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Performance of recycled aggregate concrete using copper slag as fine aggregate

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ABSTRACT

The present study experimentally investigates the mechanical and durability performance of recycled aggregate concrete (RAC) incorporating copper slag as fine aggregate. The coarse aggregate obtained from recycling of construction waste is used as natural coarse aggregate and copper slag, the industrial by-product is used as fine aggregate in the current research work. Recycled aggregate concrete formed by substituting 50 % recycled aggregate as natural coarse aggregate is considered as the control mix for this experimental work. A total of seven RAC mixtures are made with copper slag as a substitution of fine aggregate of varying proportions (0%–100 %) giving an increment of 20 %. Compressive strength, split tensile strength, and microstructural behaviour of RAC mixtures were carried out for up to 90 days of curing to assess the mechanical property of RAC mixes. To evaluate the effect of copper slag on long-term properties of RAC mix water absorption, rapid chloride permeability and resistant to sulphate attack test is carried out for up to 90 days. The findings revealed that the mechanical properties of RAC mixes are improved up to 40 % substitution of copper slag. When exposed to sulphate, RAC mixtures gained weight while losing compressive strength. Results of water absorption and RCPT test showed a remarkable improvement with the incorporation of copper slag up to 40 %; beyond that point, the results were comparable to RAC mix (control). The progression of calcium silicate hydrate gel formation within the RAC blend was verified through scanning electron microscopy, energy dispersive spectroscopy, and X-ray diffraction analysis across a range of curing periods spanning from 7 to 90 days.

1. Introduction

Consumption of huge number of natural resources towards the production of concrete in the present decade creates a serious environmental issue in terms scarcity of natural resources and ecological imbalance for the most of the developed countries. Aggregates are the primary constituents in the production of concrete as it plays a significant role in strength enhancement and contributes 75–80 % [1] of total concrete material. Worldwide approximately about 48.3 billion tons of natural aggregates are consumed every year in the construction industry [2] which lead to scarcity of natural resources with lots of environmental disorder. So, it is the right time to think about the other alternative and sustainable materials which can replace both fine and coarse aggregate successfully and produced an eco-friendly concrete [3]. On the other hand, the waste released from various sectors are increasing day by day due to heavy industrialization and activities like reconstruction and destruction of old concrete structures which causes both environmental and disposal problem [4]. Therefore, the right use of these waste materials in the construction sector can reduce the need for natural

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resources, decrease the need for landfill space, and create concrete that is environmentally friendly [5,6]. In this regard, recycled concrete aggregate (RCA) and copper slag (CS) both are the most promising alternatives at the present day towards the construction of sustainable concrete [7]. In the current study, recycled concrete aggregate is employed as the partial replacement of natural coarse aggregate (NCA), and copper slag is utilised to substitute fine aggregate (FA) for producing an environmentally friendly concrete.

Recycled concrete aggregate, the waste product produced from the construction and demolition waste (C&D) after proper crushing and sieving. RCA is one of the primary research topics in the construction industry because of its wide range of qualities, including water absorption, bulk densities, and gradation curves that may aid in the manufacture of superior concrete. The basic difference between NCA and RCA is the old attached mortar which inferiors the quality of RCA to that of NCA [8]. The recycled aggregate concrete's behaviour is influenced by two major factors that is amount of RCA in concrete and the source of extraction of RCA. Many researchers [9–13] have studied the mechanical and physical performances of concrete by incorporating RCA as a replacement of NCA and reported that, the recycled aggregate concrete (RAC) shows poor performance in comparison to conventional concrete due to the weak interfacial transition zone (ITZ) developed in between RCA and attached mortar. Various studies revealed that, the compressive strength of RAC can be comparable to the normal concrete up to 30 % replacement of NCA by RCA as it can achieve the target strength and the loss of strength is marginal because the aggregate surface is attached with less porous mortar [11–16]. However, the strength of RAC decreases to 10–25 % as the amount of RCA content increases even up to full replacement in comparison to normal concrete. Majhi et al. [8] reported the strength loss of 15–20 % at 100 % replacement of RCA up to 90 days curing with equal w/c ratio. Similarly, the split tensile and flexural strength of concrete has been reduced up to 10 % and 23 % respectively with the increasing replacement level of RCA. Similarly, the durability properties of RAC is also affected with increased percentage of RCA as observed from the various research works [17–22]. It is attributed to the high-water absorption property of RCA than that of NCA. The elastic modulus of RAC has also been reduced significantly as compared to natural concrete which is attributed to the formation of poor bond between old and new mortar [9,12].

In addition, another waste product found by the researchers is copper slag which can replace the fine aggregate successfully in the recent decade because of its low water absorption capacity and glassy texture. Copper slag is a by-product of the copper production sector produced during matte smelting and refining processes either by slow air cooling or fast cooling method [2]. All over the world approximately 68.8 million tons of CS is produced from which India contribute around 3 % of global production [23]. In this context, it is a great challenge to the researchers for proper utilization of copper slag in construction industry in order to minimise the environmental pollution due to huge land filling as well as scarcity of natural resources [24]. It is anticipated that the building sector will benefit greatly from the application of CS in both performance and sustainability aspects. Over the past ten years, researchers have put their interest in the utilization of copper slag as a construction material due to its low energy consumption and zero carbon imprint. From a technological and commercial standpoint, the advantageous qualities of CS have made it a viable substitute for fine aggregates. From the previous research work [1,23,25–34] it has been observed that adding a certain quantity of CS to certain types of concretes has been shown to improve their physical, mechanical and durability qualities. The study also revealed that, the strength properties of normal vibrated concrete with CS up to 50 % replacement is comparable to the control concrete [1]. Maharshi et al. [34] developed a CS based normal vibrated concrete by replacing natural fine aggregate (NFA) with CS from 0 to 100 % and found that as compared to the control mix CS with 40 % replacement improved the compressive and split tensile strength of about 13 % and 8 % respectively. Patil et al. [35] suggested that, the replacement of CS as NFA up to 20 % yield 33 % higher strength than that of 100 % CS based normal vibrated concrete. According to Jabri et al. [1] the workability and density of concrete was improved by the incorporation of copper slag up to 100 % substitution. However, the compressive strength of concrete was increased up to 5 % on the substitution of CS up to 40 % and the water absorption values were decreased up to 50 % replacement of CS. The inclusion of CS as fine aggregate up to 40 % in the formation of self-compacting concrete (SCC) results in improved compressive strength at relative curing periods. According to Gupta & Siddique [27], the properties of SCC in fresh state was enhanced with the incorporation of CS up to 60 % because of its smooth surface texture and low water absorption properties. The maximum compressive strength and split tensile strength of SCC was achieved by inclusion of 30 % and 60 % CS respectively. Similarly, Sharma et al. [36] developed SCC by incorporating CS as fine aggregate up to 100 % substitution and evaluated the mechanical properties of SCC up to 120 days curing periods. The findings showed that adding CS up to 30 % boosted the strength features of SCC, however the strength began to deteriorate beyond 30 % CS. As per durability concern the incorporation of CS up to 60 % replacement over fine aggregate proved to be beneficial as suggested by the Sharma et al. [37]. Similarly, Gupta & Siddique [28] investigated the long term properties of SCC using CS as fine aggregate varying from 0 to 60%with an increment of 10 %. It has been reported that the long-term properties of SCC mixes like water absorption, rapid chloride permeability and sorptivity were improved significantly with the incorporation of CS up to 30 % and the properties show similar results to that of control concrete with the increase in CS content.

It has been observed from the various reviews of the literature that, several studies were performed to determine the impact of RCA as coarse aggregate and CS as fine aggregate on the characteristics of various types of concrete. However, there are very few literatures available that have compared the impact of copper slag on the performance of recycled aggregate concrete. Raghavan et al. [38] made a comparison between the mechanical properties of recycled concrete and natural concrete by using copper slag, iron slag, and recycled concrete aggregate as fine aggregate and coarse aggregate with various proportions of mix respectively. The results revealed that the concrete made with 25 % recycled concrete aggregate, 40 % iron slag, and 40 % copper slag can be comparable to the conventional mix. According to Ashral et al. [31] the properties of concrete mixes were improved by adding CS up to 20 % as a substitution of fine aggregate and coarse aggregate with RCA up to 30 %. Kumar et al. [39] studied the various effect of CS on strength properties of recycled aggregate based SCC and found that the strength properties are enhanced to 28 % with the addition of CS up to 40 %. In the current study, the replacement percentage of RCA is set at 50 % based on the previous research works [7,8,18,40,41] since the increased amount of RCA affects the strength and durability qualities of concrete due to the porous attached mortar.

The novel aspect of the study is to check the performance of recycled aggregate based concrete in terms of strength and durability by utilizing industrial wase product copper slag as a substitution of fine aggregate. The utilization of RCA and CS as a construction material has potential to minimise the lack of natural resources in the construction sector and forward a step for making a sustainable concrete. As per the author's knowledge, studies dealing with the strength and durability aspects of.

RAC using CS is not available in the research forum. The objective of this research work is to determine the different properties of recycled aggregate concrete (RAC) by incorporating coper slag varying from 0 to 100 % as a substitution of fine aggregate with an increment of 20 % and study its effect on the performance of RAC in long-term. In the previous research work [7] the authors have studied the mechanical properties of recycled aggregate concrete using RCA and CS of varying proportions and compared the results with that of natural aggregate concrete (NAC). The results revealed that the RAC with the combination of 33 % RCA and 20 % CS attained superior mechanical properties in comparison to NAC after 28 days curing period. So, in the current research work authors further analysed the effect of CS on strength and durability properties of RAC in long-term by considering 50 % RCA as a replacement of NCA which is referred as control mix for this study. To fulfil the research objective at first, the mechanical properties of RAC with and without CS mixtures were performed at 7, 28, 56 and 90 days of curing period. After that, the durability properties like water absorption, resistant to sulphate attack and chloride ion penetration test were conducted up to 90 days. Scanning electron microscope (SEM), Energy-dispersive X-ray analysis (EDAX) and X-ray diffraction (XRD) analysis were performed to study the microstructural behaviour of RAC at 90 days to investigate the potentiality of CS in RAC mixes.

2. Materials used

2.1. Cement

In this experimental work, OPC-53 [42] is used as cement with the fineness of 3200 cm^2/gm. To determine the physical properties of cement various tests were conducted in the laboratory according to the code and the results obtained are presented in Table 1. The chemical analysis has been done through XRF test and represented in Table 2. The surface morphology and elemental analysis of cement has been done through SEM and EDAX respectively and shown in Fig. 1. The SEM analysis indicated that the cement particles

Table 1
Physical Properties of materials used in RAC mix.

Materials	Appearance	Specific gravity	Density (kg/m^3)	Water absorption (%)	Fineness modulus
OPC	Grey	3.14	1446		
Fine aggregate	Light brown	2.86	1564	1.18	2.6
Coarse aggregate		3	2662	0.82	5.34
Copper slag	Black	3.6	1950	0.6	3.4
Recycled coarse aggregate		2.6	2374	3.92	5.5

Table 2
Chemical analysis of materials used in the study.

Constituents (%)	CaO	Al_2O_3	SiO_2	Fe_2O_3	MgO	K_2O	TiO_2	P_2O_5	SO_3
Cement (OPC 53)	60.83	6.05	20.43	5.24	2.92	0.97	0.81	0.13	2.62
Fine aggregate (FA)	0.68	6.94	84.45	4.68	0.68	1.74	0.51	0.07	0.25
Copper slag (CS)	0.5	2.85	20.2	73.27	1.09	0.4	0.25	0.2	1.06

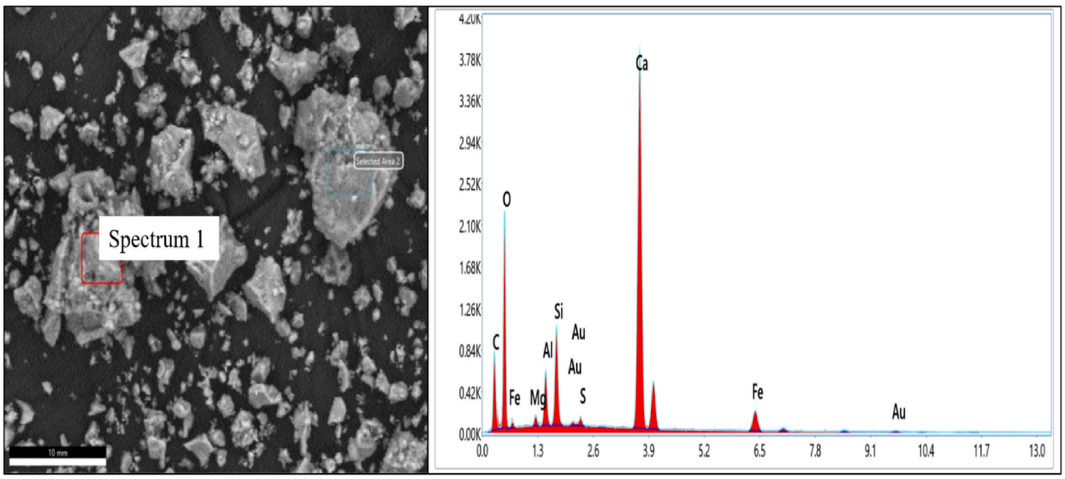

Fig. 1. SEM and EDAX analysis of cement utilised in the research work.

are smoothly arranged through out the surface with different size and geometry. The EDAX analysis shows the various elements of cement with maximum peak of O and Ca containing the weight % of 43.8 and 25.2 respectively.

2.2. Natural aggregates

The crushed stone obtained from the local crusher is used as natural coarse aggregate in the study with specific gravity 2.8. Coarse aggregates of sizes 20 mm and 10 mm down are used in the ratio of 70:30 for making mixtures according to IS 10262 [43]. Local river sand is used as Fine aggregate of size less than 4.75 mm and collected nearby river area of Jamshedpur. The grading of both coarse and fine aggregate is done as per IS 383 [44] with fineness modulus 5.34 and 2.6 respectively. As per codal provision, fine aggregate is verified to zone II [44]. The physical properties of aggregates are determined as per code and presented in Table 1.

2.3. Recycled coarse aggregate

Recycled coarse aggregate (Fig. 2 a) was collected from demolition of 14 years old petrol pump near Jamshedpur area used as the substitute of NCA after proper crushing and sieving. The waste concrete pieces collected from debris were first crushed into the smaller pieces by using crusher machine and then by using hammer it is again crushed into the nominal size of 20 mm called as RCA. In the current experimental work, recycled aggregate of particle size 10 mm is used which replaced the NCA by 50 %. Fig. 3 shows the particle size analysis of RCA as per IS 383 [44] indicating that the particles of RCA are well graded and finer than NCA. The fundamental properties of RCA are determined according to the code and provided in Table 1 which revealed that RCA has the property of high-water absorption and low specific gravity than that of NCA.

2.4. Copper slag

Copper slag (Fig. 2 b) was collected from Hindustan Copper Limited, Jamshedpur, India by matte smelting technique followed by the refining process in the pyrometallurgical copper production process [45]. In the present research work, CS is used as the replacement of fine aggregate. It is appeared as black in colour with glassy texture. Table 1 provides information on the physical characteristics of copper slag while Table 2 provides information on the chemical composition obtained from X-ray fluorescence (XRF) test, The particle size distribution of CS shown in Fig. 3 is performed through sieve analysis as per IS 383 [44]. It has been noticed that the nominal size of CS lies in zone I which indicated that CS is coarser than the NFA. Fig. 4 shows the SEM and EDS analysis of copper slag respectively which indicated that the particles of CS are sharp edged with irregular shape which may have improved the interaction between aggregates and paste.

(a) RCA (b) Copper slag

Fig. 2. Waste materials used in the resarch work.

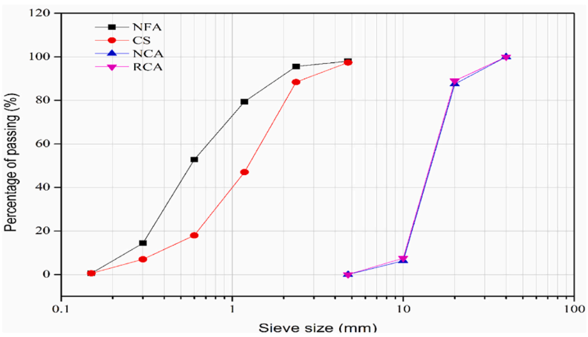

Fig. 3. Particle size distribution of fine and coarse aggregates used in the study.

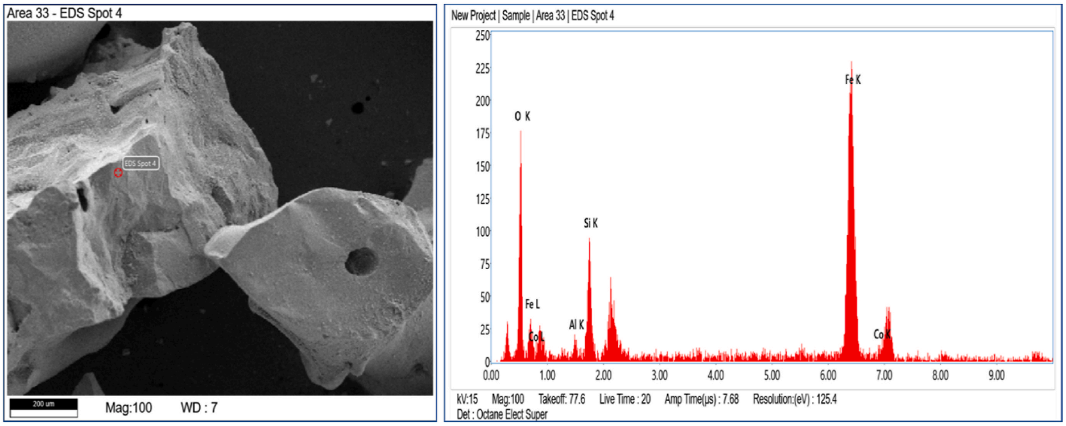

Fig. 4. SEM and EDAX analysis of CS used in the research work.

2.5. Admixtures

PCE-200 was used as superplasticizer (SP) conforming to IS 9103:1999 [46]. It has a low viscosity and a significant water-reducing admixture. The pH value is in the range of 6–7.5 and it is light brown in colour with specific gravity of 1.09. In the mix design the SP is taken as 1 % of total cement content. The solid content is found to be about 41 % of total mass in liquid form.

3. Mix proportions

There are all total of 6 trial mixes has been prepared including the control mix which is prepared with 50 % of RCA by replacing NCA. The mixed proportion of control mix is calculated as 1:2.42:2.02:1.34. Another five trial mixes have been prepared by replacing NFA with CS of varying proportions from 0 to 100 with the increment of 20 %. All the mix designs are carried out for M30 grade concrete with target strength of 38.25 N/mm^2 in accordance with IS10262:2019 [43]. All the materials are taken by weight and the cement content for all the mixes are kept constant as 360 kg/m^3. The w/c ratio is taken as 0.45 for all the mixes. The aggregates are soaked in water for 24 h before casting to obtain the surface saturated dry condition (SSD). The details of mix proportions with designation are provided in Table 3. After calculating the mix proportions of each mixture, the materials were mixed thoroughly in the laboratory concrete mixture for 1 min. After uniform mixing of all dry constituents of concrete 70 % of total quantity of water was poured in to the concrete mixture and allowed to mix for 2 min for achieving homogeneous mix. Another 30 % water was then poured in the mixture with required amount of superplasticizer and mixed it for another 2 min to obtain a workable concrete. The fresh property of concrete was then determined in terms of workability using slump cone apparatus. The prepared concrete mixes were placed in the specified moulds for 24 h (Fig. 5) and after that, the specimens were allowed for curing in water curing chamber by maintaining room temperature until they reached the requisite testing age as shown in Fig. 6.

4. Experimental procedure

The fresh property of various concrete mixes has been performed by slump cone test for evaluating the flowability of mixes in terms of workability followed by the guidelines of IS 456:2000 [47]. Strength properties of trial mixes including cube compressive strength and indirect tensile strength are evaluated after curing at different ages according to IS code of practice. The compressive strength test of various concrete mix has been carried out at 7, 28, 56 and 90 days as per IS: 516 [48] by using compression testing machine (CTM) of 3000 KN capacity with a fixed rate of loading of 14 N/mm^2/min. For evaluating 28 days split tensile strength, cylindrical specimen of dimension (150 X 300) mm has been placed horizontally between the platens of a CTM and applying a load at a rate of 1.2 N/mm^2/min until failure as per the provision of IS: 5816 [49]. Water absorption, Rapid chloride permeability test (RCPT) and sulphate attack test were performed in the laboratory to evaluate the durability properties of various RAC mixes. Water absorption of all the mixes after 28-, 56- and 90-days curing has been determined as per ASTM C 642-13 [51]. For conducting RCPT

Table 3
Design mix proportion for RAC mix.

Mix	RAC-CS0	RAC-CS20	RAC-CS40	RAC-CS60	RAC-CS80	RAC-CS100
OPC (kg/m^3)	371	371	371	371	371	371
FA (kg/m^3)	792	626	479	313	158	0
CS (kg/m^3)	0	158	313	479	626	792
NCA (kg/m^3)	568.5	568.5	568.5	568.5	568.5	568.5
RCA (kg/m^3)	568.5	568.5	568.5	568.5	568.5	568.5
W/C ratio	0.45	0.45	0.45	0.45	0.45	0.45
SP (%)	1	1	1	1	1	1

Fig. 5. RAC specimens.

Fig. 6. Curing of RAC specimens in curing chamber.

test, the cylindrical specimens of dimension (100 x 50) mm were prepared and evaluated the chloride ion permeability of each trial mix after 28 56 and 90 days of water curing in accordance with ASTM C1202-10 [52]. The complete set-up for RCPT test is shown in Fig. 7. According to ASTM C 1012-04 [53], sulphate attack tests were performed on 150 mm cube specimens that had been water cured for 28 days. The water cured specimens were first kept at ambient temperature for 24 h and then weighed and immersed in 1 % sodium sulphate solution for the desired period of 28, 56 and 90 days by maintaining pH of the solution above 7. The sulphate solution has been changed in regular one month interval up to the desired age and the solution was frequently mixed to prevent salt deposition in the tank. The specimens were removed from solution at a specific testing age and their weight and compressive strength was assessed respectively after storing the cubes at ambient temperature for 24 h. The surface texture of the concrete matrix is identified by SEM examination, and for evaluating mineral characteristics of concrete mixes, XRD technique was used. The analysis was done on a powdered sample of 28-day-cured concrete sieved through 90-μm sieve after tested in CTM. The powdered specimen was then

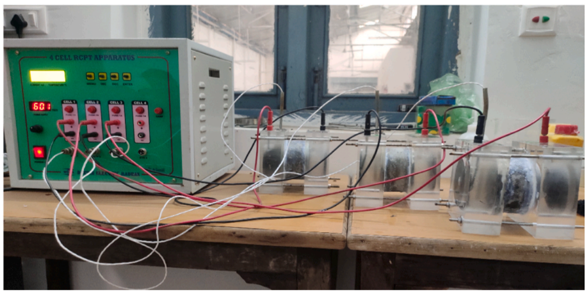

Fig. 7. Rapid chloride permeability test for RAC specimens.

mounted on the SEM stub for SEM examination, and images were captured using the secondary electrons image mode. The XRD investigation covered 2 theta diffraction angles ranging from 10° to 80°.

5. Result analysis

5.1. Workability

The workability of various RAC mixes with different CS content has been represented in Fig. 8 in terms of slump value. It has been noticed from Fig. 8 that, with the incorporation of CS as fine aggregate the slump value of fresh RAC mixes increased gradually. The mixtures containing 20 %, 40 % 60 %, 80 % and 100 % CS showed higher workability of about 11 %, 20 %, 22 %, 16 %, and 9 % respectively with respect to the control mix. This higher workability is may be caused by the slag grains' smooth and glassy texture and low water absorption properties, which improved the flowability of RAC mixtures. The finding is consistent with earlier research [27,36,50,51] that the fresh concrete exhibited decreased flow resistance with higher CS concentration. Though, the test results showed improved workability as compared to the control mix but the mixes containing CS beyond 60 % exhibited symptoms of bleeding and segregation. This may be attributed to the larger particle size of copper slag grain than that of fine aggregate which settles down and allows the free water on the surface of concrete mix, as a result reduces the workability of the mix.

5.2. Compressive strength

The strength results obtained from compression test of various RAC mixes containing copper slag up to 100 % after curing up to 90 days were presented in Fig. 9. The RAC mixes showed improved compressive strength with the incorporation of CS. The peak strength of control RAC mix after 28 days curing was observed to be 38.23 MPa and it has been increased to 43.67 MPa after incorporating the CS from 0 to 60 %. Similarly, the 56- days and 90-days strength of RAC mix including copper slag from 0 % to 40 % increased from 40.3 to 45.88 and 43.58–49.13 MPa respectively. The RAC mix with 40 % CS (RAC-CS40) achieved the maximum strength at all ages. This increase in strength is mostly related to the physical characteristics of copper slag and enhanced mortar absorption capacity of RCA as well as the efficiency of the ITZ, which produced a strong link between the aggregate and mortar. Copper slag grains are generally consisting of sharp edge particles which increased the cohesiveness of the mix by creating a stronger bond between the old and new matrix. However, the strength of RAC mixes has been reduced significantly beyond 60 % replacement of CS. It has been noticed that the curing period from 7 to 90 days, the strength of RAC mix containing 100 % CS is decreased from 12.7 % to 13.88 % as compared to mix with 60 % CS. The reduction of strength in the mixes is attributed to the smooth texture with high specific weight of CS grains which is easily settles at the fresh state and the free water rises on the top surface creating voids and cracks and increased the

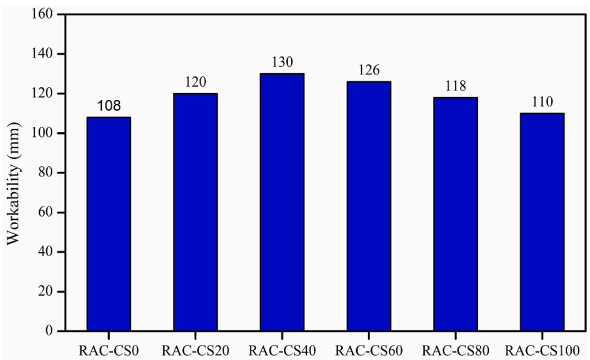

Fig. 8. Workability of RAC mixes.

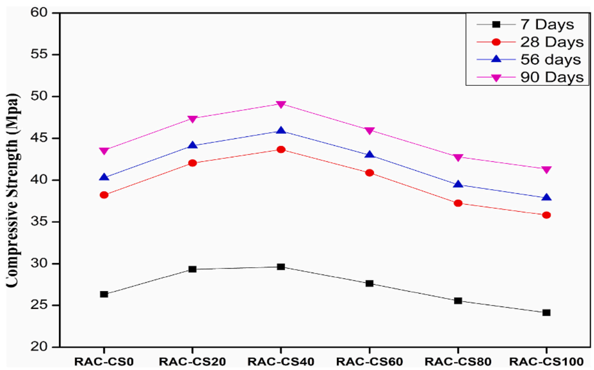

Fig. 9. Impact of CS content on compressive strength of RAC mixes.

thickness of ITZ. The variation in compressive strength between various RAC mixes and the control mix at various curing ages is shown in Fig. 10. It has been noticed that the rate of compressive strength increased up to 14 % with the inclusion of CS up to 60 % and beyond that the rate of strength decreased marginally i.e., up to 6 % at 28 and 56 days and up to 5 % at 90 days of curing period with respect to the control RAC mix. The findings of the compressive strength test proved that the addition of CS up to 60 % as fine aggregate in recycled aggregate concrete had no negative consequences in its hardened state. According to the previous research work [7], the 28-days compressive strength of recycled aggregate concrete is improved about 7 % and is comparable to natural aggregate concrete after addition of CS up to 40 %. Gupta and Siddique [27] asserted that the compressive strength of SCC containing copper slag up to 60 % was comparable to the conventional SCC mix. Sharma and Khan [36] included copper slag (0–100 %) as a sand replacement in Self-compacting mixes and concluded that the long-term strength properties showed superior performance up to 20 % substitution of copper slag, Wu et al. [52], examined high strength concrete and obtained maximum compressive strength of approximately 98 MPa at the age of 90 days by substituting 60 % copper slag with sand. According to Jabri et al. [1], the concrete made with copper slag as a substitution of fine aggregate up to 50 % showed a maximum compressive strength of 47 MPa at 28 days curing period.

5.3. Split tensile strength

The results of split tensile strength test of various RAC mixes containing copper slag up to 100 % after curing up to 90 days were presented in Fig. 11 indicating that, with the addition of up to 60 % copper slag in RAC mix boosted split tensile strength of RAC from 7 to 90 days of curing. However, a remarkable variation is observed between the early age (7 days) and long term (28–90 days) split-tensile strength. The 7 days split-tensile strength of RAC mixes including CS were found less in comparison to long term strength (28–90 days) because of heavy metal content in copper slag, that slower the rate of hydration of cement in RAC mixtures at early age [37]. However, with the addition of 20 %, 40 % and 60 % CS the split tensile strength of RAC was enhanced by 17 %, 28 % and 21 % respectively, in comparison to the control RAC mix at the curing ages from 7 to 90 days. The concrete mix including 40 % CS produced the maximum splitting tensile strength at all curing ages. The main reason of increase in strength is the sharp edges with corners of the copper slag particles which improved the cohesiveness of the RAC paste. Similar observations were deduced by Sharma et

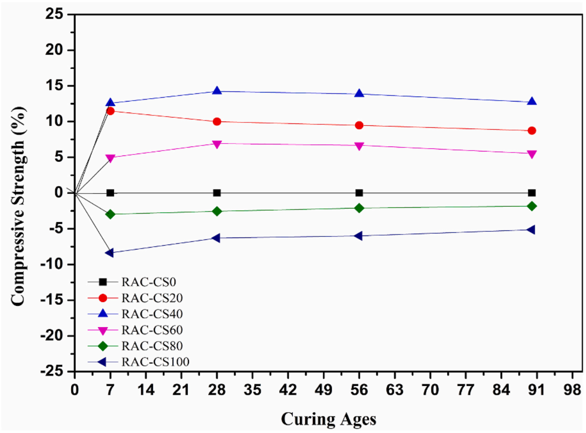

Fig. 10. Variation in Compressive strength between RAC mixes and the control mix at progressive curing ages.

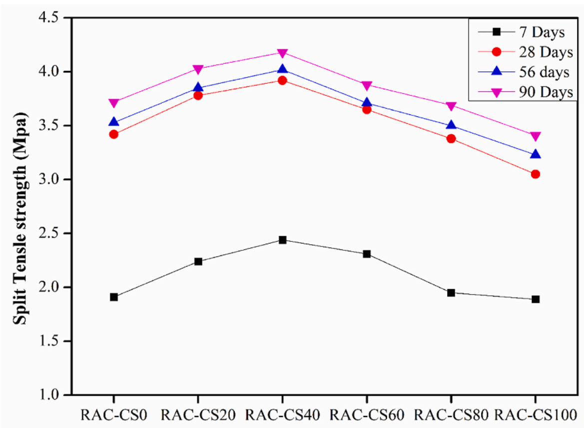

Fig. 11. Impact of CS content on split tensile strength of RAC mixes.

al. [36], that the addition of up to 80 % of copper slag boosted the tensile strength of SCC. s seen from Fig. 11, the rate of increase in tensile strength of all mixes were reduced as the curing ages increased, though the strength values were still increased at the same age. For example, the rate of increased split tensile strength of RAC-CS20 mix is reduced to 17 %, 10.52 %, 9 % and 8.33 % at the age of 7, 28, 56 and 90 days respectively with respect to the control mix. This decreased rate of strength gain is attributed to the porous attached mortar of RCA which increased the porosity of the mix with the increased curing period. Further it is noticed from Fig. 11 that, as the CS content rose above 60 %, the split tensile strength of the RAC mix decreased. This decrease in strength was maximum in 100 % CS substitution as fine aggregate i.e about 10 % at 28 days. The reduction of strength is may be either due to the bigger size of CS grain that increased the number of voids in the mix or as a result of more mortar being stuck to the recycle aggregates' surface, which impedes the hydration process and decreases bulk densities, weakening the interfacial transition zone [40].

A strong correlation has been established between compressive and split tensile strength through linear regression as represented in Fig. 12 to predict the split tensile strength from the experimental results of compressive strength of various RAC mixes at all curing ages. Fig. 12 showed a direct inter-relationship in between compressive and split tensile strength which is found to be $f_t = 0.538\sqrt{f_c'}$ with a correlation factor of 0.98, where f_c' denotes the compressive strength and f_t denotes split tensile strength of recycled aggregate concrete.

5.4. Water absorption

Water absorption capacity of different RAC mixes incorporating copper slag of various proportions were evaluated at different curing ages up to 90 days and the variations are represented in Fig. 13. Water absorption values of all mixes are reduced with the increasing of age due to the compactness of the aggregates which decreased the number of pores and voids. The absorption capacity of control RAC mix after 28days immersion was found to be 5.34 % which is reduced to 4.88 % and 4.54 % respectively after 56- and 90-days immersion. Similarly, with the addition of CS the water absorption of RAC mixes was decreased at all curing ages having maximum reduction with 40 % CS. The absorption rate is reduced by 8.23 %, 11 % and 15.85 % respectively with respect to control mix from 28 to 90 days curing ages. However, the water absorption value of RAC increased when the CS content increased from 60 % to 100 %. Though the values still reduced with respect to control mix but it was comparable with 100 % CS substitution at all ages. The increased in water absorption was due to the increased amount of CS content in the mix, forms new voids and were ascribed to

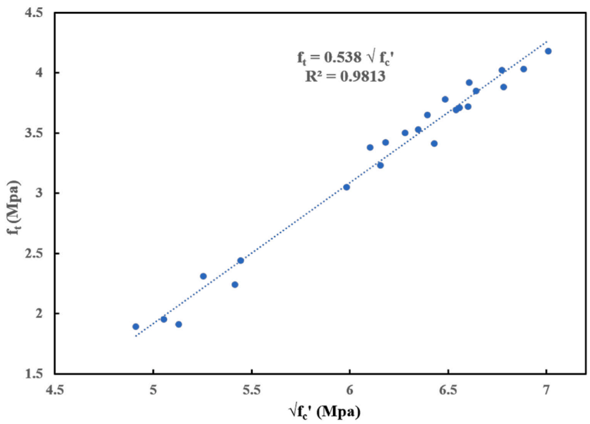

Fig. 12. Correlation between compressive and split tensile strength.

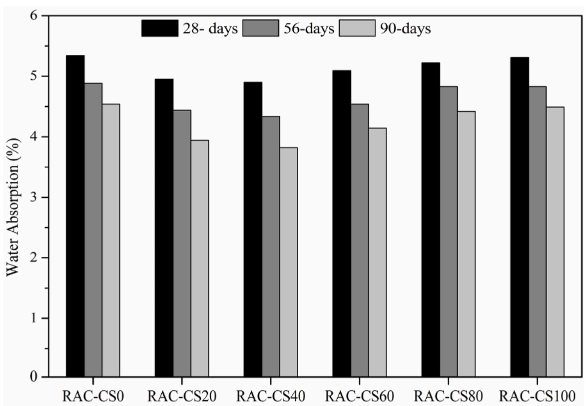

Fig. 13. Water absorption of RAC mixes at different curing ages.

the increase in free water content. The results of this study agreed with the researchers [28,50]. Gupta et al. [28] reported that, replacing fine aggregate in SCC mixtures with copper slag decreased water absorption values by up to 30 %. However, after the copper slag percentage approached 30 %, the values became comparable to control concrete. When CS was substituted for fine aggregate in typically shaken concrete, Jabri et al. discovered reductions in water absorption readings of up to 40 % [50]. The concrete then became comparable to the control concrete with further additions of copper slag until 100 % substitution.

5.5. Rapid chloride permeability test

RCPT is performed for various RAC mixes to measure the total charge passed inside the concrete in order to determine the chloride ion penetrability. Fig. 14 shows the RCPT test results of RAC mixes incorporating CS as fine aggregate of varying proportions at 28, 56 and 90 days of curing. The RCPT value of all mixes substantially reduced with the increased age as the total charge passed inside the mix became reduced. Ageing may play a substantial role in determining the chloride ion penetrability because as the curing time goes up the microstructure of concrete gets denser that minimized the amount of charge passed. The total charge passed for control mix was found to be 1645.23 C at 28 days and it is reduced to 742.34 C at the age of 90 days. Further with the addition of CS the total charge passed decreased with respect to the control mix. The RAC mix with 40 % CS showed the less chloride ion penetrability in comparison to control mix that is about 34 % at 28 days, 26 % at 56 days and 45 % at 90 days of curing. However, the chloride ion penetrability increased beyond 40 % CS incorporation, though it is still less than control mix. According to ASTM C1202-10 [52], the values of all mixes as shown in Fig. 14 are categorised under low to very low chloride ion penetrability at 28–90 days curing periods. The total charge passed in RAC mixes is varied between 1000 and 2000 C at 28 days curing, 600 to 900 Coulombs at 56 days and 400 to 800 Coulombs at 90 days of curing respectively. Similar finding has been made by the researchers [28] that, up to 40 % incorporation of CS to various types of concrete could decreased the chloride ion penetrability. These findings lead to the conclusion that recycled aggregate concrete used in structural parts can achieve enough resistance to chloride ion penetration. With the addition of copper slag, the resistance can be improved more successfully.

5.6. Resistant to sulphate attack

The sulphate attack on recycled aggregate concrete is evaluated in terms of change in mass and compressive strength of various RAC mixes after exposure to sulphate solution for 28, 56 and 90 days. Sulphate attack on concrete is a deterioration process caused by the reaction between sulphate ions and the components of hydrated minerals in concrete. This reaction can lead to the formation of expansive compounds, resulting in the disruption of the concrete matrix [18]. Fig. 15 shows the specimens before and after exposed to sulphate attack. It has been noticed that, after sulphate exposure the surface of the specimen became uneven, colourless and flake off as compared to the specimen without sulphate exposure. This is due to the expansion of the sulphate compounds, which exert pres-

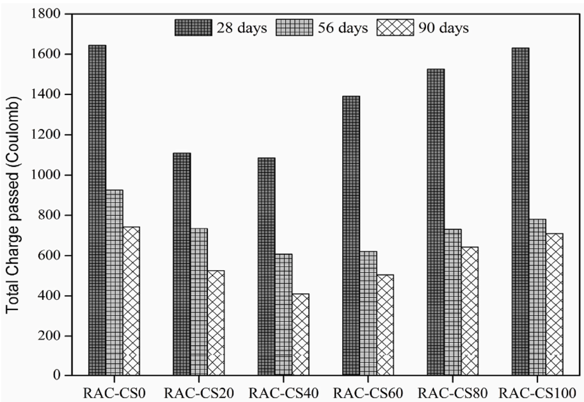

Fig. 14. RCPT values of RAC mixes at different curing ages.

(a) Before (b) After

Fig. 15. Specimens exposed to sulphate attack.

sure on the surrounding concrete, leading to the breakaway of layers. The reaction with sulphate ions can result in the formation of crystalline sulphate minerals within the concrete matrix which can cause the expansion and disruption of the material and discoloration of the concrete surface.

5.6.1. Mass gain from sulphate attack

The resistance to attack by sodium sulphate of RAC mixes containing various fractions of CS is calculated in terms of mass gain and represented in Fig. 16. The mass gain (measured in %) for each concrete mix specimen is determined in relation to the mass of specimens from that concrete mix that have been water-cured for 28 days. It is observed from Fig. 16 that the mass of all mixtures is increased with the increased age in sulphate solution and from 28 to 90 days of sulphate exposure, there was a substantial difference in mass gain. The lowest mass gain is achieved by control mix of about 0.08 %, 0.16 % and 0.25 % at 28, 56 and 90 days of sulphate exposure. Similarly with the incorporation of CS up to 100 % the mass gain of RAC mixes increased from 0.11 % to 0.24 % at 28 days, 0.27 %–0.52 % at 56 days and 0.39 %–0.67 % at 90 days immersion in sulphate solution. The RAC mix with 100 % CS substitution showed a maximum mass gain among all the mixes. The development of calcium sulpho-aluminate (ettringite) inside the concrete matrix formed by the reactions of sodium sulphate and calcium hydroxide ($Ca\ (OH)_2$) may be responsible for this mass gain. Further, the cavities filled with sulphate solution at a greater replacement level of CS may also contribute to the mass gain of concrete mixes [37].

5.6.2. Strength loss from sulphate attack

Fig. 17 depicts the loss in compressive strength of various RAC mixes containing copper slag after immersion in sodium sulphate solution for 28, 56, and 90 days. The strength loss of all mixes is determined with respect to their respective 28-days compressive strength. The strength loss of all RAC mixes is found to be increased with the increased immersion period from 28 to 90 days. The strength losses of control mix (RAC-CS0) after 28-, 56- and 90-days immersion are found to be 2.04 %, 5.65 % and 7.84 % respectively. This increased in strength loss with increased immersion period is due to the attached mortar of RCA which increased the porosity and $Ca(OH)_2$ content in RAC mix [18]. However, the reduction is minimum with the addition of CS up to 40 % at all ages as the mixture forms a dense structure with rich C–S–H gel. The reduction in strength loss is about 1.73 %, 3.35 %, 5.75 % for RAC-CS20 and 1.69 %, 5.31 %, 7.30 % for RAC-CS40 at 28-, 56- and 90-days exposure of sulphate solution. Further, it has been noticed that the strength loss again increased when the CS content in the RAC mix is increased. The mixture RAC-CS100 exhibited higher strength loss of about 5.58 % at 28 days, 10.27 % at 56 days and 11.64 % at 90 days of immersion in sodium sulphate solution respectively. The development of ettringite, that increases volume and tension within the microstructure and causes microcracks with degradation of concrete mixtures. Additionally, because the specimens are continuously exposed to the sulphate solution, the strength loss of all concrete mixes continues to grow over time. Similar results inferred by Sharma et al. [37] for SCC mix where the

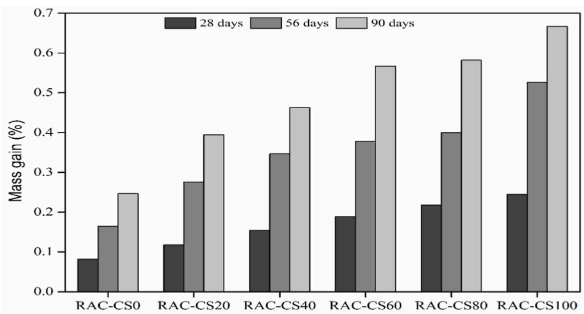

Fig. 16. Mass gain of RAC mixes due to sodium sulphate attack.

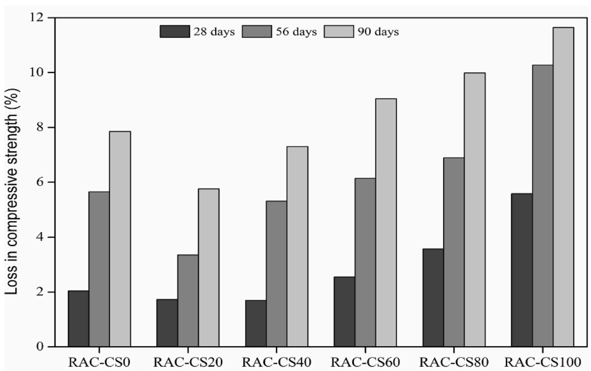

Fig. 17. Compressive strength loss of RAC mixes due to sodium sulphate attack.

Compressive strength keeps declining with increased CS content as immersion time in sodium sulphate solution increases from 28 to 120 days.

5.7. Microcharacterisations

5.7.1. SEM and EDAX analysis

Microstructural formations of concrete mixtures have a big impact on their rheological and structural characteristics. In this research work SEM and EDAX analysis were carried out at IMMT, Bhubaneswar, Odisha to investigate the morphology and elemental composition of various RAC mixes. After conducting the compressive strength test, SEM and EDAX were carried out by coating the powdered sample taken from the inner core of the recycled aggregate concrete. To comprehend the microstructural changes of the matrix at 90 days of curing, comparisons have been done for various RAC mixes. Fig. 18 (a) to 21 (a) displayed the microstructure development of RAC at the age of 90 days. Additionally, the elemental composition of RAC mixtures was investigated using EDAX; their spectra at 90 days of curing age are shown in Fig. 18 (b)-21 (b) which contained major elemental peaks including those of calcium (Ca), silicon (Si), aluminium (Al), potassium (K), oxygen (O), iron (Fe), sodium (Na), and magnesium (Mg). However, only those photos that had significant morphological alterations were displayed in this research. Fig. 18 (a) depicts the formation of calcium silicate hydrate (C–S–H) gel with little amount of ettringite for RAC mix with 20 % CS. The EDAX analysis of mix RAC-CS20 also revealed the peaks of O, Si, Ca, Al, and S (Fig. 18b). Uneven calcium silicate hydrate (CSH) layer development became increasingly noticeable as the CS % increased to 40 % (Fig. 19a). The concrete matrix becomes denser when C–S–H layers build up on top of one another as slag filled the gaps and created a refined structure that had improved the strength consequently [28]. Some voids also developed in the RAC matrix of mixes containing 40 % CS. The maximum Peaks of Ca and Si from the EDAX analysis (Fig. 19 b). further supported the formation of C–S–H gel in the RAC matrix. The highest concentration of silica and calcium in mix could be brought on by the transformation of calcium hydrate into CSH layers, increasing the overall porosity and fineness of the RAC matrix [37]. Strength was shown to diminish when the proportion of copper slag was raised further, or more than 40 %. Copper slag has a low water absorption rate, therefore the extra moisture created gaps and fractures that decreased the strength of the concrete [37]. According to SEM investigation, gel crystals were found in the mix containing 80 % copper slag is comparatively less as illustrated in Fig. 20a. Additionally, the synthesis of calcium alumino-sulphates in concrete was further supported by peaks of Al and S (Fig. 20 b). The morphology of RAC

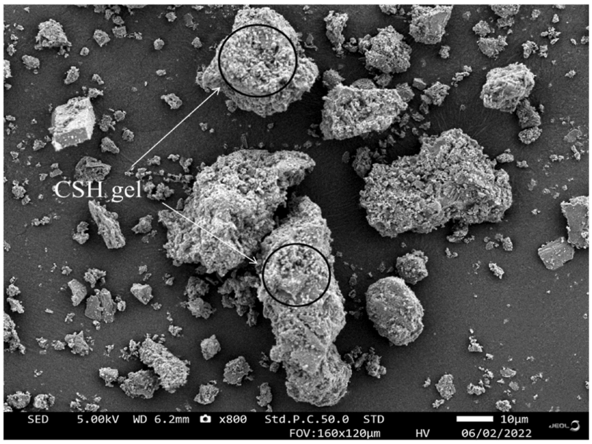

Fig. 18(a). Sem 20 % CS.

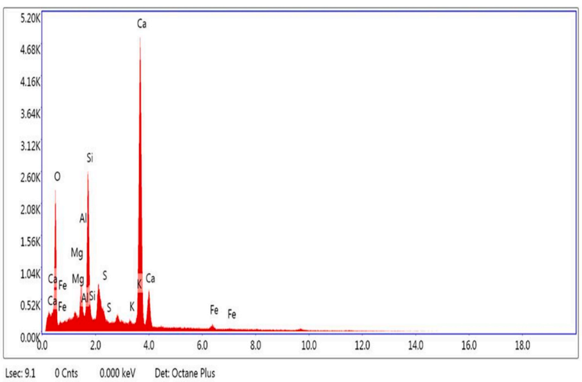

Fig. 18 (b). Edax 20 % CS.

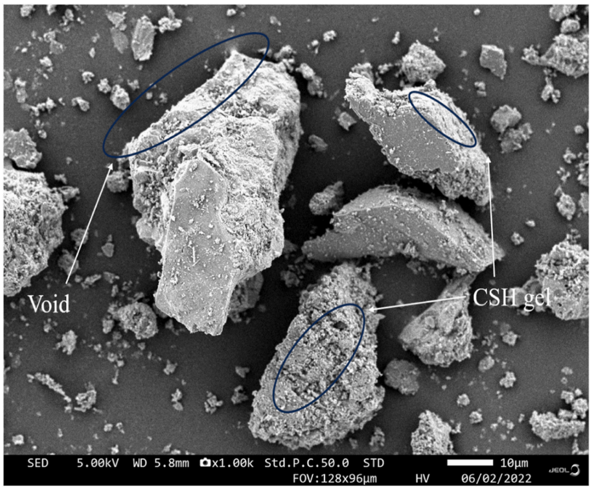

Fig. 19 (a). Sem 40 % CS.

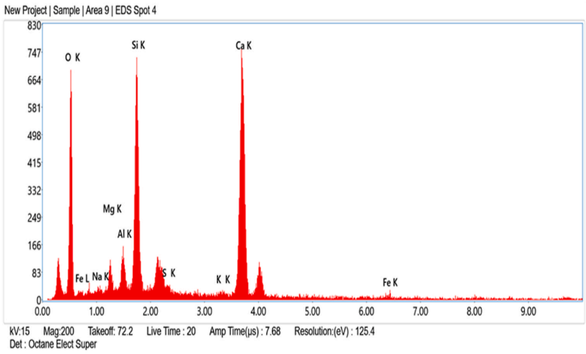

Fig. 19(b). Edax 40 % CS.

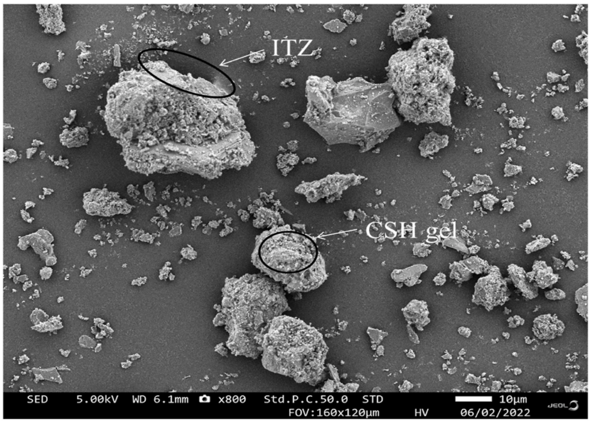

Fig. 20(a). Sem 80 % CS.

containing 100 % copper slag showed the presence of many unreacted CS particles (Fig. 21a). Unreacted particles of copper slag production under SEM were evidenced by the presence of interfacial transition zone (ITZ) in the RAC mix. In Fig. 21b, an EDAX examination of RAC containing 100 % copper slag is displayed with major peaks of Ca, Si, and O which is responsible of gel formation and minor peaks of S and Al confirms the development of ettringite.

5.7.2. XRD analysis

The X-ray diffraction (XRD) technique is a powerful analytical method used to study the crystallographic structure of materials. In this study, XRD was employed to analyse hardened RAC mixes with varying amounts of copper slag to identify the different phases

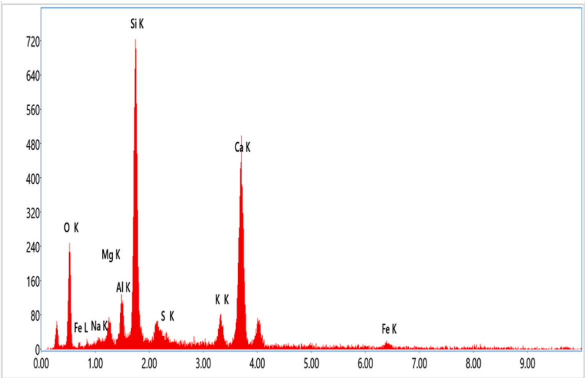

Fig. 20 (b). Edax 80 % CS.

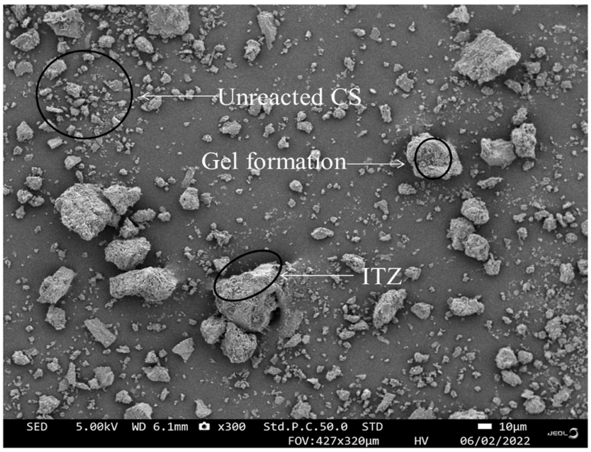

Fig. 21 (a). Sem 100 % CS.

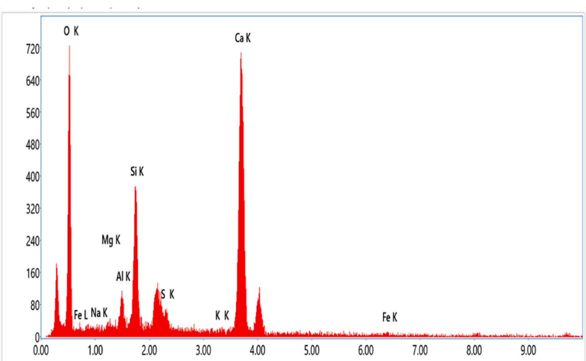

Fig. 21 (b). Edax 100 % CS.

presented in Fig. 22. To begin the analysis, powder samples were extracted from both copper slag-containing and slag-free RAC samples after conducting a 90-day compressive strength test. XRD analysis was carried out with 2 theta angles spanning from 10 to 80°. The results showed that both concrete mixes exhibited multi-phase peaks, indicating the presence of various crystalline structures [37]. The XRD patterns confirmed the presence of a crystalline structure at each replacement levels of copper slag in RAC. However, the primary phase alteration occurred as the CS content in RAC increased. One prominent peak observed in the RAC mixes was associated with quartz, which possesses a hexagonal crystal structure [27]. This quartz peak was present in all mixes up to 90 days. After 90-day curing period, calcium oxide, calcium silicate hydrate, and calcium hydroxide were discovered in addition to quartz as other hydrated phases. Gismo dine and Calcium Silicide were also found in small amounts in the RAC mixes except to RAC-CS0 mix. The quantity of silicon oxide and quartz, observed in the XRD patterns, was highest between 25 and 30° in all mixes. These components play an important role for the development of CSH, a crystal gel which is responsible for the strength of concrete [28]. The highest

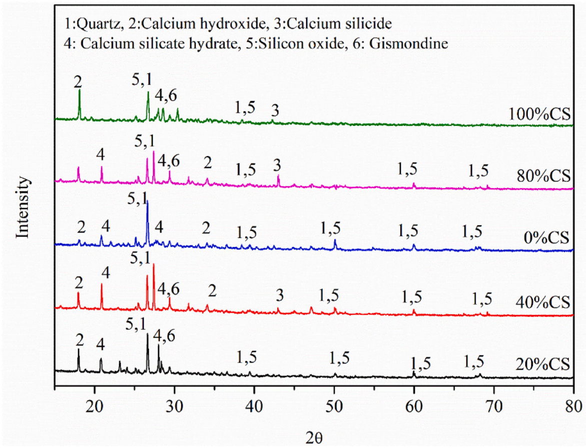

Fig. 22. XRD analysis of the CS mix at 90 days.

concentration of silicon oxide and quartz, coinciding with the most pronounced peaks, was observed when the copper slag content reached 40 % in the mixes. This indicates that the mixes with 40 % copper slag exhibited enhanced strength. With the increased in CS content from 40 % to 80 %, the amount of calcium oxide also increased. Additionally, a phase of Calcium Silicate with the chemical formula $CaSi_2$, representing the monoclinic crystal system, was also identified. Small quantities of quartz and silicon oxide phases were still present in the RAC mix containing 80 % copper slag after 90 days of curing. However, in the mix with 100 % copper slag, the peaks corresponding to quartz and silicon oxide disappeared at 50, 60, and 70°. This absence of quartz and silicon oxide peaks could be a contributing factor to the reduction in strength observed in these mixes. The XRD analysis of hardened RAC mixes with varying amounts of copper slag revealed the presence of different crystalline phases [27]. The study demonstrated that the inclusion of copper slag affected the crystalline structure and composition of the recycled aggregate concrete, with varying impacts on its strength depending on the percentage of copper slag used. These findings provide valuable insights for the development of RAC mixes incorporating copper slag as a complete replacement of fine aggregate.

6. Conclusions

The current research work 'examines the various properties of recycled aggrgate concrete incorporating CS as fine aggregtae successfully and the outcomes are discussed below.

1. The inclusion of CS as a substitution of fine aggregate enhanced the workability of recycled aggrgate concrete. The slump value of RAC mixes were increased to 22 % over control mix with the addition of CS up to 60 % and beyond that the value is reduced to 9 % due to larger particle size of CS than NFA.
2. Compressive strength of RAC is increased at all ages of curing with the incorporation of CS up to 60 % and beyond that the strength is marginal and comparable to control mix. The mixture containing 40 % CS (RAC-CS40) attained the maximum compressive strength at all ages of curing due to low water absorption capacity of CS and enhanced mortar absorption capacity of RCA.
3. Inclusion of CS up to 40 % enhanced the split tensile strength of RCA by 28 % at all ages of curing due to the cohesiveness between the CS particles and RCA. However, the strength of RAC mixes reduced to 10 % with the increased CS content beyond 60 %. Increased amountn of mortar around the aggragtes surface that retards the hydration process of RAC mixtures, resulting decreased in split tensile strength.
4. The water absorption rate in RAC has been reduced up to 16 % with the incorporation of CS upto 40 % at all ages of curing. However, RAC blends shows incresed water absorption above 40 % CS substitution as the high concentration of CS in the mixture creates new voids and increase in the amount of free water, thus enhanced the water absorption rate.
5. The effect of copper slag on chloride ion permeability was greatly enhanced by later stages of curing. After 90 days of curing, RAC mixes were categorised as "very low" ion permeability due to their less penetrability of chloride ion. The RAC-CS40 mix exhibited mimimum chloride ion permeability (26–45 %) over control RAC mix at all ages of curing.
6. The increased porosity and Ettringite-induced expansion is identified as the primary cause of the mass gain and strength loss of RAC mixes after exposed in sulphate solution. The mix containing 100 % CS (RAC-CS100) experienced heighest mass gain and strength loss after 90 days of sulphate exposure whereas the RAC mix containing 20 % and 40 % CS exhibited less reduction in strength with respect to control concrete.
7. The SEM micrograph of RAC mixes showed a compact and uniform CSH layer emerged with higher CS percentages up to 40 %, escalating the strength properties through refined structure. However, the reduction in strength is accelerated by inclusion of CS above 40 % due to the formation of gaps and fractures in the RAC mixes. The EDAX analysis of RAC matrices shows the maximum peaks of Ca and Si which confirms the formation of CSH gel in each spectrum. The mix with 40 % copper slag had the highest silica and calcium concentration in comparision to other mixes as observed from the EDAX analysis.

8. The most notable peaks corresponded to the highest levels of silicon oxide and quartz concentration, which were detected when the copper slag content reached 40 % within the mixtures. This observation underscores the augmented strength displayed by mixtures containing 40 % copper slag. The presence of copper slag influenced both the composition and crystalline structure of the recycled aggregate concrete, yielding diverse effects on its strength contingent upon the proportion of copper slag employed.

Overall, the performance of recycled aggregate concrete in terms of strength, durability and microstructural characterization is improved by incorporation of CS up to 40 % as fine aggregate. The previous literatures suggested that the ideal fine aggregate content range is 40 %–60 % for regular vibrated, self-compacting and high-performance concrete. Further, this study also encourages to develop sustainable waste management practices in the production sector by conserving natural aggregates and reduces the difficulties associated with waste disposal and the environment.

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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