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Research Paper

Effect of Coarse Recycled Concrete Aggregate on the Microstructural and Durability Properties of Self Compacting Concrete

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ABSTRACT

This paper presents the influence of different amounts of Coarse recycled concrete aggregate (CRCA) obtained from a Construction and Demolition Waste (CDW) Plant in Delhi, on the durability properties of a 40 MPa Self Compacting Concrete (SCC). 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 mixes was prepared. In addition, SCC was also made using aggregate mixtures in which the Natural coarse aggregate (NCA) was replaced with CRCA at 0% and 100 % (of the total coarse aggregate content). It has also been observed with the Mercury intrusion porosimetry (MIP) and Scanning electron microscopy (SEM) analysis that the incorporation of fly ash in SCC mixtures containing different contents of CRCA, resulted in the production of SCC-CRCA mixtures, with higher/comparable performance to that of control SCC mixture. The test results indicated that the SCC mixtures SCC mixtures exhibited very low chloride ion permeability at 28 days, lower carbonation depth. SCC made with CRCA up to 45% replacement can be used for structural concrete which is higher than that recommended in Indian specification (20 %) for normal concrete.

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, high fluidity and ability to fill formwork under its own weight, facilitating rapid placement in a short time, exhibiting noiseless construction, a superior level of finishing and, resulting in durable structure. Aggregates in SCC occupy 55-60 % of its volume and play a significant role in determining its workability, strength, dimensional stability, and durability [1]. The coarse aggregates comprise 45-50 % of the total volume of aggregate. In the recent decade, much of the research has been carried out on the usage of Recycled Aggregate (RA) in normal concrete

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manifesting its technological advancement [2, 3]. Indian specification IS383 [4] recommends 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 [1].

One of the challenges of SCC-CRCA is its low durability [5, 6]. The porous adhered mortar on CRCA is considered as responsible for its high water absorption and porosity, and influences the durability properties of concrete. The average amount of adhered mortar generally varies from 13% to 33.1%. To overcome this problem, many researchers have concluded that the CRCA should be used in a pre-saturated condition [7-9]. Alternatively, the adhered mortar either should be removed through different methods [10, 11], or its effect can be reduced by addition of mineral admixtures like flyash (FA), ground granulated blast furnace slag (GGBFS), silica fume (SF) or metakaolin (MK) as partial replacement of cement in the concrete mix.

SCC mixtures are generally produced with higher quantity of powder / paste content to provide the required flowability [12]. While the paste content in conventional concrete varies between 23-32 % [13], the same in SCC-NCA mixtures varies between 30-42 % [14]. 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. Sasanipour et al. (2019) [15] used a binder content of 33% (552 kg/m³) while Kapoor et al. (2016) [7] used 38 % (615 kg/m³).

Tuyan et al. (2014) [9] reported that the water absorption and chloride ion penetration increased and, freeze-thaw resistance decreased by the incorporation of CRCA upto 60% in total coarse aggregate. This was attributed to increase in porosity of SCC mixtures with the increase in CRCA content. Kapoor et al. (2016) [7] also reported increase in chloride ion penetration and depth of water penetration of SCC mixtures made with 30% FA at 56 days with increase in CRCA content. However, the chloride ion penetration and depth of water penetration of SCC mixtures decreased with the addition of SF and metakaolin at 10% by weight of cement, indicating that mineral admixtures are useful to compensate for reduction in durability properties when NCA was replaced with CRCA. Singh and Singh (2016) [16] studied the carbonation and electrical resistance of SCC made with CRCA and metakaolin. From their study, it was observed that with the addition of metakaolin, the carbonation and electrical resistance of the SCC mix made with CRCA at 50% were improved. The electrical resistivity of SCC-CRCA made with FA at 28 days varied in the range of 5.7 K-Ω-cm–11.2 K- Ω -cm, and the same decreased with the increase in CRCA content, indicating increased chances of corrosion in SCC-CRCA. Sasanipour et al. (2019) [15] reported increase in electrical resistivity of SCC mix with the increase of CRCA at 25%. However, resistance to chloride ion penetration decreased with the increase in CRCA content. Pereira et al. (2014) [17] reported zero air permeability of SCC mixtures made with CRCA. The mixtures were made with Ordinary Portland cement (OPC) and lime stone powder as binder whose proportion was 655 Kg/m³. Barroqueiro et al. (2019) [18] observed that decrease in depth due to abrasion of SCC specimen containing RA at 0%, 25%, 50% and 100% and, CRCA at 100% varied in the range of 3.0-4.1 mm and, 3.0-3.3 mm respectively. It is evident that the reduction in thickness due to abrasion was higher in SCC-CRCA mixtures than that was recommended (3.0 mm) for a conventional concrete as per ASTM C 779 [19], and the same increased with the increase of RA and CRCA content.

The drying shrinkage of SCC is also a significant durability parameter due to its higher paste content. Gesoglu et al. (2015) [20] reported that the shrinkage strain in conventional mix at 56 days was found to be 465 μ at a water/binder (w/b) ratio of 0.43 and, 415 μ at a w/b ratio 0.30, while the same in SCC – CRCA mix at 100% CRCA at the same age was 593 μ at w/b ratio 0.43 and 503 μ at w/b ratio 0.30, respectively.

As may be observed the durability investigations on SCC-CRCA mixtures made with CRCA are scarce and random. However, it is necessary to carry out a comprehensive investigation on its 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 durability properties (water permeability, rapid chloride penetration test, carbonation, electrical resistivity, volume of permeable voids) of SCC made with CRCA, of 20 mm, for a designed characteristic compressive strength of 40

MPa (5.8 ksi), and the findings of this experimental study are presented in this paper. With the help of a MIP and SEM the microstructure of SCC mixtures was also studied. 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 Experimental Program

2.1 Materials used

OPC of grade 43 conforming to IS 269 [21] and Class F FA conforming to IS 3812 (Part 1) [22] were used. The fineness of cement and FA 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 CRCA was used in as-collected condition and was not processed any further. The gradation curve for NCA and CRCA are given in Figure 1 and the properties of coarse aggregates are presented in Table 1. Class F FA 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 (BIS 2016), available in Delhi region was used as fine aggregate. A superplasticizer (SP) based on second-generation polycarboxylic ether was used. It was a light brown liquid with a relative density of 1.08.

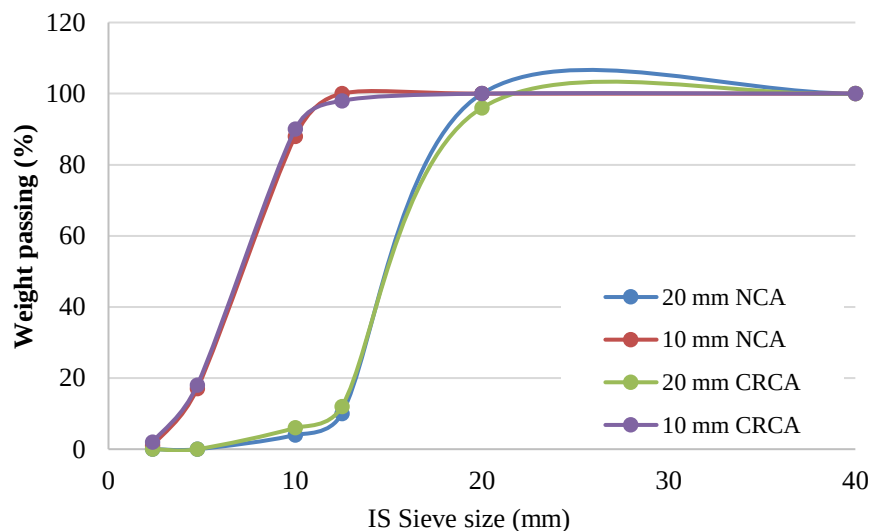


Fig. 1 – Gradation curve of NCA and CRCA

Table 1 – Properties of aggregates used in the present study

SI. No	Property (%)	NCA 20mm	NCA 10mm	CRCA 20mm	CRCA 10mm	Test Method (IS 2386:1963) [23-25]
1	Abrasion Value	22	29	24	26	Part IV
2	Crushing Value	23	26	24	27	Part IV
3	Impact Value	14	16	20	22	Part IV
4	Flakiness	9.0	20	3.0	6.0	Part I
5	Elongation	15	8.0	14	15	Part I
6	Soundness	0.97	0.67	11	12	Part V
7	Adhered mortar	-	-	29	51.67	Thermal Treatment

2.2 Mixing, Casting and Curing

APD method [26] 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 natural fine aggregate (CA: NFA)

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 0% and 100% indicate the reference concrete (100% NCA) and 0% NCA concretes. The binder content was fixed as $1.1 V_c$, where V_c is the total void content in the aggregate mixture [26]. The extra paste content was added to facilitate the flow properties of SCC mixtures. The binder content thus used was 32.44 % (452 kg/m³) 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 [27]. 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 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. Three 150 x 150 mm cylinders, six 100 x 200 mm cylinders, three 300 x 300 x 100 mm slabs, six 100 x 100 x 500 mm prisms were cast and investigations were conducted to study the durability and microstructure properties of all SCC mixtures. The details of test specimen cast, the tests carried out, and the test methods adopted are given in Table 3.

Table 2 – Mix Proportion of the SCC mixtures studied

Mixtures	% CRCA	Cementitious		Water	Mix Proportions				NFA	SP
		C	FA		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	45	350	102	181	241	241	197	197	876	2.70
A-3	100	350	102	181	0	0	441	441	882	2.70

Table 3 – Details of tests conducted

Property	Age at test (days)	Specimens size mm (inch)	Test method
Water permeability	28	Cylinder – 150 Φ x 150 (5.91 Φ x 5.91)	DIN 1048 Part V [27]
Rapid chloride penetration	28	Disc – 95 Φ x 50 (3.74 Φ x 1.97)	ASTM C1202 [28]
Volume of permeable void	28	Disc – 100 Φ x 50 (3.94 Φ x 1.97)	ASTM C642 [29]
Electrical resistivity	28	Slab – 300 x 300 x 100 (11.81 x 11.81 x 3.94)	Wenner's probe
Carbonation test	70, 140	Prism – 500x100x100 (19.68 x 3.94 x 3.94)	ISO 1920: Part 12 [32]

3 Results and Discussion

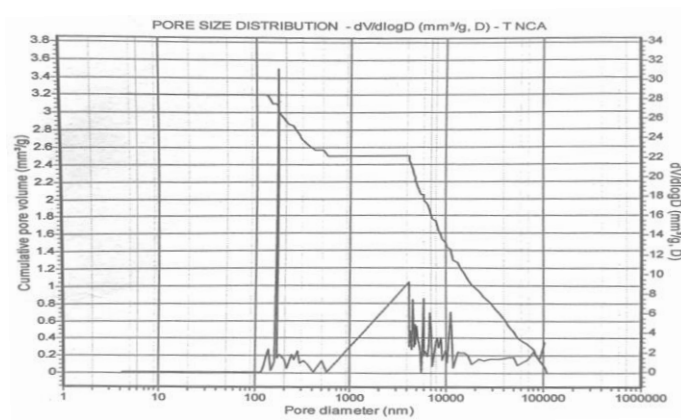
3.1 Microstructural Characteristics of SCC mixtures

3.1.1 Mercury Intrusion Porosimetry

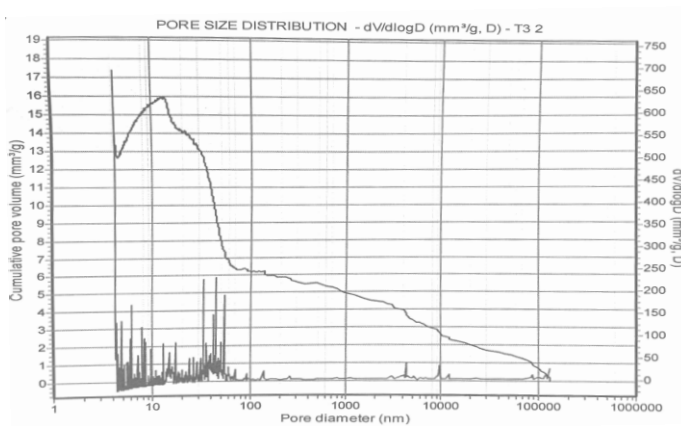
MIP test was used to investigate the pore characteristics of SCC mixtures. MIP test setup is shown in Figure 2. The pore size distribution curves of SCC mixtures A-1, A-2 and A-3 are shown in Figure 3. It well known that a lower amount of mercury is needed to fill the larger size pores whereas higher amount of mercury is required to fill the smaller size pores. Figure 3 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.



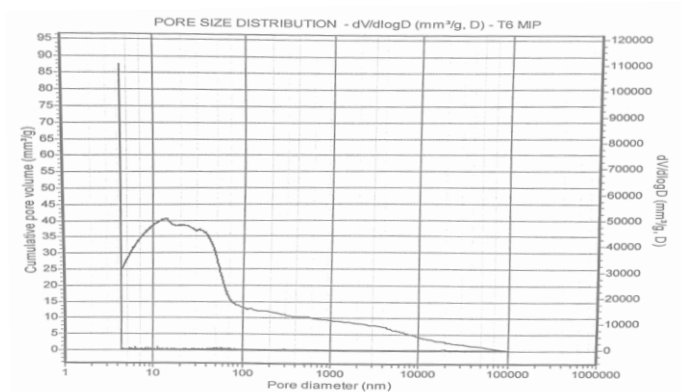
Fig. 2 – Mercury intrusion porosimetry test setup



Mix A-1



Mix A-2



Mix A-3

Fig. 3 – Pore Size Distribution curves of SCC mixtures

The total cumulative pore volumes of A-1, A-2 and A-3 SCC mixtures were $3.2 \text{ mm}^3/\text{g}$, $16 \text{ mm}^3/\text{g}$ and $40 \text{ mm}^3/\text{g}$, 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 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.

3.1.2 Scanning Electron Microscopy

The interfacial transition zone (ITZ) microstructure of Recycled aggregate concrete (RAC) is known to have a very complex structure as it is composed of more than one ITZ [24]. 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 Figures 4, 5 and 6, 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 Figure 4. 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 5 and 6. Similar observations were reported on the SEM of normal concrete [33], and SCC-fine recycled aggregate mixtures [34].

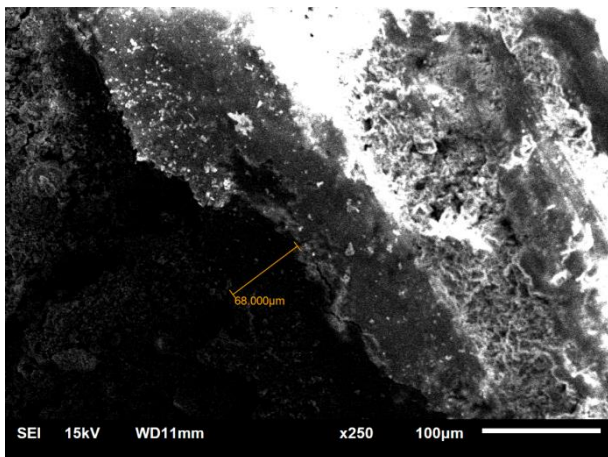


Fig. 4 – SEM image of SCC mixture A-1

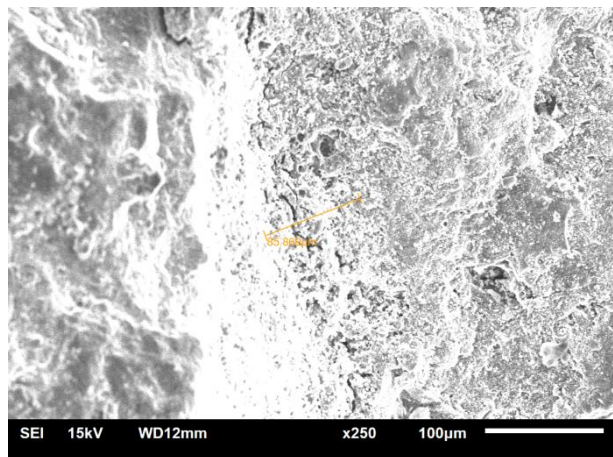


Fig. 5 – SEM image of SCC mixture A-2

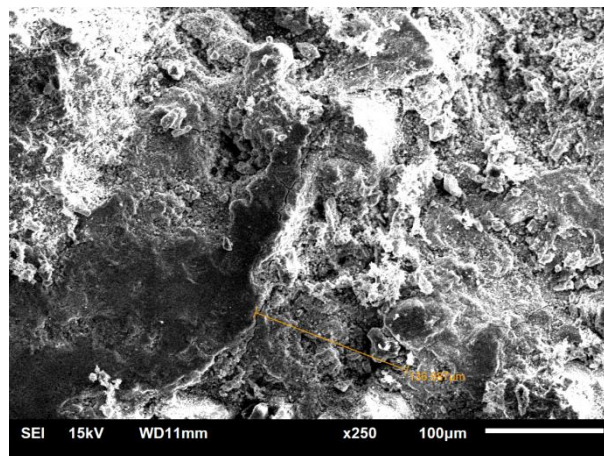


Fig. 6 – SEM image of SCC mixture A-3

3.2 Durability Properties

3.2.1 Water Permeability

The test set up of water permeability test is shown in Figure 7. The test results of depth of water penetration of SCC-CRCA specimens are given in Figure 8 and the results indicate that all the SCC mixtures fulfil the criteria for low permeability as indicated in Table 4. The low porosity (than the normally accepted range for conventional concrete) of these mixtures could have contributed to their low permeability. The depth of water penetration obtained was 3.80-5.10 mm. It was observed that the depth of water penetration at 28 days increased with increase in the CRCA content. The high water absorption capacity and porosity of CRCA might also be responsible for the higher permeability of mixture A-3 because the available pores of CRCA were not even filled by cement-paste or products of pozzolanic reaction as both were present in insufficient quantity. Kapoor et al. (2016) [7] reported a maximum water penetration of 3.5 mm in SCC mixtures of similar concrete strength grade (as used in this study) made with 100 % CRCA and binder containing cement, and FA. The CA: NFA ratio used by Kapoor et al. (2016) [7] was 42:58, as against the 50:50 (for type A-3 mix) used in this study.



Figure 7- Water permeability test set up

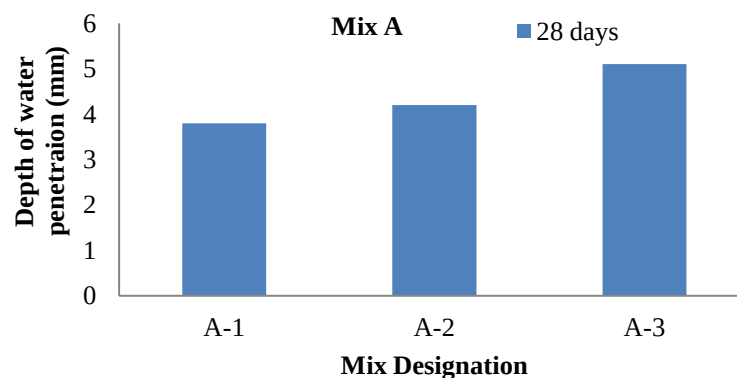


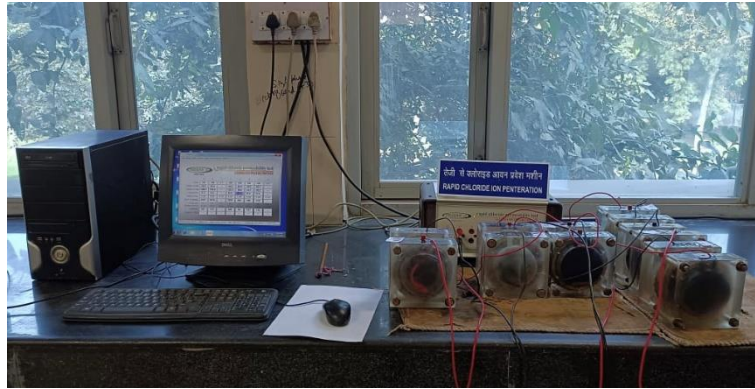
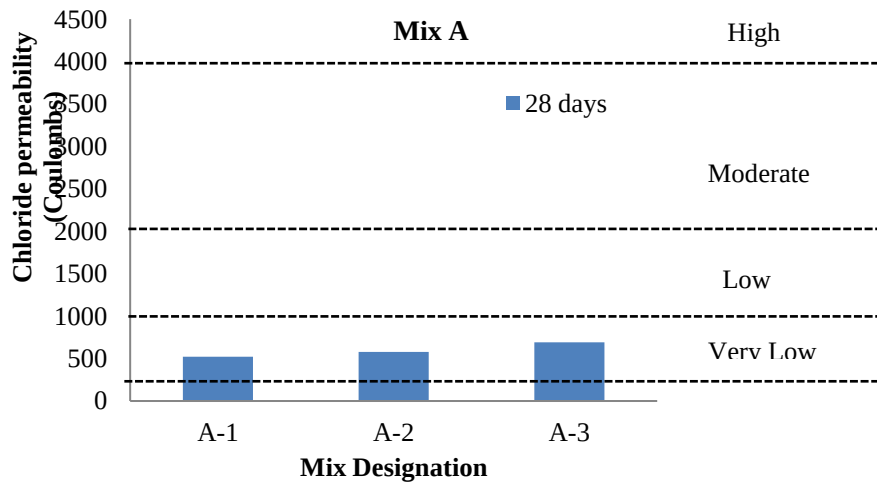
Fig. 8 – Water Permeability of SCC mixtures

Table 4 – Permeability ranges as per standard DIN-1048 [27]

Permeability as per DIN 1048 standard	Penetration Depth (mm)
Low	<30
Medium	30-60
High	>60

3.2.2 Rapid Chloride Permeability test (RCPT)

The test set up of RCPT is shown in Figure 9 and the results of various SCC-CRCA specimens are presented in Figure 10, which indicates that the charge passed through the test specimen, at 28 days, increased with the increase in CRCA content.

**Fig. 9 – Rapid chloride permeability test set up****Fig. 10 – Rapid chloride permeability of SCC mixtures**

The charge passed through test specimen of SCC mixtures A-1 to A-3 varied in the range 520-690 coulombs. It is well known that the chloride permeability depends upon the porosity. Therefore, increase in RCPT of SCC-CRCA mixtures correlate with the observations made about the porosity of the SCC mixtures as discussed in Section 3.1.1. The charge passed through specimen indicates that all the SCC mixtures fulfil the criteria for ‘very low’ chloride ion permeability, when assessed as per ASTM C1202 [28]. A similar trend on RCPT variation was reported by Sasanipour et al. (2019) [15] and Kapoor et al. (2016) [7], however, higher binder content was used in these studies as compared to the present study.

3.2.3 Electrical Resistivity

Electrical resistivity is a simple non-destructive test used to predict the possibilities of reinforcement corrosion; it also gives the direct measure of impermeability or interconnectivity of pores in the system. The variation of resistivity in the

SCC specimens is presented in Figure 11. The resistivity of SCC-CRCA mixtures obtained was 18-32 K- Ω -cm. It was found that SCC-CRCA mixtures exhibited higher resistivity in comparison to SCC-NCA mixtures indicating that use of CRCA up to 45 % can delay the initiation of reinforcement corrosion. Singh and Singh (2016) [16] reported that resistivity of SCC mixtures decreased with the increase in CRCA content; however Sasanipour et al. (2020) [15] reported increase in electrical resistivity of SCC mix with the increase of CRCA at 25% and beyond 25% CRCA, it decreased.

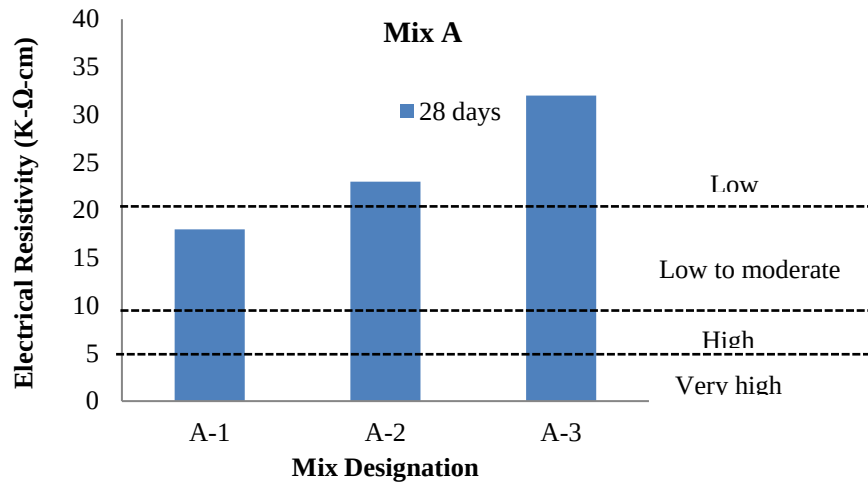


Fig. 11 – Electrical resistivity of SCC mixtures

It was observed that the SCC mixtures A-2 and A-3 conformed to ‘low’ chloride ion permeability criteria as per AASHTO T-358 [35], based on electrical resistivity measurements. Also, the electrical resistivity of SCC mixtures A-2 and A-3 which is significantly above 20 K- Ω -cm, corresponds to a ‘good’ quality concrete with negligible probability on corrosion of reinforcement embedded in this type of concrete as per CEB-FIP [36].

3.2.4 Volume of Permeable Void

Figure 12 presents the variation in Volume of Permeable voids of SCC-CRCA specimen. The volume of permeable voids of SCC-CRCA mixtures varied in the range of 3.85-6.10%. The permeable voids of SCC mixtures gradually increased with the increase in CRCA content. This may be attributed to the fact that CRCA contained porous adhered mortar, and therefore the concrete has increased volume of permeable voids. The increase in Volume of Permeable Voids in SCC mixtures could be correlated to the increase in the porosity in the matrix as was observed from the MIP and SEM studies as discussed in Section 3.1. Sasanipour et al. (2020) [15] reported higher volume of permeable voids of SCC mixtures containing CRCA at 25%, 50%, 75% and 100% than that obtained in this study. The authors have employed higher total binder content (552 kg/m³) as compared to 452 kg/m³ used in the present study.

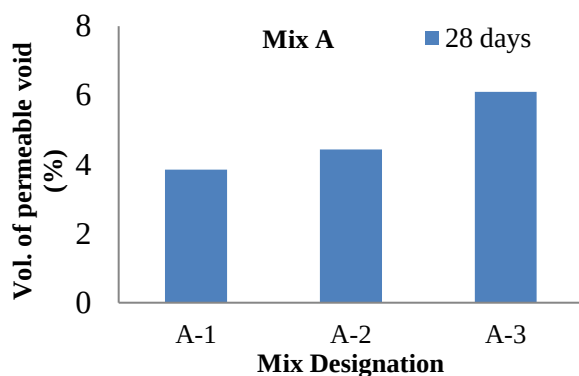


Fig. 12 – Volume of Permeable voids of SCC mixtures

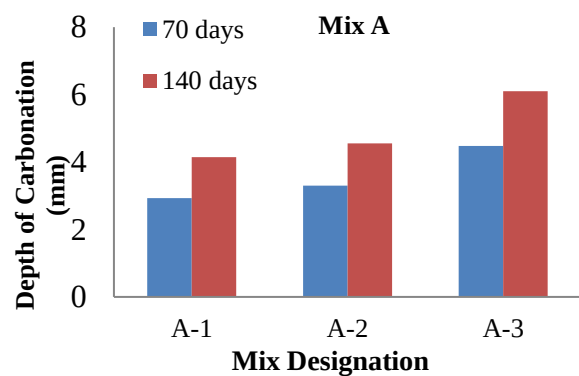


Fig. 13 – Carbonation Depth of SCC mixtures

3.2.5 Carbonation

The change in carbonation depth of SCC-CRCA specimen with an exposure period at 70 and 140 days is presented in Figure 13. For an exposure period of 70 days, the depth of carbonation of SCC mixtures A-1 to A-3 varied in the range of 2.93–4.48 mm. The increased porosity of SCC-CRCA mix, with increase in CRCA content, could be responsible for increase in the depth of carbonation.

Figure 13 presents the depth of carbonation at the higher exposure period also, i.e. 140 days. As the carbonation depth increases with increase in the exposure period, an increase in carbonation depth by 6% and 41% at 140 days in comparison to that at 70 days was observed. Also, the carbonation depth of mixture A-3, was higher by 47% in comparison to that of specimen of mixture A-1. The increase in carbonation depth of the SCC mixtures with the increase of CRCA content could be due to the increase in the amount of tiny size pores in concrete mixtures as was made evident from the MIP and SEM studies (discussed in Sections 3.1). A similar trend was reported by Singh and Singh (2016) [16] also.

4 Conclusions

The microstructural and durability properties of SCC-CRCA from 0%, 45% and 100% were investigated. The aggregate proportions for this study were obtained using APD. The following conclusions are drawn from this experimental study.

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.

Test specimen of SCC mixtures exhibited very low chloride ion permeability at 28 days, lower carbonation depth. This may be attributed to higher aggregate particle bulk density of Mix A specimen with fewer voids.

The SCC-CRCA mixtures can be categorized as ‘low’ permeability mixtures as per DIN: 1048 based on the water permeability test results obtained from the experimental programme,

The resistivity of SCC-CRCA specimen was higher than that of SCC-NCA, indicating their use in structural concrete can be recommended for delaying the initiation of reinforcement corrosion. It was also noted that the resistivity of the SCC-CRCA mixtures studied fulfilled the criteria for ‘low chloride ion permeability concrete’, when assessed as per AASHTO T-358.

Therefore, the experimental results indicated that there was no significant variation in the properties of SCC-CRCA vis-à-vis the SCC-NCA up to replacement of 45% suggesting that higher quantities of CRCA can be used in cement concrete as against that recommended in IS specifications for normal concrete. Also, the 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.

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