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Effect of copper slag on recycled aggregate based self-compacting concrete

Sanjay Kumar *, Anasuya Sahu, A.K.L Srivastava

Department of Civil Engineering, National Institute of Technology, Jamshedpur 831014, India

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ABSTRACT

The present research paper investigated experimentally the effective use of copper slag (CS) in recycled aggregate based self-compacting concrete (SCC). The work is carried out in two series. In the first series SCC mixes are prepared with recycled coarse aggregate (RCA) as a replacement of natural coarse aggregate of various proportions (0%, 33%, 66% and 100%). In the second series copper slag of various proportions (0%, 20%, 40%, 60%, 80% and 100%) is incorporated as fine aggregate in SCC mix made with 33% RCA and studied the behaviour of recycled aggregate based SCC mixes. Different properties of all mixes including fresh and hardened properties were determined according to EFNARC guidelines and IS code of practice and compared with the control concrete. The morphology of various SCC mixes is examined through scanning electron micrograph to verify the strength of SCC mix. The test results revealed that, with increased in RCA content the compressive strength of SCC decreased whereas the tensile strength of SCC is found marginal and comparable to control mix. However, by incorporating copper slag to the recycled aggregate concrete the compressive and split tensile strength of SCC enhanced up to 7% and 28% respectively in comparison to control SCC mix. The cost-effective and environmental impact analysis of RCA based SCC was carried out and it is revealed that, the combined use of RCA and copper slag could cut the cost of SCC by 8–11% and the maximum reduction in CO_2 emission was about 3% which enables the construction sector to develop more sustainably and make a significant contribution towards the preservation of natural resources.

1. Introduction

In the current scenario, the use of recycled materials in construction sector is a challenging issue with respect to its proper utilization, cost-effectiveness, and environmental impact assessment. Due to heavy industrialization and urbanization the construction sector required large number of natural resources for production of quality concrete from which aggregates can occupy three-fourth volume of concrete. So, in order to overcome the use of high volume of aggregates (both fine and coarse) alternative materials obtained from the construction and industrial waste can be utilized as aggregates in the concrete production which minimizes the cost of concrete, reduces the landfill space and scarcity of natural resources. In this context, one of the most promising options for a wide range of options in the usage and reuse of construction materials in the Civil Engineering Industries is the use of recycled concrete aggregate (RCA) from construction and demolition waste and copper slag (CS) from the copper industry.

Copper slag is one of the waste materials obtained in huge amount during the matte smelting and refining processes of copper metal from copper industry. The primary components of copper slag are iron sulphides and copper oxides, with SiO2, Al2O3, CaO, and MgO rounding out the composition [1]. According to the researchers [2,3], India has been contributed 3.4% of the global CS production from various copper industries and produced a total of 2.4 million tonnes of CS annually. As an alternate material for improving the mechanical properties of concrete, CS has been discovered in earlier studies [4–7] to exhibit the fundamental characteristics of fine aggregates. Similarly, the utilization of the significant growth in construction and demolition waste over the past ten years represents another major challenge for construction sector. So, in order to preserve natural resources, protect the environment, save energy, and promote sustainable development, it is crucial to employ industrial wastes and recycled concrete aggregate from the building industry. The present research work is focussed on the production of SCC by using CS as fine aggregate, along with RCA.

Self-compacting concrete is the most revolutionary types of concrete with the ability to flow and compacted under the self-weight without the need of vibration effort because of its excellent deformability and cohesiveness [8]. SCC was first introduced in 1988 by H. Okamura [9].

* Corresponding author.
E-mail addresses: sanjaykumar.civil@nitjsr.ac.in (S. Kumar), anasuyasahu1980@gmail.com (A. Sahu), aklsriv.civil@nitjsr.ac.in (A.K.L Srivastava).

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The use of SCC in concrete industry is rapidly increased in the recent decade due to its high workability, excellent strength, and durability properties though it is costly and requires more quantity of cement and other cementitious materials as compared to the normal concrete. Different waste materials like recycled aggregate, iron slag, copper slag, silica fumes, metakaolin that have been used in SCC as fine and coarse aggregate or cement substitutes for minimizing its cost and making an environment friendly concrete. In the last decade many research [10–20] has been carried out by utilizing RCA and CS in SCC individually to evaluate different properties of concrete and it has been proven that both recycled concrete aggregate and copper slag can successfully replace coarse and fine particles in SCC. The current research work aims to examine the impact of employing CS as fine aggregate on the strength and microstructural characteristics of recycled aggregate based SCC as there is no research has been carried out on CS and RCA combinedly for development of SCC.

The novelty of the research work is to study the effect of CS on mechanical performance of SCC made by recycled aggregate concrete. Though, so many research work is carried out using RCA and CS for the development of SCC but the combined effect of RCA and CS in SCC are not studied till now. Further, as both CS and RCA could address the lack of natural resources in the infrastructure development sector of the building industry so the author's main consent is the effective use of RCA and CS towards the production of sustainable self-compacting concrete. In order to validate the research work, the experimental work is carried out by constructing SCC with 33%, 66% and 100% RCA as a replacement of NCA and fixed the % of RCA by comparing their mechanical properties with control SCC. Then the copper slag of various proportion (0%, 20%, 40%, 60%, 80% and 100%) as fine aggregate is added to the SCC made with 33% RCA and studied their combined effects on fresh and mechanical properties of SCC experimentally by comparing with control SCC. The properties on fresh state including slump and T500 slump flow, V-funnel and L-box test has been performed based on EFNARC guidelines and the strength properties including compression test and split tensile test has been done as per the Indian code of standards. The morphological behavior of various concrete mixes is studied through scanning electron micrograph (SEM).

2. Experimental programme

2.1. Materials required

OPC (ordinary Portland cement) of 53 grade conforming to IS12269 (1987) [21] is required for the experimental work. Fly ash (FA) with class F is used in the study to replace OPC by 30%. Crushed basalt stone sieved through 12.5 mm and retained on 10 mm sieve is utilized as natural coarse aggregate in self-compacting concrete. RCA derived from waste concrete collected from demolition of old petrol pump is used in the present investigation. The waste concretes so obtained were crushed by using crusher machine and produced recycled coarse aggregate. The RCA is again crushed manually to remove the old mortar attached to the aggregate surface in order to reduce the water absorption and converted into required size as NCA. Copper slag used in the study is collected from Hindustan Copper LTD, Jamshedpur and replaced the NFA partially in SCC. PC-200, a poly-carboxylic ether-based superplasticizer (SP) with reduced viscosity is used in the study. The SP dosage is fixed to 1.5% of the cementitious material in accordance with IS 10262:2019 [22]. The physical properties of OPC, NCA, RCA, NFA and CS are presented in Table 1after tested in the laboratory as per IS specification.

Table 1
Physical properties of materials used in the study.

Properties	OPC	FA	NCA	RCA	NFA	CS
Specific Gravity	3.14	2.0	2.8	2.6	2.63	3.6
Density	1446	–	2665	1954	1564	1950
Water Absorption	–	–	0.83	3.52	0.83	0.6
Fineness modulus	–	–	5.35	5.6	2.5	3.4

2.2. Mix proportioning

In this experimental work, there is two series of mix. In the first series total 4 trial mixes have been prepared including one control SCC mix designated as S. Another 3 mixes are prepared by replacing NCA with 33%, 66% and 100% RCA by weight. The second series consists of five trial mixes that are prepared by replacing NFA with 0%, 20%, 40%, 60%, 80% and 100% by weight of CS. All the trial mixes have been designated according to the proportions of RCA and CS. For example, the trial mix of SCC with 33% RCA and 0% CS is designated as S33R0C. The details of mix design proportions with their designations are provided in Table 2.

All the mix proportions have been designed for target strength of 30 N/mm^2 in accordance with IS 10262 and FNARC guide lines. It must be noted that, for all mixes the cementitious content was kept constant with 70% OPC and 30% fly-ash (FA) with water binder ratio 0.45. In order to obtain a workable concrete, the coarse aggregates used in the study is taken in surface saturated dry condition by pre-soaking of aggregates for 24 h prior to casting.

2.3. Concrete properties

The fresh properties including slump flow test, T500, V-funnel and L-box of all the groups of concrete is determined after homogenous mixing of all the materials using laboratory concrete mixture followed by EFNARC guide lines [8]. The hardened properties including compressive strength and split tensile strength test of different trial SCC mixes have been carried out after 7 and 28 days of curing as per IS:516 [23] and IS:5816 [24] respectively on compressive strength testing machine with capacity 3000 KN. Minimum 3 nos. of cube- specimens having 150 mm size for compression and 3 cylindrical specimen of 150 mm dia for spit tensile are casted for each trial mix and kept as air dried for 24 h and then allowed for curing prior to test.

3. Result analysis

3.1. Fresh state properties

The properties of various SCC mixes on fresh state are conducted in the laboratory and the values obtained were compared with the EFNARC [8] classification. The results revealed that all the trial mixes are satisfied with the EFNARC limit and the workability results has been improved with the addition of CS.

3.1.1. Slump flow test and T500 sump flow

Fig. 1 represented the slump and T500 slump flow values of control SCC mix, SCC with RCA mix and RAC based SCC with CS mixes. Fig. 1(a) showed the slump flow value of all the mixes which were likely to be in the range of 583–745 mm and satisfies the EFNARC [8] limits. It has been observed that the slump value declined when the RCA substitution increased in the mix. However, the SCC mix with 33% RCA showed improved workability with respect to control and other RCA mixes. The flow value of SCC mix containing 66% and 100% RCA is decreased by 4.58% and 11% respectively with respect to the control mix. The down grading in the flowability of fresh concrete is due to the high-water absorption and lower density of RCA which increased the coarse aggregate volume and reduced the free water content in the mix. Further the flow values shown in the figure has been increased up to 14% with respect to control mix by the addition of copper slag in RCA based SCC mix, reaching 745 mm for the mix containing 33% RCA and100% CS (S33R100C). The even surface of CS grains with low water absorption capacity boosted the passing ability of SCC mixtures, resulting in an increase in slump flow [19]. Fig. 1 (b) described the T500 slump flow

Table 2
Details of mix proportions with mix designations.

Group	Mix description	Cement (kg/m^3)	FA (kg/m^3)	NFA (kg/m^3)	CS (kg/m^3)	NCA (kg/m^3)	RCA (kg/m^3)	Water (kg/m^3)	SP (lt/m^3)
	S-Control	309	133	913	0	860	0	190	6.63
Series 1	S33R0C	309	133	913	0	576	284	190	6.63
	S66R0C	309	133	913	0	292.4	567.6	190	6.63
	S100R0C	309	133	913	0	0	860	190	6.63
Series 2	S33R20C	309	133	730	183	576	284	190	6.63
	S33R40C	309	133	365	548	576	284	190	6.63
	S33R60C	309	133	548	365	576	284	190	6.63
	S33R80C	309	133	183	730	576	284	190	6.63
	S33R100C	309	133	0	913	576	284	190	6.63

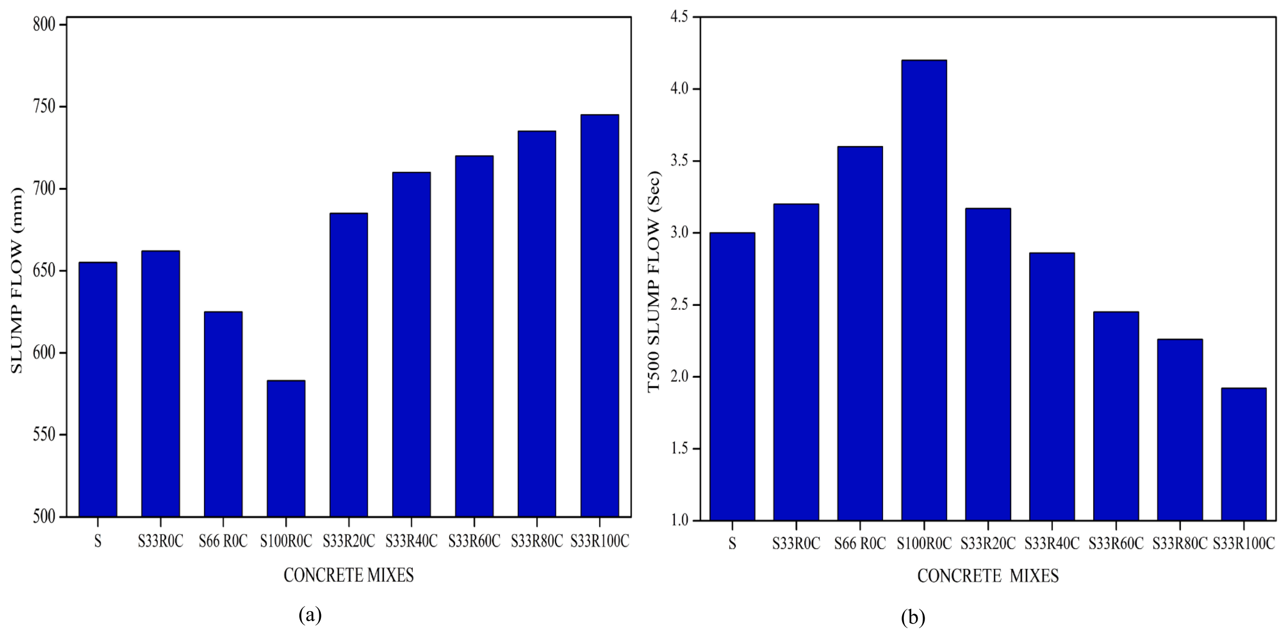

Fig. 1. Slump flow and T500 slump flow test results of various SCC mixes.

measurement of all SCC mixes which met the permissible limit of EFNARC (2–5 s). The figure indicated that the time elapsed by mixtures for reaching 500 mm diameter is decreased as the copper slag content increased. The T500 slump flow increased initially by 6% with the inclusion of 33% RCA to SCC but with the inclusion of CS from 20 to 100% the T500 value has been reduced from 6 to 36 % as compared to the SCC-control. This could be due to the lack of cohesiveness between the new and old attached mortar at the surface of RCA as well as low water absorption properties of CS.

3.1.2. V-funnel test

Fig. 2 presented the V-funnel test results of SCC mixes that determine the viscosity of the flow i.e., the maximum time taken to vacant the funnel. The values of all mixes were obtained are within the range of EFNARC [8] limits i.e., 6-12sec. The maximum time taken is found 8.48 for SCC- control whereas the value increased by 0.15 times with the addition of RCA from 0% to 100%. However, because of the smooth and glassy appearance of CS grains the SCC mixes have reduced viscosity and the funnel empty time was decreased with increased in copper slag content. It has been decreased to 27% and 16% respectively in comparison to SCC-control and RCA mix (S33R0C) when the CS is added up to 100%. However, the mixture containing 100% fine aggregate grasped maximum time to empty the funnel as compared to the other mixes.

3.1.3. L-box test

The L-box measured the capacity of mix to pass through narrow passages and clogged reinforcements. The L-box ratio at various replacement level of mixes was shown in Fig. 3. The values obtained for all the mixes from the current study are found within the range of 0.83 to 0.97 confirmed to the guidelines of EFNARC [8]. From the Fig. 3 it has been observed that the SCC mixes showed improved passing ability with the addition of RCA due to high water absorption capacity than that of NCA. The values increased by 8.4% as the RCA content increased from 0 to 100%. S.C Kou et al. [17] inferred the similar results where the L-box values varies between 0.85 and 0.93 in SCC mixes using 100% RCA with various percentage of recycled fine aggregate. Similarly, the L-box values has been increased at a constant rate in all RCA based SCC mixes with CS content from 20 to 100% which revealed that all the mixtures were made with appropriate passing ability and are ready to use.

3.2. Hardened properties

3.2.1. Compressive strength test

Fig. 4 represented the compressive strength test results of various SCC mixes at the age of 7- and 28-days curing. From the figure it has been found that in the first series the compressive strength of SCC mixes reduced both at 7 and 28 days with the increased in RCA content. However, the SCC mix with 33% RCA showed negligible reduction in 28 days strength of about 2.5% with respect to the control mix. The SCC mix with 100% RCA showed maximum reduction i.e., about 19.3% at 28 days. The results were validated to the previous research works [13,17,18] i.e., reduced SCC compressive strength will result from an increase in RCA replacement. This is probably caused by the RCAs' high porosity and the weak mortar matrix that the RCAs were bonded to.

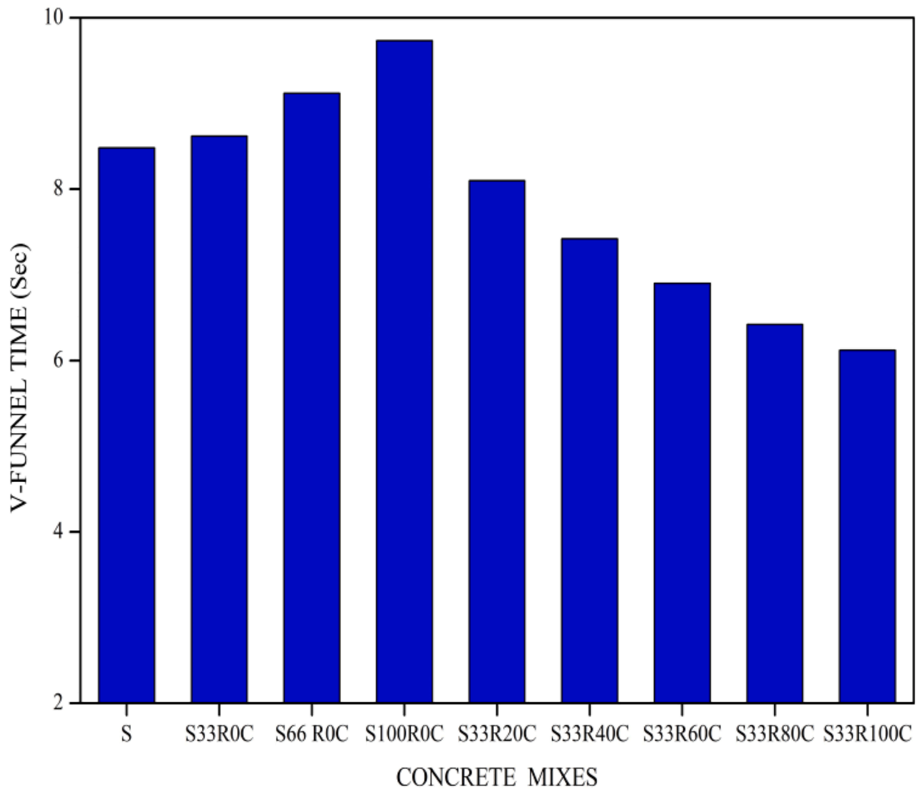

Fig. 2. V-funnel test results for SCC mixes.

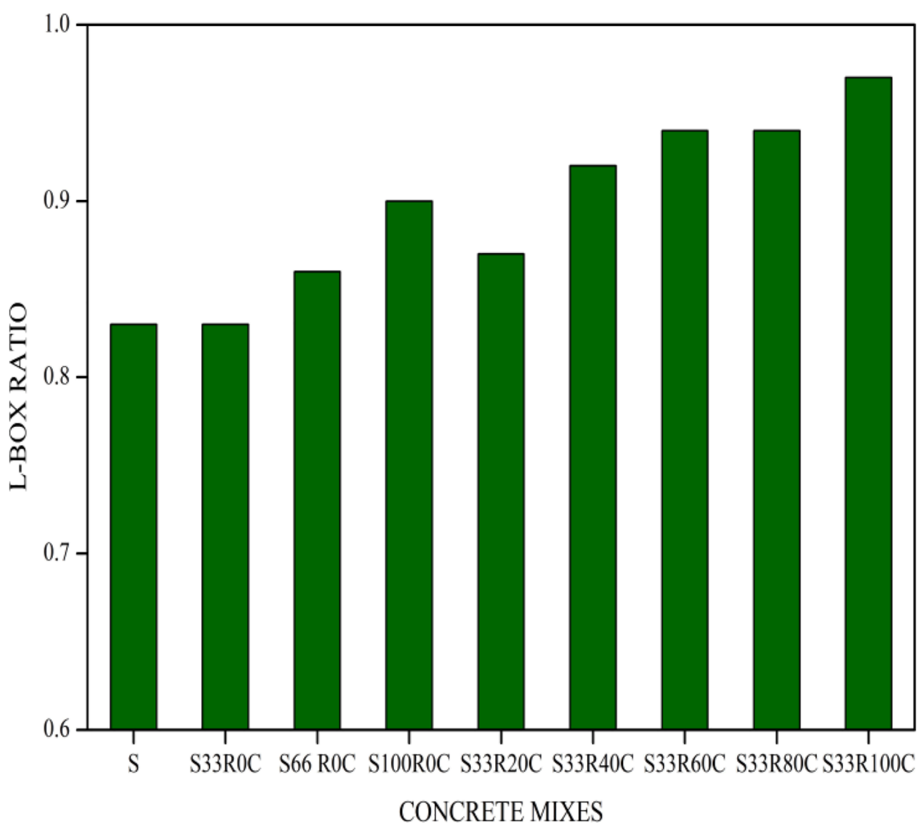

Fig. 3. L- box test results for SCC mixes.

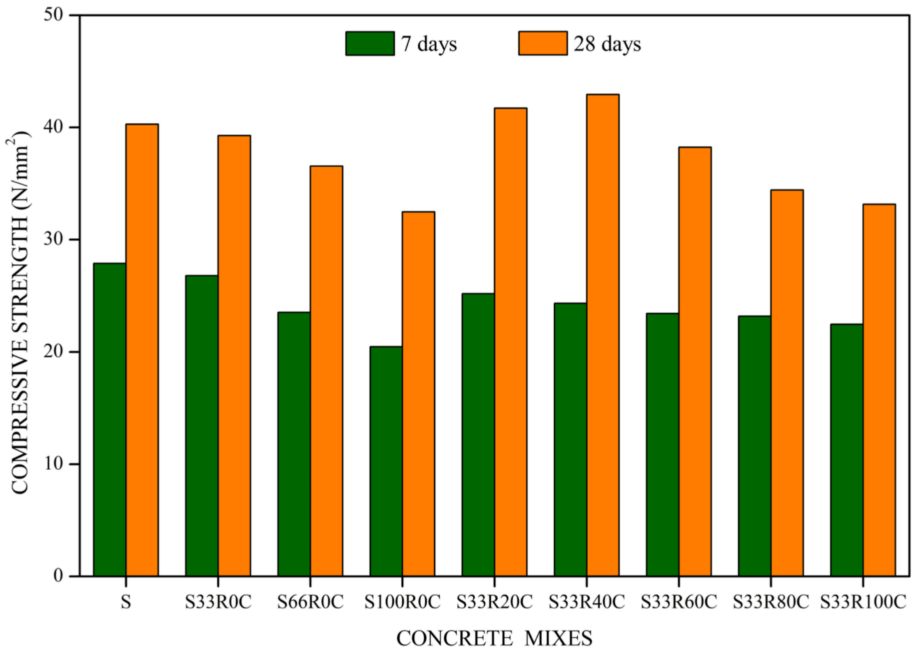

Fig. 4. Compressive strength of SCC mixes.

Contrarily, RCAs are more compact than NCA, that increases the aggregates' specific surface area and, facilitates the production of a significant number of interfacial transition zones (ITZ), thus Compressive strength is reduced.

Similarly, the 7-days compressive strength of RAC based SCC mixes is decreased with the increase of CS content in comparison to control mix. The maximum reduction in strength of about 19% was found on 100% substitution of CS whereas the reduction percentage was minimum i.e., 17%, 16%, 13%, 9.7% and 4% respectively on 80%, 60%, 40%, 20% and 0% substitution of CS. The reduction of strength is may be either due to the high porosity and weak mortar characteristics of RCA or due to the large particle size of CS grain [25] which delays the process of early hydration causing loss of strength. However, with the inclusion of CS up to 40 % the 28-days compressive strength of RCA based SCC mix showed increasing nature with respect to the SCC-control. It was increased by 4% and 7% respectively with respect to control concrete for mix containing 20% and 40% CS. lower water absorption property than that of NFA and smooth glassy texture of CS may accelerate the strength of RAC based SCC mix.

3.2.2. *Split tensile strength test*

Fig. 5 shows split tensile strength test of control, RCA mixes and RCA based SCC mixes at various replacement level of CS as fine aggregate from 7 to 28 days curing. The results indicated that, with the addition of RCA in first series the tensile strength reduction was marginal at higher level of replacement. The strength is decreased to 1.77% and 7.69%

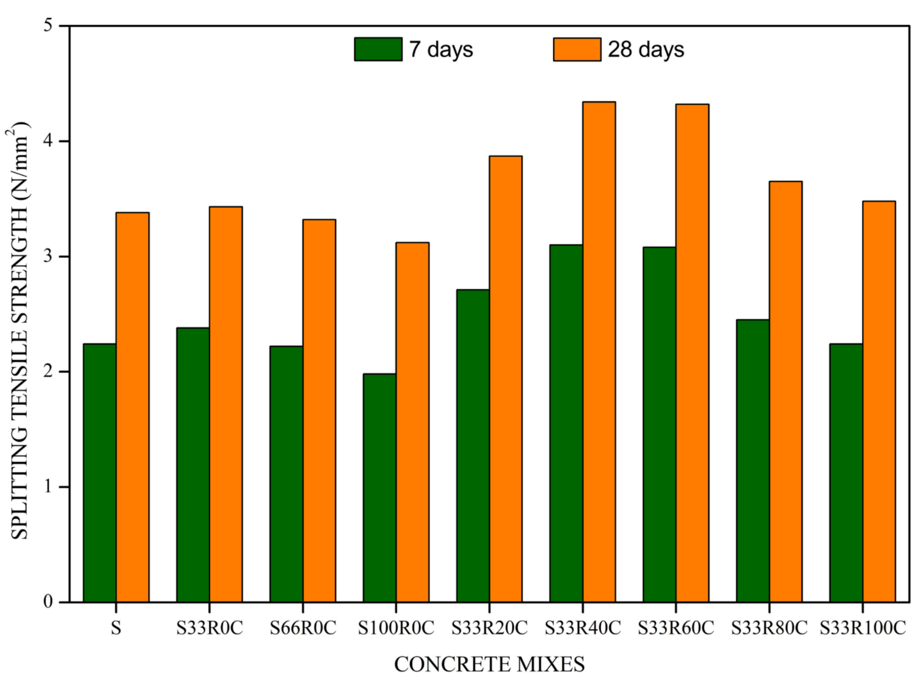

Fig. 5. Split tensile strength of SCC mixes.

respectively with respect to the control mix for mix with 66% and 100% RCA. However, the strength is increased to 1.47% for SCC with 33% RCA (S33R0C). This minor variation in strength is attributed to the strong bonding between the recycled concrete aggregate and mortar. Other investigations also discovered that the RCA replacement in SCC did not significantly contribute to the reduction in tensile strength [13,26].

Similarly, in the second series of test the split tensile strength is enhanced up to 28% as compared to control SCC with the addition of CS to the 33% RAC mix. The maximum strength is found in RCA based SCC mix with 40% CS substitution from 7 to 28 days curing. It has been increased from 2.38 to 3.10 at 7 days and 3.43 to 4.34 at 28 days for RCA based SCC mix from 0 to 40% CS substitution. The angular edges of copper slag grains enhanced the cohesiveness of the concrete matrix which led to improve the strength of mix [25]. However, the tensile strength of SCC mix is continuously decreased as the CS content increased from 60 to 100% which is attributed to the low water absorption and high-density characteristics of slag grains as compared to the NFA.

3.3. Microstructural analysis

In this research work, the morphological behaviour of various SCC mixes has been studied by using SEM technology. The powdered form of various SCC matrix obtained after performing 28 days compression test is used for SEM analysis and studied the microstructural performances like the formation of hydration products with un-hydrated cement inside the matrix of SCC sample. However, in the present study the SEM micrograph of SCC-control, S33R0C and S33R40C is provided to observe the major changes as these mixes have higher compressive strength than the other mixes which are represented in Fig. 6, Fig. 7 and Fig. 8. The image of SEM indicates the formation of hydrated products like calcium hydrate (CH), calcium silicate hydrate gel (CSH), formation of ettringite and voids in the samples of SCC mixes.

The micrograph of RCA based SCC mix without CS (Fig. 7) shows a comparatively more porous and less dense structure as compared to SCC-control (Fig. 6). The cracks are more prominent with the formation of ettringite in S33R0C mix which influences the mechanical characteristics of mixes. This is due to the weak interfacial transition zone (ITZ) developed between the aggregate and cement matrix [27]. The Fig. 8 shows the SEM morphology of S33R40C mix which exhibited a compact dense microstructure as compared to SCC-control and S33R0C mix. The morphology of 40% CS mix shows a clear spread of CSH gel over the entire matrix with small pores and voids as compared to SCC-control. This could be due to the lower water absorption value of CS than that of NFA which increased the water content in the SCC mixes. This excess free water is absorbed by RCA resulting less voids and micro cracks formation in the cement matrix, thus increased the strength of the mix.

3.4. Cost and environmental benefit analysis

As the RCA and CS are the waste materials used in this study for developing a sustainable self-compacting concrete so it is important to examine the economic and environmental benefit of SCC. The economy of SCC was determined by calculating the cost of different RCA based SCC mixes utilizing market and industry data and compared the benefit with SCC-control. The embodied CO2 emission (ECO_2e) of various SCC mixes were estimated to assess the environmental benefit of RCA based SCC with sand/ CS over SCC control. The ECO_2e is the amount of carbon dioxide that is released during the extraction of raw materials, transportation, manufacture, and installation of any product system. The environmental (ECO2e) factors of the ingredients used in the study were gleaned from the related research work [20,28,29]. The detail calculations of cost and ECO_2e various SCC mixes are presented in Table 3.

It has been observed that, the RCA based SCC mix using CS as a replacement for NFA produced a more cost-effective material as compared to SCC-control. The cost is reduced by 8% and 11% respectively with the incorporation of 40% and 100% CS to the RCA based SCC mix. From an ecological point of view, the ECO_2e of SCC-control, S33R40 CS and S33R100C are found to be 324, 321 and 317 kg CO_2e/m^3 which shows that the mixtures including CS reduced approximately about 1.22% to 2.33% carbon foot print with respect to the SCC-control.

4. Conclusion

From the experimental study, it was examined how different fractions of CS as fine aggregate affected the characteristics of RCA-based SCC. The study revealed that it is practicable to produce SCC with 33% RCA and maximum replacement of NFA with CS up to 40% in the mix design. The main conclusion of this research work are as follows.

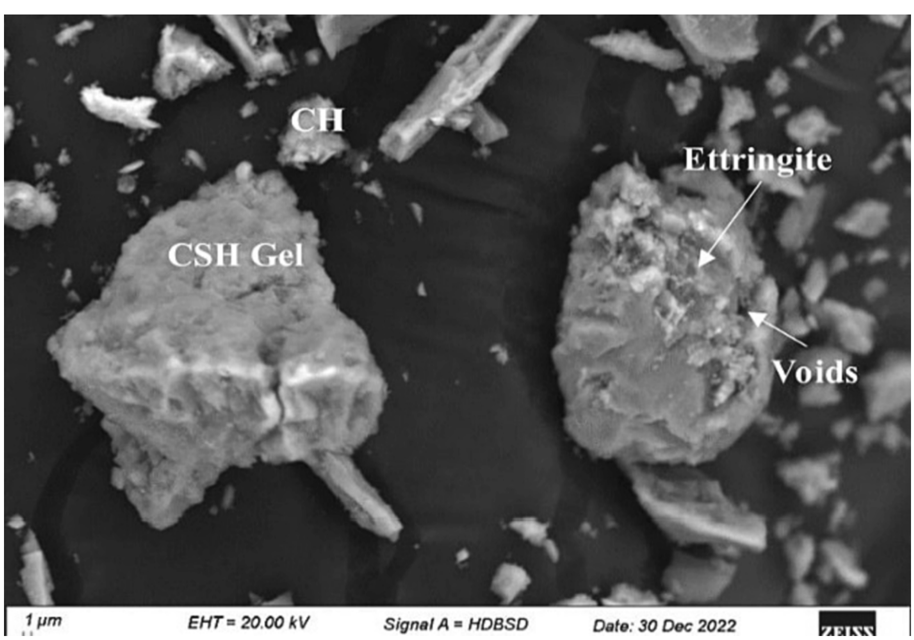

Fig. 6. Micrograph of SCC-control.

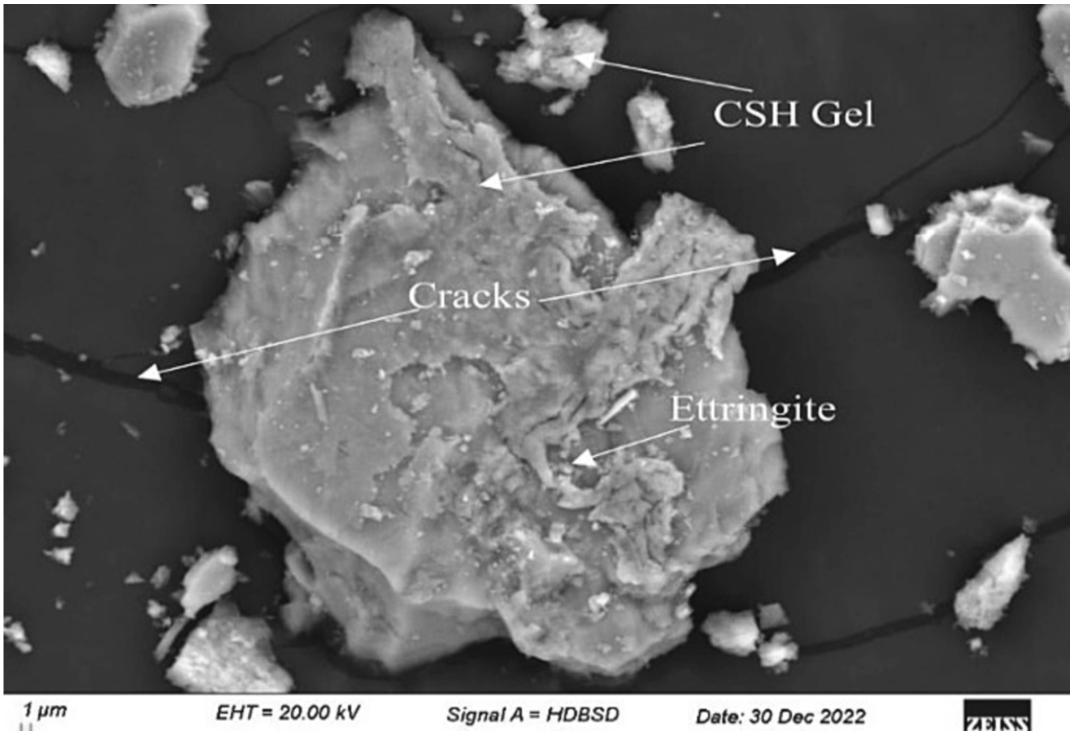

Fig. 7. Micrograph of S33R0C mix.

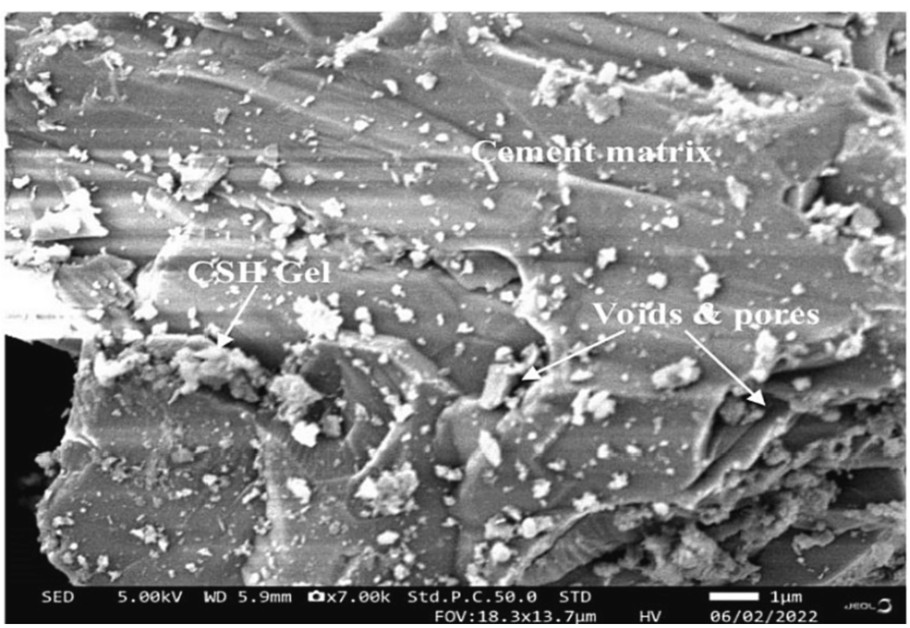

Fig. 8. Micrograph SEM image of S33R40C mix.

- Based on the findings of several tests performed on freshly mixed SCC containing RCA and CS, the values obtained are within the EFNARC limits. The values of slump flow and L-box ratio of SCC mixes are increased with the increasing of CS content whereas T500 slump and V-funnel time shows a downward trend which is attributed to the even and glassy texture with relatively low water absorption capacity of CS than that of NFA.
- The compressive strength of SCC in the first series is decreased with the increased in RCA content as the amount of mortar increased on RCA surface at higher replacement level. However, there is a minor variation in split tensile strength with the increased amount of RCA.
- The compressive strength of recycled aggregate based SCC mixes is enhanced up to 7% at 28 days with the incorporation of CS up to 40% and beyond that the strength remain decreased due to high specific gravity of CS grains.
- The split tensile strength of RCA based SCC mixes shows maximum strength at 7 and 28 days respectively with the inclusion of CS up to 40% because of cohesiveness of the concrete matrix.
- The SEM micrograph shows a formation of dense CSH gel and relatively less voids in S33R40C mix which enhances the strength in comparison to the control and S33R0C mix

Table 3
Cost and environmental benefit analysis of different SCC mixes.

Ingredients	Data for each material (Per kg)		Cost (INR/m^3)			ECO_2e ($kgCO_2e/m^3$)		
	COST (Rs.)	ECO_2e ($kgCO_2e$)	S	S33R40C	S33R100C	S	S33R40C	S33R100C
OPC	10	0.93	3090	3090	3090	287.4	287.4	287.4
FA	0.80	0.027	106.4	106.4	106.4	3.6	3.6	3.6
NFA	0.50	0.0098	456.5	182.5	–	8.95	3.57	–
NCA	1	0.024	860	576	576	20.64	13.82	13.82
RCA	0.50	0.029	–	142	142	–	8.24	8.24
CS	0.05	–	–	18.25	45.65	–	–	–
SP	70	0.25	464	464	464	3.98	3.98	3.98
TOTAL			**4977**	**4579.15**	**4424.05**	**324.57**	**320.61**	**317**

- The RAC based SCC mixes incorporating CS as fine aggregate proves to be beneficial from economical as well as ecological point of view as it cuts the cost of concrete and shows a comparable carbon footprint with respect to the control mix.

So, in the current study recycled aggregate based SCC incorporating copper slag up to 40% as a substitution of fine aggregate is proved to be the best replacement over SCC-control. The usage of CS as a substitution of fine aggregate in RCA based SCC has been proven to have technological, financial, and environmental advantages. Reusing of CS and RCA as fine and coarse aggregate in SCC not only minimizes the amount of material disposed in landfills, but it also advances the development of environmentally friendly substitute building materials with improved performance.

CRediT authorship contribution statement

Sanjay Kumar: Conceptualization, Methodology, Editing and Supervision. **Anasuya Sahu:** Methodology, Investigation, Writing – original draft. **A.K.L Srivastava:** Supervision, Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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