at 90 minutes the passing ability of mixes A-1 to A-4 conformed to class PA2, and while the mixes C-1 and C-2 conformed to class PA2, the mixes C-3 and C-4 exhibited signs of blockage. Singh et al. [40] reported increase in passing ability with increase in CRCA content in the SCC mixes, but Kapoor et al. [42] reported decrease in passing ability with increase in CRCA content.

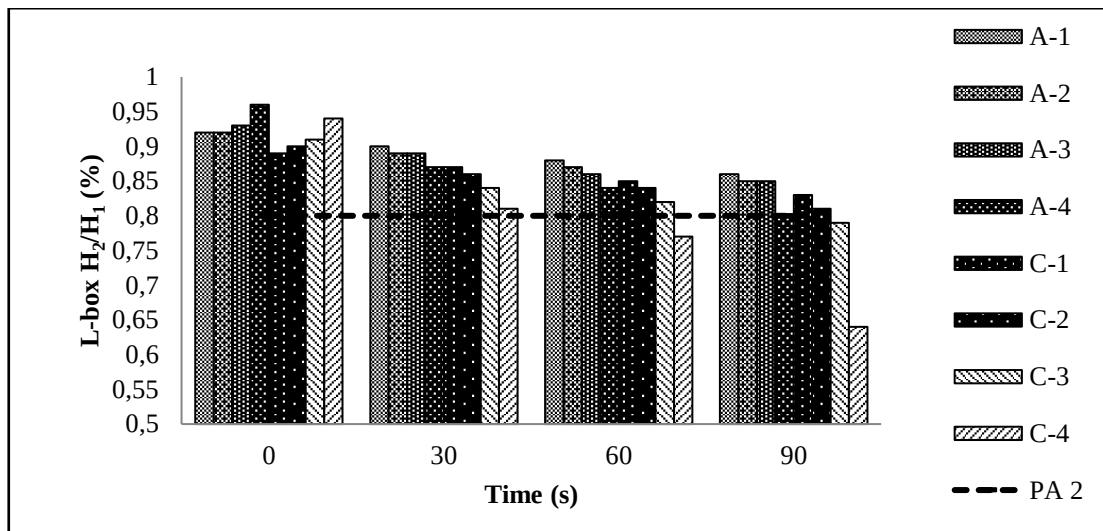


Figure 4 - Passing ability of SCC mixes of Type A and C

5.1.4 Segregation Resistance

The segregation resistance of all SCC mixes in terms of segregation ratio is presented in Figure 5. All concrete mixes B-1 to B-4 showed signs of bleeding and segregation at initial mixing time. The segregation ratio of Mix A and Mix C conformed to segregation class SR2. Grdic et al. [43] also reported a decrease in segregation ratio of the SCC mixes, 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. [9] reported increase in segregation ratio with the increase in CRCA content.

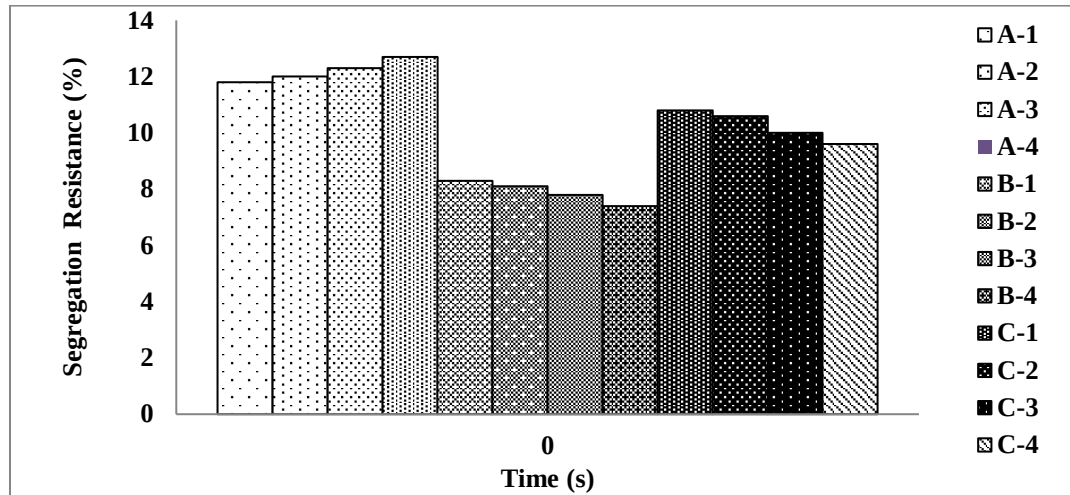


Figure 5 - Segregation resistance of SCC mixes of Type A, B and C

5.2 Mechanical Properties

All the mixes of Mix B were getting blocked between steel bars in the L-box test. Therefore, the SCC mixes of Mix B did not fulfill the requirements of passing ability; no further study was carried out on these mixes. Therefore, the mechanical properties of SCC mixes of Mix A and C only were evaluated in this study.

5.2.1 Compressive strength

The results of compressive strength of the Type A and Type C SCC-CRCA mixes at various ages are summarized in Figure 6. It may be noted that all the mixes achieved higher compressive strength than the characteristic strength of 40 MPa. It may also be seen from the above Figure that 7, 28, 56 and 90 day compressive strengths of Mix A are higher than those of Mix C. It may be recalled that Mix A has higher aggregate packing density as compared to Mix C resulting in less void content. It is clear from the results that the compressive strength increased with the increase in CRCA content up to 45%, and beyond 45 %, the compressive strength decreased. Such an inverse relationship between the CRCA content and compressive strength could be due to the poor quality of the adhered mortar creating zones of weakness within the concrete, at higher proportions of CRCA, as mentioned by Akbarnezhad et al. [44]. When NCA was replaced with CRCA at 100%, the strength of mixes A-4 and C-4 had decreased by only 12.84 %, and 13.60%, at 28 days, 11.79% and, 13.95 %, at 56 days, and 15.29% and 16.33 % at 90 days. Thus, the compressive strength of concrete is comparable with the control mix when NCA was replaced with CRCA at 100%, and which is encouraging for promotion of the use of CRCA in structural concrete.

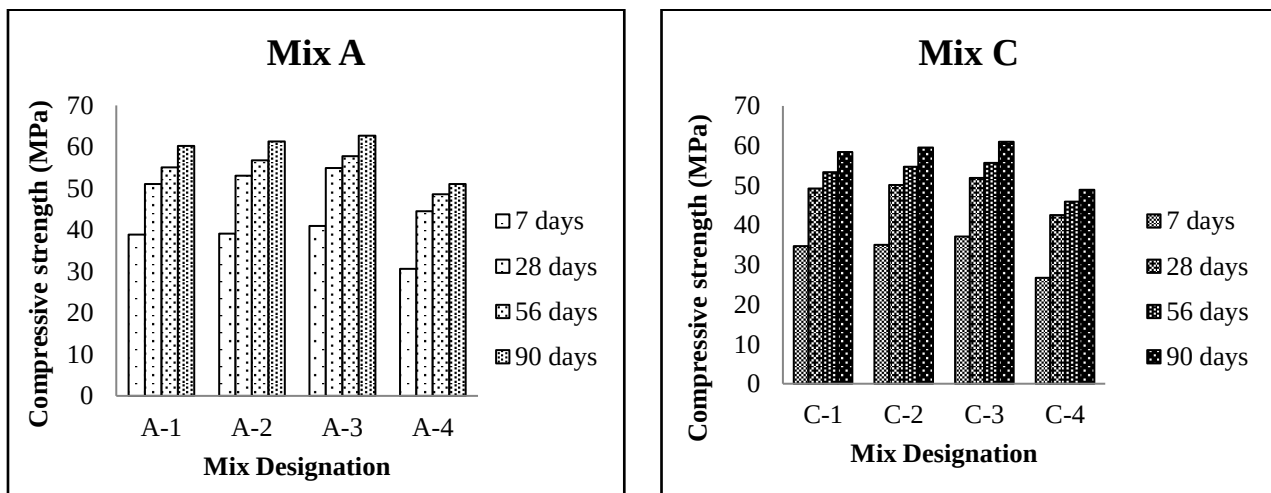


Figure 6 - Compressive strength of SCC mixes of Type A and C

Singh et al. [40] and Kapoor et al. [42] also reported decrease in compressive strength with increase in CRCA content in SCC mixes made with fly ash. However, the compressive strength obtained in the present study was higher than that reported by Singh et al. [40] and Kapoor et al. [42] at similar proportions of CRCA, despite a higher total binder content used in their study (615 kg/m^3) as compared to 452 kg/m^3 used in the present study.

5.3 Sustainability Considerations of SCC-CRCA

5.3.1 Comparison of the Mix Proportions of SCC-CRCA by APD, CPM and IS Code Methods

A comparison of mix proportions of SCC-CRCA mixes obtained by APD (used in this study for 40 MPa concrete and for CA: FA ratio of 50:50) was made with those estimated for similar strength concrete and w/c ratio using CPM and IS 10262 mix design methods, (assuming CRCA of 45 % in total coarse aggregate). It was noted that adoption of APD method resulted in lower cement and water contents in the SCC-CRCA mixes by up to 122 kg/m^3 and 89 kg/m^3 , respectively, indicating that this method is more economical and sustainable.

5.3.2 Reduction in CO₂ Emission with the use of SCC-CRCA in place of SCC-NCA

The experimental results indicated that up to a replacement of 45% of CRCA can be used in SCC, suggesting that higher quantities of CRCA can be used in cement concrete as against that recommended in IS specifications (i.e. 20 %) for normal concrete. The use of higher quantities of CRCA, in place of NCA, would help in conservation of equal quantity of natural resources (natural aggregate) and contributes to a corresponding reduction in the amount CO₂ emission. Also, the APD method used in this study to obtain optimum aggregate proportions resulted in requirement of lesser quantity of cement. The mix proportions of the SCC-CRCA mix based on APD method (Cement: 350 kg/m^3 , natural coarse aggregate: 482 kg/m^3 , CRCA: 394 kg/m^3 , fine aggregate: 870 kg/m^3) is compared to those of a normal SCC-NCA mix (Cement = 371 kg/m^3 , natural coarse aggregate = 922 kg/m^3 , fine aggregate = 910 kg/m^3), based on IS 10262 design method, for a 40 MPa concrete, in terms of CO₂ emission and cost.

Table 4 shows the estimates of Energy consumed (E_c) and CO₂ emitted (CO₂ e) for each raw material used in SCC-CRCA and SCC-NCA based on the reported emission factors [45-46] and the material quantities in the respective concretes.

It is evident that the APD method resulted in a reduction in total E_c by 94 kg/m^3 (5.10%), total CO₂ e by 34 kg/m^3 (9.23 %) and material cost by 1090 Rs. / m^3 (14.44 %) at the prevailing rates in comparison to the IS 10262 design method.

Table 4 - E_c , CO₂ e and cost comparisons between SCC-CRCA and SCC-NCA

Materials	$(E_c\text{-MJ/m}^3)$		CO ₂ e kg/m^3		Cost- Rs./ (kg/m^3)	
	APD	IS 10262	APD	IS 10262	APD	IS 10262
Cement	1610	1707	315	334	2660	2820
Fly ash	10.20	10.5	1.02	1.05	143	147
NCA	29.88	57.16	20.24	38.72	964	1844
CRCA	34.67	-	4.33	-	66.98	-
NFA	17.52	18.20	2.63	2.73	2190	2275
Water	36.20	38.0	0.054	0.057	163	171
SP	31.05	33.35	1.94	2.09	270	290
Total	1770	1864	345	379	6457	7547
Reduction (%)	5.10		9.23		14.44	

6 Conclusions

The flow and mechanical properties of SCC-CRCA at 0%, 20%, 45% and 100% were investigated. The aggregate proportions for this study were obtained using APD method. Three SCC mixes were prepared with proportion of CRCA varied in the range from 45 to 55%. Flow properties were investigated up to 90 minutes after mixing with 30 minutes interval. The following conclusions are drawn from this experimental study:

- The flow test result revealed that all mixes of Type A fulfilled the workability parameters as per EFNARC. Therefore, Mix A can be used for site applications with a transit time of up to 90 minutes. The mixes of Type B and Type C with CRCA at 100% incorporation lost their SCC characteristics at 90 minutes.
- It was observed that all the SCC-CRCA mixes achieved the compressive strength of more than 40 MPa. The experimental results indicated that there was no significant variation in properties of SCC-CRCA up to replacement of 45%, suggesting that higher quantities of CRCA, than that was recommended by various specifications, can be used in cement concrete and RCC.
- The higher compressive strength at relatively lower binder contents were attributed to use of aggregate packing mixture with higher bulk density.
- Use of CRCA in larger quantities will not only address the waste disposal issues but can also act as a potential source of alternative coarse aggregate for SCC towards its applications such as RCC, building infrastructure and structures, both in situ and precast construction.
- The proportioning of SCC-CRCA mixes showed a reduction in CO₂ emission by 9.23 % and cost by 14.44 % per cubic metre of concrete as compared to that proportioned using IS 10262, for a given strength.

Therefore, the results of the study revealed that replacement up to 45% of CRCA in total coarse aggregate can be used in structural concrete with satisfactory flow and mechanical properties.

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