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Research Article

Recycled Coarse Aggregate for Sustainable Self-Compacting Concrete and Mortar

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The utilization of construction and demolition waste is useful for sustainable infrastructure development and protecting the environment. In this research, the properties of self-compacting concrete produced by replacing the natural coarse aggregates (NCA) with inferior recycled coarse aggregates (RCA) were investigated. The properties of self-compacting concrete (SCC) and self-compacting mortar (SCM) with varying replacements of RCA (0, 25, 50, and 100%) in NCA were determined. The flow, strength, early shrinkage tests, and microstructure using X-ray diffraction (XRD) and a scanning electron microscope (SEM) were investigated. The fresh property results indicated that the viscosity of freshly mixed SCC increased with higher replacement levels of RCA, thus reducing flow. The compressive strength of RCA SCC was reduced up to 30% for a 100% replacement level, while the flexural strength was reduced by about 15%. The compressive strength and flexural strength of SCMs, however, increased up to 12% and 28% for 100% replacement with RCA. The mechanical strength of SCM increases with RCA because of high fine content which reduces the porosity and makes the system denser. The early age linear shrinkage increases with RCA due to its greater water absorption. The results indicate that recycled coarse aggregate can be effectively used as the replacement of NCA in SCC to produce sustainable and eco-friendly structural concrete.

1. Introduction

A large amount of aggregate waste is generated in the construction industry. The waste aggregate can be recycled for new construction to help in the conservation of natural resources. The energy requirements, emissions, and carbon footprint associated with the production and processing of natural aggregate can also be reduced. The utilization of waste aggregate will not only improve sustainability but also decrease construction costs and reduce disposal and landfill issues.

There are several studies that demonstrate the effective utilization of waste materials in concrete [1]. According to Silva and De Oliveira Andrade [2], replacement of natural coarse aggregate (NCA) with recycled coarse aggregate (RCA) and cement with fly ash in concrete lowers its compressive and tensile strength at early stages. However, the pozzolanic reaction between Ca $(OH)_2$ of RCA and fly ash showed improved strength properties at higher ages closer to natural concrete. The tensile strength after 50 days was even superior than the control. Several studies explored the best composition of concrete made with recycled aggregate achieve strength and properties comparable to the control. It is agreed that small substitution of NA with RA is feasible. The addition of fly ash in OPC as a partial replacement in cement can improve the adverse effects caused by recycled aggregate [3]. At low w/c ratios, RCA concrete shows a much denser structure and improved properties, and with an increase in RCA, the mechanical and durability properties decrease [4]. They also presented a correlation to estimate elastic modulus from 28 days of compressive strength and carbonation of RCA concrete with a w/c ratio of 0.4 to 0.6. This helps estimate the RA replacement level in normal concrete for the given conditions. The work highlighted the need to consider the water absorption capacity of RCA in concrete.

The utilization of self-compacting concrete in the construction industry is gaining wide acceptance. Self-compacting concrete (SCC) consolidates under its own weight without the need for compaction. SCC has favorable flowability, filling, and passing abilities. It is a nonsegregating concrete which can flow easily and covers the reinforcement in formwork without the need for mechanical consolidation [5]. Moreover, it shortens the duration of concreting and provides a healthier working environment by reducing unpleasant noise and vibrations during casting. The use of self-compacting concrete was proposed during 1986 by Professor Okamura as an alternative to conventional concrete [6]. Ozawa and Maekawa developed the prototype of SCC in Japan in 1988, encompassing the workability of concrete as a major parameter [7].

The behavior and stability of fresh self-compacting concrete are defined by four main properties. These include flowability, viscosity (indicated by flow rate), filling ability, passing ability, and segregation resistance [8]. These are also referred to as fresh properties and can be enhanced with the use of chemicals in concrete. For example, using superplasticizers combined with additives such as viscosity modifying agents (VMA) and with the use of fine mineral additive powders as secondary raw materials (SRMs) [9].

The volume fraction of aggregate in self-compacting concrete is about 60 to 70%. The proper selection of aggregate has a main role in the fresh and hardened properties of concrete [10]. The aggregates have a major impact on the cost of SCC [11]. Consequently, cost-effective aggregates are preferred. In recent decades, the focus has been on utilizing recycled coarse aggregate (RCA) from the waste of construction and demolition [12]. A large quantity of construction and demolition waste is dumped in landfills, which creates environmental issues [13, 14]. Furthermore, there is a shortage of natural coarse aggregate (NCA) and the increasing charges of landfill [15]. One sustainable solution to this problem is the utilization of RCA as a substitute for natural coarse aggregates in concrete [4]. Several researchers have studied the partial and full substitution of natural coarse aggregate with RCA. It has been argued that the properties of SCC made with RCA remain satisfactory, and it can produce durable and sustainable concrete mixes [16–20].

Santos et al. has summarized studies on SCC made with fine and coarse recycled aggregate. SCC is a concrete technology that tends to substitute conventional concrete with several advantages. Thus, it creates the necessity to evaluate the viability and effect of NA replacement with RA. The review reports on the viability of recycled aggregate SSC to produce traditional/noncomplex structural elements to very complex/densely reinforced elements, in which vibration issue can influence the final quality of concrete. Boudali et al. [21] used recycled coarse aggregate for SCC and self-compacting sand concrete to evaluate the attack of sulfate. The recycled materials did not adversely affect the strength of SCC. The concrete containing recycled coarse aggregate and recycled fine concrete indicated better performance than natural aggregate and pozzolana in a sulfate environment.

Jagadesh et al. [22] and Martínez-García et al. [23] comparatively studied various works for the role of design parameters such as water-cement (w/c) ratio, total aggregate to cement (TA/C) ratio, fine aggregate to coarse aggregate (FA/CA) ratio, and superplasticizer content etc., on the mechanical properties (compressive and split tensile strengths) of SCC with recycled coarse and fine aggregates. It was observed that with respect to different grades of SCC, designed parameters affect the mechanical properties of SCC with recycled aggregates used. A 100% replacement of NCA is possible. The authors in [24] studied the flexural strength of reinforced concrete with a four-point bending test. The failure form, moment deflection curve, and flexural capacity were similar for both types of concrete, while the cracking moment and crack width of the RASCC samples were less than those of the NASCC.

According to [25], the strength characteristics at 25% to 75% RCA replacement levels were not impacted. The modulus of elasticity was significantly reduced for 100% RCA, indicating an issue of SCC brittleness. The fracture energy reduction was noted for 75% and 100% RCA replacement. The author reported an optimum of 25 to 50% RCA replacement level without impacting workability, strength, and fracture properties. Santos et al. [26] evaluated SSC using RCA and recycled fine aggregate (RFA) from precast industry waste. The properties are reported to be affected by the type and content of recycled aggregate. Similarly, the authors in [27] used recycled aggregate from out-of-service ballast and sleepers. SCC produced from these wastes was found to be effective for use in the construction of a new slab track.

The quality of recycled coarse aggregate (RCA) is dependent on its two main constituents including main aggregate and adhered mortar [26]. The amount and quality of adhered mortar affect the properties of RCA. Zitouni et al. [28] investigated the microstructure of new paste with different levels of recycled aggregate in comparison to the normal SCC. 30% RA replacement did not affect the new paste of SCC. A variation of porosity was observed for new paste 50 and 100% replacement; however, recycled aggregate improved the pore structure of the new paste. The macropores increased due to the release of water adsorbed by recycled aggregate during the presaturation process. The compressive strength is affected not only by the porous old paste of recycled aggregate but also by the porosity of the new paste.

The properties of RCA are inferior as compared to those of natural coarse aggregate. The interfacial transition zone (ITZ) characteristics are affected by RCA [29]. Moreover, RCA has lesser density, higher porosity, and higher water absorption in comparison to natural coarse aggregate [30]. This is due to adhered mortar present on the surface of RCA [31, 32]. Therefore, a proper mix design is needed to obtain the required quality of concrete made with RCA [11]. This research builds on the existing understanding of SCC through an investigation of the properties of fresh and hardened concrete. This study evaluates the utilization of inferior recycled aggregate in self-compacting concrete with a total replacement of natural aggregate. The self-compacting mortar (SCM) was used to study the effect of RCA on the hardened properties of concrete mortar.

2. Materials and Methods

2.1. Materials. Ordinary Portland Cement (OPC) Grade 53 Type-I, conforming to ASTM C150, was selected as the binder. The physical and chemical properties of cement are presented in Tables 1 and 2, respectively. The aggregates included natural coarse aggregate (NCA), recycled coarse aggregate (RCA), and natural fine aggregate. The NCA and RCA had a similar gradation as shown in Figure 1. The NCA was locally available Margalla crush and recycled coarse aggregate (RCA) of the same source were extracted from the tested concrete cylinders with a compressive strength of 3000 psi and an age of 6 months. The aggregate was obtained through manual hammer crushing. The nominal maximum size of both coarse aggregates was 16 mm with a D_{50} of about 10 mm. Locally available sand was selected as a fine aggregate with a nominal maximum size of 2 mm. The physical properties of NCA, RCA, and fine aggregate are listed in Table 3.

Ordinary tap water was used in all SCC mixes. A superplasticizer was added to achieve the required flow using reduced water content. Glenium®51 manufactured by BASF (Netherlands) was used as a liquid superplasticizer (SP) conforming to ASTM C494 Type F. The plasticizer had 40% total solid content.

2.2. Mix Proportions. The proportion of self-compacting concrete mix was calculated according to the EFNARC 2005 [33] and ACI 237R-07 guidelines [5]. Several trial concrete mixes were prepared with different superplasticizer dosages using NCA and RCA to obtain the same target flow. The suitable SCC mixes meeting the workability requirements (filling ability, passing ability, and segregation resistance) were selected from the trial mixes. Four SCC mixes with different replacements RCA (0%, 25%, 50%, and 100%) of NCA were produced. The mix proportions of concrete were determined on the volumetric basis and 2% entrapped air content. The water-cement ratio was 0.45 for all batches. The mix proportioning of different SCC mixes is presented in Table 4.

Table 1: Physical properties of OPC.

Properties	Values
Water demand	26.5%
Initial setting time	170 min
Final setting time	220 min
Specific gravity	3.15

2.3. Mixing Regime. The mixing sequence and duration influence the workability of SCC. All materials were placed in a 60 liter pan mixer by adding coarse aggregates, and then sand and cement were added to ensure efficient mixing. The constituents were mixed in a dry state at a slow rate for one minute. Then, 80% of water was introduced into the dry mix, and mixing was carried out for two minutes at the same rate. Finally, the remaining water blended with the superplasticizer was added to the loose mix. After this, mixing was carried out for 3 minutes at a faster rate to produce fresh concrete.

2.4. Test Methods

2.4.1. Flow Tests of Fresh Concrete. The characterization of self-compacting concrete is carried out by flow tests including filling ability, passing ability, and segregation resistance. After the completion of mixing, all the fresh properties are investigated within 20 minutes. The objective was to reduce the resulting variability due to loss of workability.

(1) Filling Ability Tests. The workability of SCC in an unconfined test condition is called filling ability. It is assessed by slump flow with T_{50} and V-funnel flow times. First, the standard slump cone flow test was carried out to measure the flow spread under the self-weight of SCC without the presence of obstructions. In this method, the cone was filled with SCC without compaction. Then, the cone was lifted, and slump flow was obtained by taking the average diameter of two perpendicular measurements (Figure 2). The T_{50} slump flow time is the duration of the flow spread of 500 m, and it indicates the viscosity of SCC.

The V-funnel test was also performed to measure workability. The V-funnel flow time is the duration required for the SCC to fall under the effect of gravity through a small opening in the V-shaped apparatus (Figure 2). It also shows the viscosity of the SCC batch. The shorter the flow time, the lower the viscosity and greater the filling ability, and vice versa.

(2) Passing Ability Tests. The passing ability is a measure of SCC to flow in confined conditions. It was measured through L-box and J-ring tests as shown in Figure 3. The L-box test evaluates the ability of SCC to pass through reinforcing bars. The apparatus consists of a rectangular assembly containing horizontal and vertical parts. There is a movable partition between these parts that contains vertical bars in front of it. The vertical part is filled with SCC, and the partition is removed to cause flow into the horizontal part. After the flow has stopped, the height of concrete at the end

Table 2: Chemical properties of cement.

Oxide composition	SiO_2	TiO_2	Al_2O_3	FeO_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI
OPC grade 53	19.19	0.29	4.97	3.27	0.04	2.23	65.00	0.58	0.51	0.08	3.84

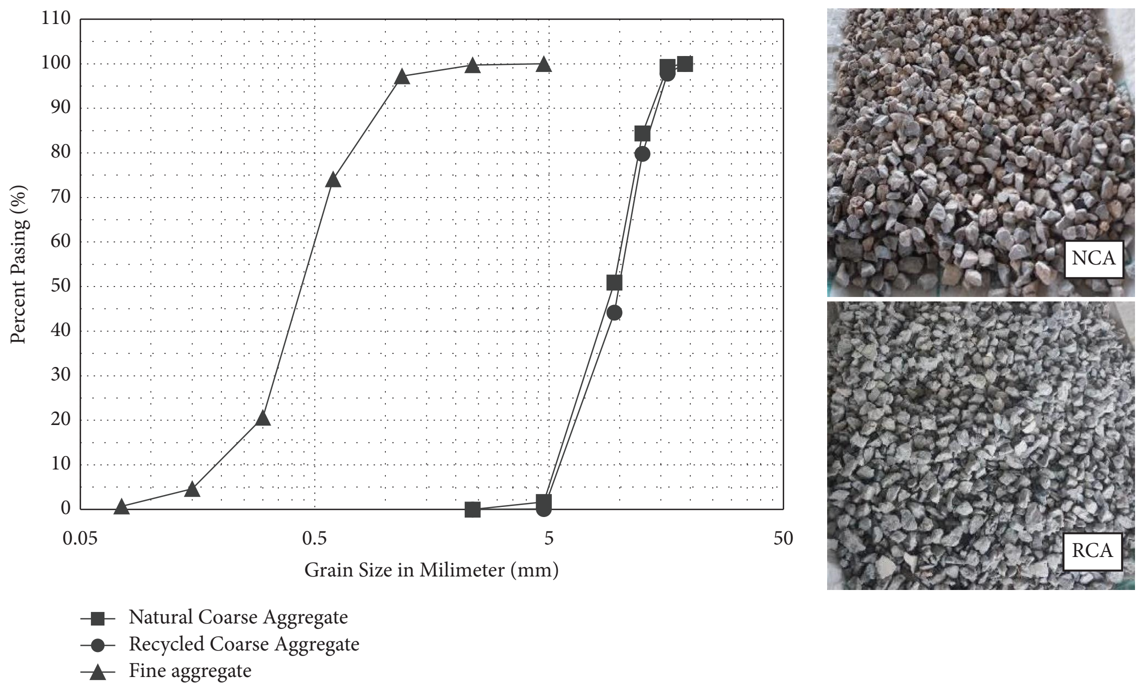


Figure 1: Gradation curves of aggregates.

Table 3: Properties of aggregates.

Properties	Natural coarse aggregate	Recycled coarse aggregate	Fine aggregate
Fineness modulus	6.47	6.56	2.04
Bulk specific gravity (SSD)	2.75	2.53	2.69
Absorption capacity (%)	1.1	3.81	0.81
Dry rodded bulk density (kg/m^3)	1476	1419	1596
Impact value (%)	20.79	22.4	—
Crushing value (%)	23.86	25.97	—
10% fine value (Tons)	20.1	18.68	—
Los Angeles abrasion value (%)	15.34	20.62	

Table 4: Mix proportions of 1 m^3 of SCC mixes.

% of RCA	Mix designation	Cement (kg)	Fine aggregate (kg)	Coarse aggregate (kg)		Water (kg)	SP (kg)
				NCA	RCA		
0	NCASCC	520	820	820	—	234	1.30% = 6.76
25	RCASCC-25	520	820	620	186	234	1.30% = 6.76
50	RCASCC-50	520	820	408	374	234	1.45% = 7.54
100	RCASCC-100	520	820	—	750	234	1.70% = 8.84

of the horizontal part and in the vertical part is measured to calculate H_2/H_1.

The procedure for the J-ring test and cone slump flow test is similar, except that in the former, a ring of vertical and even-spaced smooth bars surrounds the slump cone (Figure 3). J-ring is the most stringent flow test for SCC. Once the flow has occurred, the difference in concrete height between the central position and just outside the J-ring is used to measure the blocking step (BJ). In addition to this, the passing ability was evaluated using the blocking index

Figure 2: Standard slump cone test and V-funnel test.

Figure 3: L-box test and J-ring test.

(BI), which is the difference between slump flow and J-ring flow.

(3) Segregation Test. The segregation resistance of a fresh SCC mix is measured by the GTM sieve stability test. In this test, 10 liters of concrete are placed in a bucket and allowed to stand for 15 minutes. The bucket is covered with a lid to avoid evaporation effects. After this, concrete is poured over a 5 mm sieve. The weight of the mortar collected in the pan is measured after 2 minutes. The ratio of the weight of the concrete passing through the sieve to the total weight is used to calculate the segregation ratio.

(4) Density and Air Content of Fresh SCC. The density of fresh SCC was calculated by dividing the weight by the known volume of concrete. The pressure method was used to measure the air content of fresh mixed SCC. In this method, a container of known volume is filled with SCC, and the upper surface of the container is leveled using a straight edge. The air content was measured with a gauge by placing the lid of the pressure meter on the container.

The test sequence of SCC mixes was the slump flow test, V-funnel, L-box, J-ring, sieve stability test, air content, and density test. The tests were performed as per EFNARC 2005 guidelines [33].

2.4.2. Hardened Concrete Tests. The hardened properties of SCC mixtures were measured with compressive and flexural strength tests. The tests were carried out on 100 mm × 200 mm SCC cylinders and 100 mm × 100 mm × 400 mm SCC prisms to measure compressive and flexural strengths, respectively. The rate of loading was 0.25 MPa/sec for compressive strength and 0.025 MPa/sec for flexural strength as per BS EN 12390-1. Nine concrete cylinders and prisms were cast for each mix proportion. The strengths were taken as the average of three concrete specimens for each mix proportion at 3, 7, and 28 days.

The self-compacting mortar (SCM) was obtained after passing the green SCC through sieve 10. The SCM was used to study the effect of RCA on the hardened properties of mortar. The prisms of 40 mm × 40 mm × 160 mm were cast for measuring the flexural strength of SCM. After testing three prisms in flexure, the resulting broken pieces were taken for determination of compressive strength and microstructural investigation of mortar. A total of nine SCM beams were cast for each mix proportion. The tests were performed after 3, 7, and 28 days of casting.

2.4.3. Linear Shrinkage Test of SCM. Early-age linear shrinkage responses of SCM were observed for 24 hours for all mix proportions with different replacement levels of

RCA. A modified German classical Schwindrinne (shrinkage apparatus) of $4 \times 6 \times 25\ cm^3$ with a sensitivity of 0.31 microns was used at $25 \pm 3^\circ C$ and a relative humidity of $35 \pm 5\%$. All samples were kept uncovered in the shrinkage apparatus for 24 hours. The resulting shrinkage response for all mix proportions was plotted against time.

2.4.4. Microstructure of SCC. X-ray diffraction (XRD) tests were performed on the SCM. The samples were examined for the influence of recycled coarse aggregates containing SCMs on the hydration products (calcium hydroxides, calcium silicate hydrates, and ettringite). Scanning electron microscope (SEM) tests were carried out on SCMs to study the effects on morphology due to recycled coarse aggregates. For both XRD and SEM, NCASCC (control) and RCASCC samples were selected after testing the specimens in compression on the 7th day of casting to study morphology and hydration products. Before these tests, samples were prepared by being placed in acetone for 24 hours and then in isopropanol to stop hydration.

3. Results and Discussion

3.1. Properties of Fresh SCC. The fresh properties of all SCC mixes (filling ability, passing ability, and segregation) are given in Table 5. The amount of superplasticizers was adjusted to meet the required target flow of 700 ± 20 mm. All test results for fresh properties are within the acceptable limits as per EFNARC 2005 [33] and are indicated in Table 6. The results in Table 5 show that the quantity of recycled coarse aggregates affects their fresh properties. It is concluded that SCC can be made with 100% RCA while satisfying EFNARC guidelines.

The results of the tests of filling ability vary with the replacement levels of RCA. The slump flow and T_{50} slump flow times change from 680 to 720 mm and 2.0 to 4.72 sec, respectively. The V-funnel flow time changes from 9.60 to 11.47 sec at zero and 100% RC replacement levels. The SCC minimum slump flow is generally recommended to be 650 mm for adequate self-consolidation property [34]. The slump flow decreases with the increase in T_{50} and V-funnel flow time at increasing replacement levels of RCA. This is because adhered mortar causes higher angularity and surface roughness of RCA increasing friction between coarse aggregates. This increases the harshness of SCC mixes made with RCA. Another reason for low slump flow and high flow time for RCASCC-50 and RCASCC-100 is a large number of fine aggregates. This decreases the free water content in the mix, thus increasing the viscosity of SCC.

The passing ability results for varying RCA levels are shown in Figure 4. The L-box blocking ratio (H_2/H_1) varies from 0.80 to 0.84, while the J-ring blocking step varies from 6 mm to 9.5 mm. The low values of H_2/H_1 and the high values of blocking step (BJ) show a low passing ability of concrete with increasing RCA replacement. The size of aggregate also affects the passing ability of concrete. The replacement of RCA increases the blockage tendency of the mix due to its high angularity and rough texture. According to ASTM C1621 [35], the difference between slump flow and J-ring flow, i.e., the blocking index (BI) should be less than or equal to 25 mm for SCC to ensure good passing ability. All SCC mixes in this research have good passing ability based on BI values.

The segregation index (SI) varies with replacement levels of RCA from 8.08% to 9.73% as shown in Table 5. The concrete with more RCA content displays high resistance to segregation due to the greater cohesive nature of RCA. In RCASCC-75 and RCASCC-100, the cohesion between aggregate particles increases due to the greater fine content, resulting in good resistance to segregation. Moreover, the cohesive nature of RCA is enhanced due to its particle shape and roughness, thus leading to a reduced segregation index. Figure 4 shows that the density of freshly mixed SCC decreases with the replacement of RCA, whereas the air content of SCC increases. The reduction in density and increase in air content of fresh concrete occur due to adhered mortar attached to the aggregate surface, which causes high porosity and angularity.

3.2. Mechanical Strength of Hardened Concrete (SCC). The compressive strength varies with an increase in replacement levels of RCA (Figure 5). Early-age strength is similar for all mix proportions. However, a reduction in strength is observed on days 7 and 28 of casting. The strengths achieved for RCASCC-25, RCASCC-50, and RCASCC-100 on the 28th day of casting are 88%, 80%, and 71% of NCASCC, respectively. The microstructure of the concrete with recycled coarse aggregates is an important governing factor in the development of strength [36]. Two weak interfacial transition zones were observed in concrete. One was between aggregate and adhered mortar, while the other was between adhered mortar and the new mortar matrix. This reduces the quality of concrete to a certain extent. The old weak residual mortar layer on RCA results in lower density and higher porosity, thus lowering the compressive strength. The failure in NCASCC happened within the hardened cement paste, while in RCASCC-100, the failure path not only passed through the hardened cement paste but also the aggregate particles, which are a weak component of the composite. The flexure strength of SCC decreases with the addition of recycled aggregate. The flexure strength achieved for RCASCC-25, RCASCC-50, and RCASCC-100 on the 28th day of casting is 91%, 88%, and 85% of NCASCC, respectively (Figure 5).

3.3. Mechanical Strength of SCM Derived from SCC. The mechanical strengths (compressive and flexural strengths) of SCM prisms increase with the addition of RCA as shown in Figure 6. Slightly higher strength is obtained in flexure and compression for mortar prepared by RCASCC-100. The

Table 5: Fresh properties of SCC.

Mix designation	Falling ability			Passing ability				Segregation resistance
	Slump flow (SF) (mm)	Slump flow time T_{50} (sec)	V-funnel flow time Tv (sec)	J-ring flow (JF) mm	Blocking index BI (mm)	J-ring BJ (mm)	L-box H_2/H_1	Segregation index, SI (%)
NCASCC	720	2	9.6	700	20	6.0	0.84	9.73
RCASCC-25	695	3.42	10.27	673	22	7.0	0.82	9.51
RCASCC-50	685	4.14	10.91	670	15	8.0	0.81	9.01
RCASCC-100	680	4.72	11.47	665	15	9.5	0.80	8.08

Table 6: Acceptance criteria for fresh properties of SCC.

Methods	Units	Typical values	
		Minimum	Maximum
Slump flow by Abrams cone	mm	650	800
T_{50} slump flow	sec	2	5
J-ring	mm	0	10
V-funnel	sec	6	12
L-box	H_2/H_1	0.8	1.0
GTM screen stability test	%	0	15

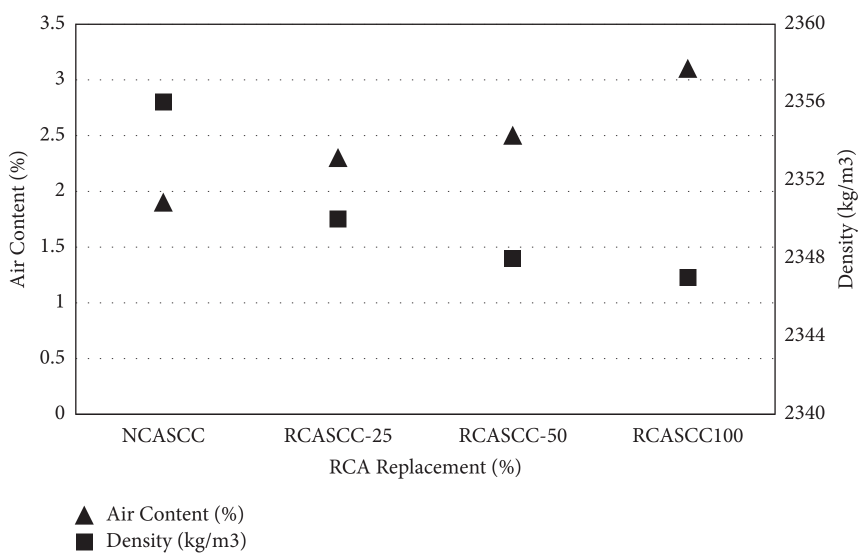


Figure 4: Density and air content of SCC.

increase in strength is due to the dilution effect of cement paste and the greater fine content of the mortar. A greater fine content makes the composition dense and reduces the porosity, thus enhancing the strength.

3.4. Shrinkage Response of SCMs. The shrinkage response against time is presented in Figure 7. It is observed that early-age linear shrinkage increases with the amount of RCA replacement. The recycled coarse aggregates demand greater water content to obtain adequate mixture properties because of their more water absorption. SCC with recycled coarse aggregates shows more shrinkage because the elastic modulus of recycled coarse aggregate is less as compared to natural coarse aggregate; therefore, it is more deformable [37]. The larger shrinkage has been observed for RCASCC-50 and RCASCC-100 due to their greater fine content which requires more water to achieve the required workability. Moreover, all the samples were placed uncovered in the shrinkage apparatus which caused evaporation of water leading to enhanced shrinkage.

3.5. Microstructure of SCC. XRD results of NCASCC and RCASCC-100 samples are presented in Figure 8. The values for 2θ ranged from 10 to 70°. In the RCASCC-100 sample, there is a higher SiO_2 intensity which shows high fine content. It justifies the increase in strength for SCM samples due to dense packing and the dilution effect. The intensity of calcium hydroxide (CH) is lower in the

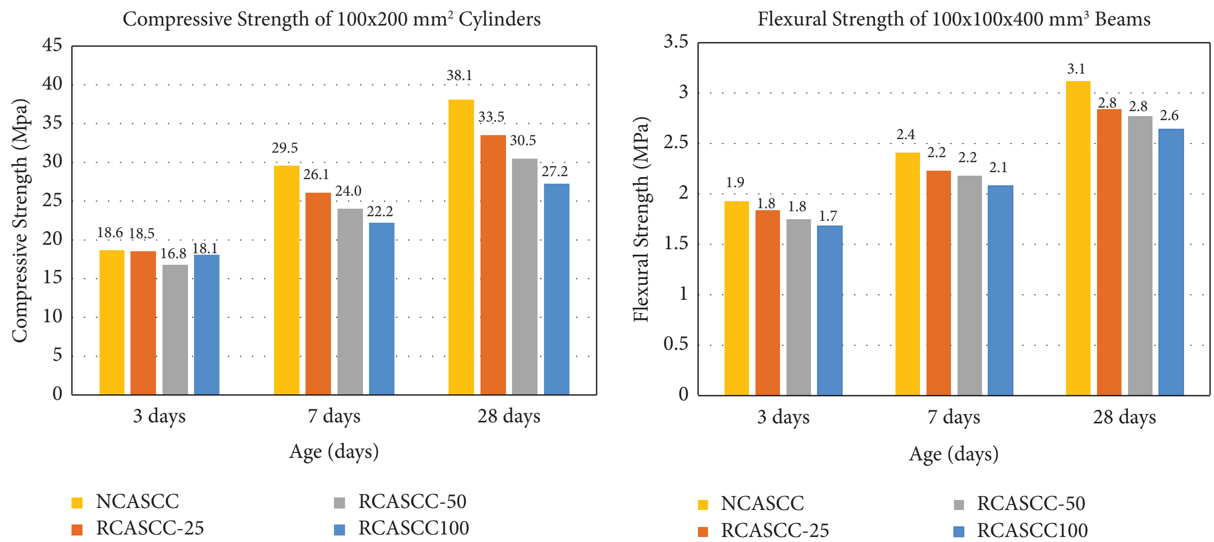


Figure 5: Compressive strength and flexural strength of SCC.

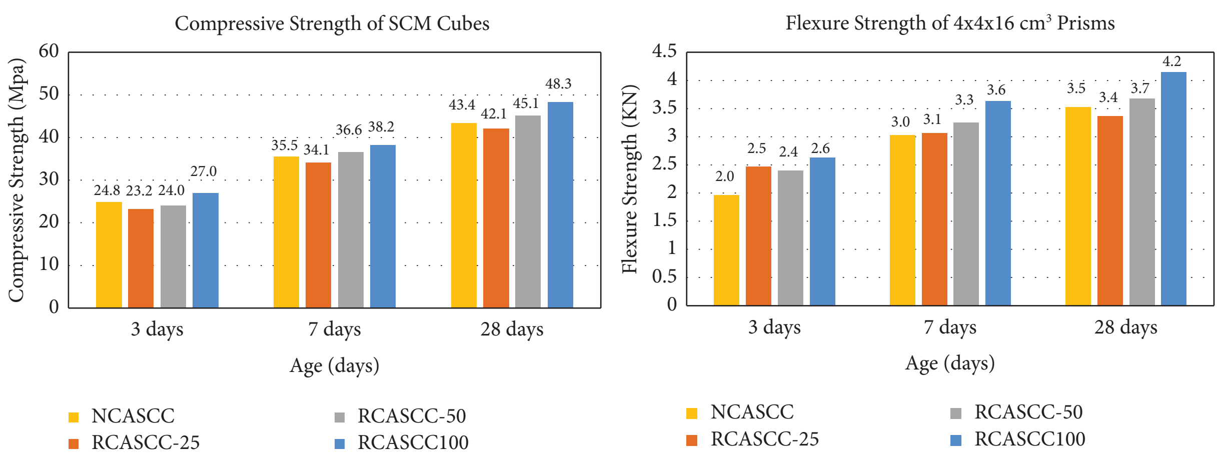


Figure 6: Compressive strength and flexural strength of SCM.

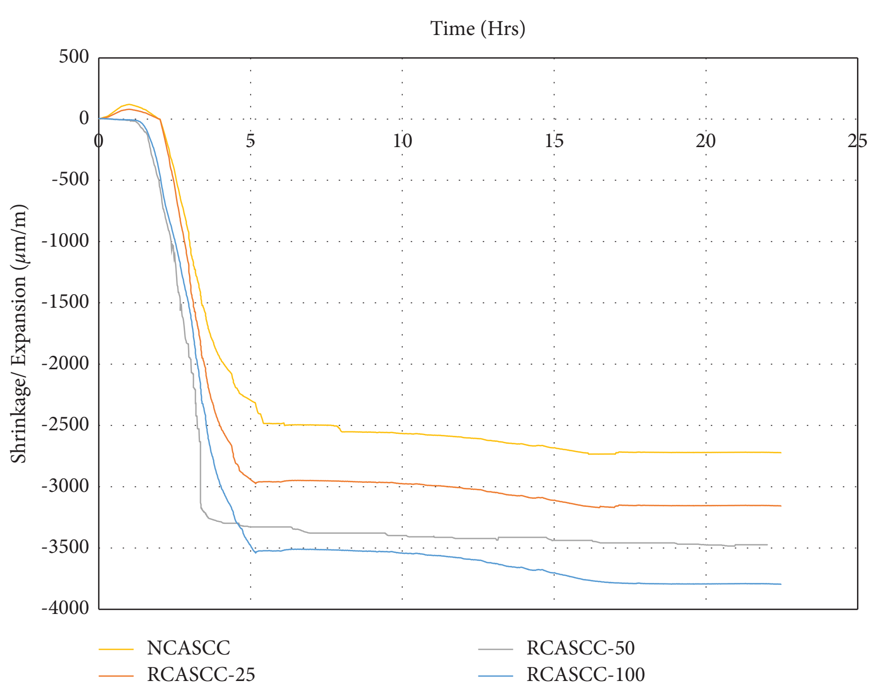
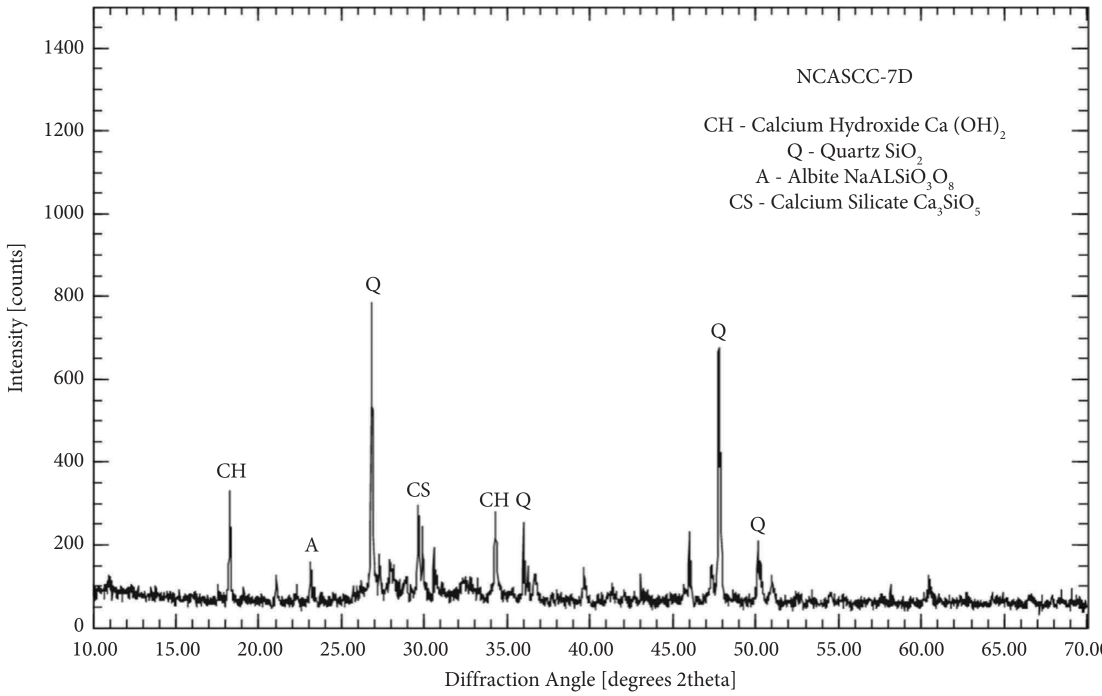


Figure 7: Shrinkage response against time.



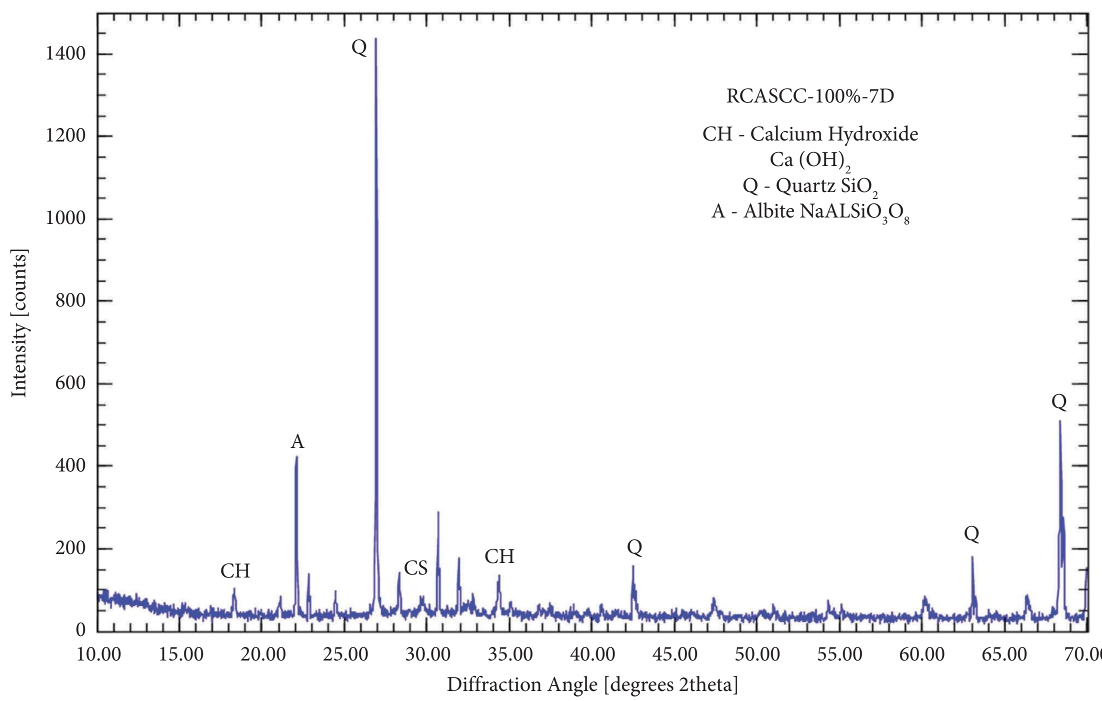


Figure 8: XRD analysis of NCASCC (a) and RCASCC-100 (b).

RCASCC-100 mortar sample which shows less expansion in the system. Thus, lower CH justifies the increase in strength. From Figure 7, it can be observed that shrinkage increases with the addition of RCA, which is due to the lower intensity of CH which causes less expansion in the system.

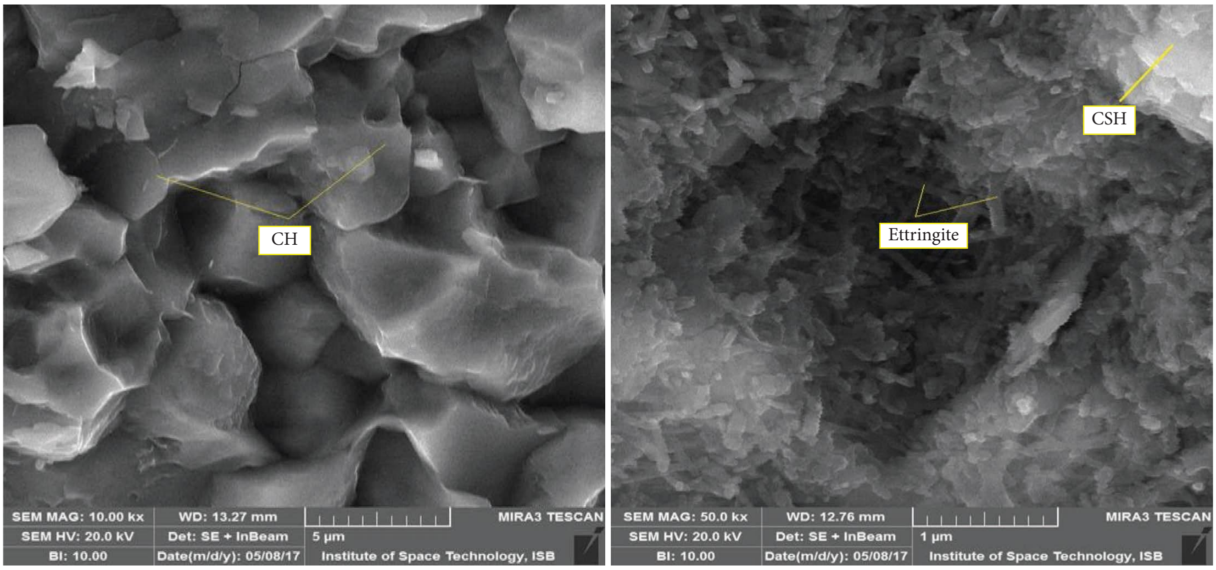


Figure 9: SEM of the NCASCC sample.

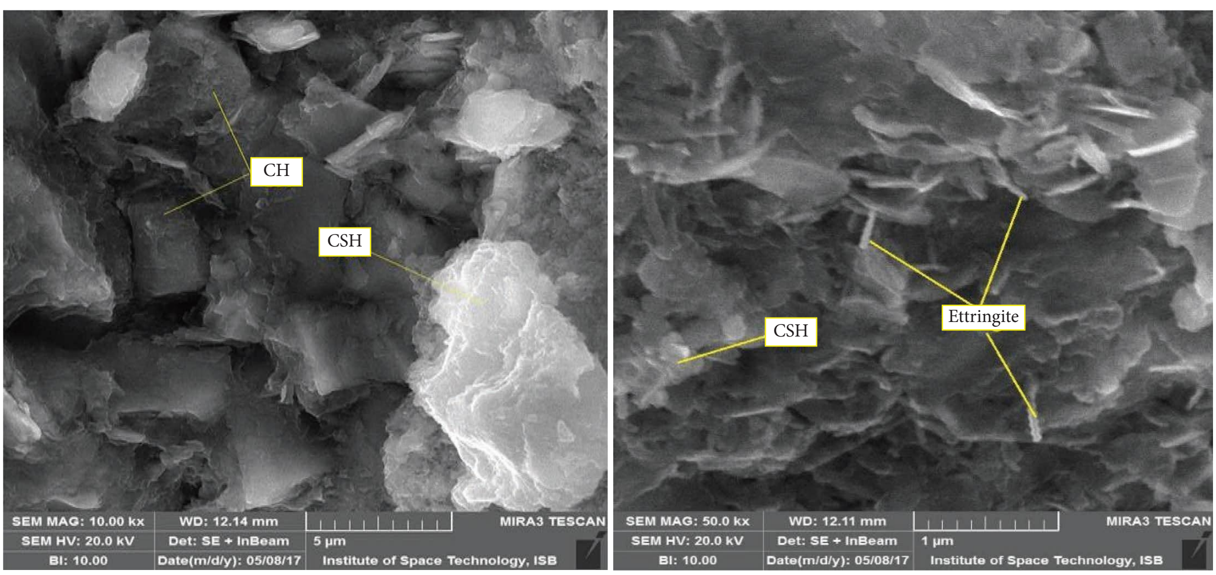
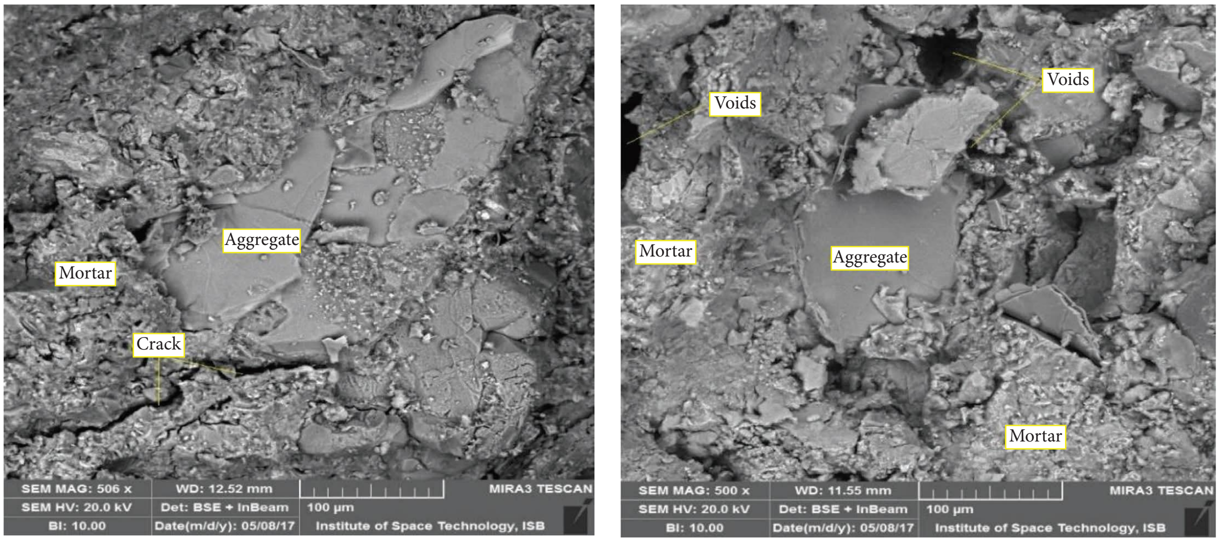


Figure 10: SEM of the RCASCC-100 sample.

SEM analysis was performed on the fracture surfaces. The hydration products of NCASCC and RCASCC-100 can be observed in Figures 9 and 10, respectively. At the same magnification, ettringite and calcium hydroxide (CH) crystals in NCASCC are larger than those in RCASCC-100. This justifies the results of the XRD analysis. Due to large



(a) (b)

Figure 11: Interfacial morphology of NCASCC and RCASCC-100.

crystals of CH, the volume of SCM increases, causing expansion in the system. Such expansion in the system causes lower shrinkage in NCASCC.

Figure 11 represents the SEM images of NCASCC and RCASCC-100 in the back-scattered electron mode (BSE). The figure shows that the microstructure of NCASCC is denser and has fewer cavities and voids, while the microstructure of RCASCC-100 is porous, causing a reduction in the compressive and flexural strength of SCC.

4. Conclusions and Recommendations

The physical properties of recycled coarse aggregate (RCA) including bulk density, specific gravity, crushing value, and impact value are inferior to those of natural coarse aggregate (NCA). RCA shows more water absorption as compared to NCA. These properties of RCA are affected by residual mortar adhering to coarse aggregate. The fresh property test results reveal that the viscosity of SCC made with RCA increases with the addition of RCA. Moreover, the fresh properties of SCC including filling ability, passing ability, and segregation resistance remain satisfactory and within the acceptable limits as per guidelines provided by EFNARC.

The hardened properties results show that the compressive strength of RCASCC-100 decreased to about 70% of NCASCC, while flexural strength decreased to about 85% of NCASCC on the 28th day of casting. Since the loss of strength is comparatively less, so it is possible to use recycled coarse aggregate as a replacement for natural coarse aggregate to produce structural concrete.

The compressive and flexural strength of self-compacting mortar (SCM) increase with higher replacement levels of RCA. The compressive strength increased up to 12%, while the flexural strength increased up to 20% on the 28^{th} day of casting for SCM produced from RCASCC-100. This increase in strength is due to high fine content which reduces the porosity and makes the system denser. The early age linear shrinkage increases for higher replacement levels of recycled coarse aggregate due to its greater water absorption. The overall experimental results encourage the use of RCA as a replacement for NCA in self-compacting concrete to produce structural concrete.

Data Availability

Data will be made available upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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