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RESEARCH

Performance of Recycled Aggregate Concrete Incorporating Copper Slag at Elevated Temperature

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Abstract

Effective and economic utilization of waste materials produced from different construction and industry sectors is a big challenge for the engineers and researchers in the recent decade due to its disposal and environmental issue. In this context, the present research work utilizes recycled concrete aggregate and copper slag as a substitution of natural coarse and fine aggregates to produce waste based and environmentally friendly concrete. This experimental study aims to analyse the impact of using copper slag as a replacement of fine aggregate on the characteristics of recycled aggregate concrete exposed at elevated temperature. For this, total seven number of mixes and 315 number of samples were prepared in two series of mixes. Natural coarse aggregates are replaced by recycled coarse aggregate of varying proportions (0%, 33%, 66% and 100%) in the first series, whereas copper slag is utilized to substitute as fine aggregate up to 60% with increments of 20% in the second series to examine the different properties of various concrete mixtures containing 33% recycled coarse aggregate. The mixtures were designed for M30 grade concrete with control mix proportion of 1:2.20:3.053 as per IS code of practice. Properties like compressive strength, split tensile strength, flexural strength, mass loss and ultra-sonic pulse velocity of various concrete mixtures were evaluated before and after exposure of different temperatures (i.e., 30 °C, 200 °C, 400 °C, 600 °C and 800 °C) and the values were compared with that of control concrete. The study revealed that, although the strength properties of all the mixes reduced with the increased temperature, the residual performance of recycled aggregate concrete is found satisfactory with the addition of copper slag up to 40% as a replacement of fine aggregate and comparable with the control concrete. The optimum performance is attained by the addition of 20% copper slag, i.e. up to 25% higher mechanical strength than the control mix at elevated temperature up to 800 °C. From the microstructural analysis, it was confirmed that by incorporating up to 40% copper slag as a replacement for fine aggregate, the development of voids is minimum in comparison with control concrete which escalated the residual strength properties. Thus, using RCA and CS as waste materials could decrease the quantity of natural resources used in the building sectors as well as reduce the amount of waste disposal.

Keywords Recycled coarse aggregate · Copper slag · Mass loss · Microstructural behaviour · Elevated temperature

1 Introduction

In the present decade, concrete plays an important role in construction sector due to its use in various construction activities, and its estimated yearly global production is 25 billion tonnes (Tung et al. 2023). As aggregates make up 75–80% of the total concrete material and have an important role for enhancing strength, its significant use in construction sector not only depleted the natural resources but also give an adverse effect to the environment. So, now it is necessary to consider new sustainable alternative materials that could successfully replace both fine and coarse aggregate in concrete to create environmentally friendly materials. On the other hand, increased industrialization and rebuilding and demolition of existing concrete structures produced huge amount of by-product waste and construction garbage every year which create a negative impact on the environment and disposal. In the recent decade, researchers have gained attention on utilization of recycled waste materials as construction materials in concrete production. Many

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research works (Abdullah et al. 2018, 2020; Ahmed et al. 2022; Mahmood et al. 2019, 2022; Mohammed et al. 2023; Muhammad et al. 2014, 2020; Unis Ahmed et al. 2022) were carried out by utilizing different waste materials like steel slag, copper slag, fly ash, egg shell powder, recycled concrete, recycled tyre rubber, etc., as a substitution of virgin materials due to their excellent building properties. For example, utilization of recycled tyre rubber as fine aggregate replacement reduced the workability, density and enhanced the pre- and post-fire behaviour properties of concrete (Abdullah et al. 2020; Muhammad et al. 2020). Similarly, by inclusion of egg shell powder as a cement replacement increased the strength and durability properties of concrete (Mahmood et al. 2019). It was also observed that with the addition of egg shell powder up to 10% as cement substitution the shear behaviour of reinforced concrete was increased to 10% (Mahmood et al. 2022). Another important waste released from water treatment plants is alum sludge which increased the shear strength of reinforced concrete slab to 12.5% after adding 5% as cement replacement (Ahmed et al. 2022). So, the proper utilization of these waste materials can not only mitigate the problem of natural resources but also reduced the disposal and environmental issues. Present study utilizes recycled coarse aggregate (RCA) and copper slag (CS) the waste materials as a substitution of natural coarse and fine aggregates, respectively.

Recycled coarse aggregate is the waste material obtained from the construction debris used to substitute the natural coarse aggregate (NCA) by the researchers and engineers due to its superior quality and extensive features for making a good concrete. As observed by the many researchers (Fernandes et al. 2021; Gholampour et al. 2020; Hung et al. 2020; Khattab et al. 2021; Liu et al. 2018; Majhi and Nayak 2019, 2020; Salahuddin et al. 2019; Tung et al. 2023), the concrete that made with RCA exhibited poor performance due to its inferior quality and weak interfacial transition zone (ITZ) characteristics of attached mortars. However, the replacement of RCA up to 30% was compared to the normal concrete as it achieved the desired strength and the strength loss was marginal due to less adhered mortar around the aggregate surface (Majhi et al. 2018, 2020; Salahuddin et al. 2019). The behaviour of recycled aggregate concrete (RAC) at high temperatures was also studied by the researchers (Salahuddin et al. 2019; Tung et al. 2023) and observed that during heating process there was significant amount of weight loss due to the grater porosity of RCA which influence the mechanical and physical qualities of concrete. Similarly, the compressive strength of RAC was seen to increase gradually in between 200 and 450 °C when the NCA was replaced by 30% RCA (Salau et al. 2015). It was also examined that at specific exposure temperatures the residual strength of concrete with RCA of varied percentages (0–100%) was increased than that of the control concrete. (Xiao and Zhang 2007).

Table 1 Characteristics (Physical) of cement

Properties	Results
Fineness	6%
Specific gravity	3.13
Standard consistency	32%
Initial setting time	45 min
Final setting time	300 min
Compressive strength (28 days)	54.8 Mpa

Table 2 XRF analysis of cement, NFA and CS

Compounds	Cement	NFA	CS
CaO	60.83	0.7	0.6
Al_2O_3	6.04	6.92	3.84
SiO_2	20.21	84.47	32.9
Fe_2O_3	5.24	4.66	57.26
MgO	2.92	0.69	2.08
K_2O	0.97	1.73	0.5
SO_3	2.61	0.23	2.05
Na_2O	0.26	–	–
P_2O_5	0.12	0.05	0.5
TiO_2	0.8	0.55	0.27

In addition, copper slag, a waste product obtained from smelting techniques and refining processes of copper industry, has gained attention of the researchers for its successful utilization as fine aggregate in construction industry. As India accounts for about 3% of the world's total CS production, which is estimated to be 68.8 million tonnes, the proper utilization of copper slag in the building industry is a significant challenge for researchers due to the massive land filling and lack of natural resources that contribute to environmental damage. Due to lower water absorption quality and glassy texture of CS, most of the researchers substituted copper slag as NFA in their studies (Ameri et al. 2021; Gupta and Siddique 2019; Sharma and Khan 2017). According to the researchers, the strength parameters of regular vibrated concrete were boosted by up to 13% when CS was substituted up to 40% of the fine aggregate (Al-Jabri et al. 2011; Maharishi et al. 2020). It was also observed that the concrete containing CS and RCA together as a replacement for fine and coarse aggregate achieved better results in comparison with other replacement after adding mineral admixtures to it (Behnood et al. 2015). The researchers also studied the performance of CS as a substitution of fine aggregate at different temperature exposures and found that the concrete made with CS up to 40% replacement showed improved strength qualities over

Fig. 1 **a** RCA used in the study. **b** Copper slag used in the study

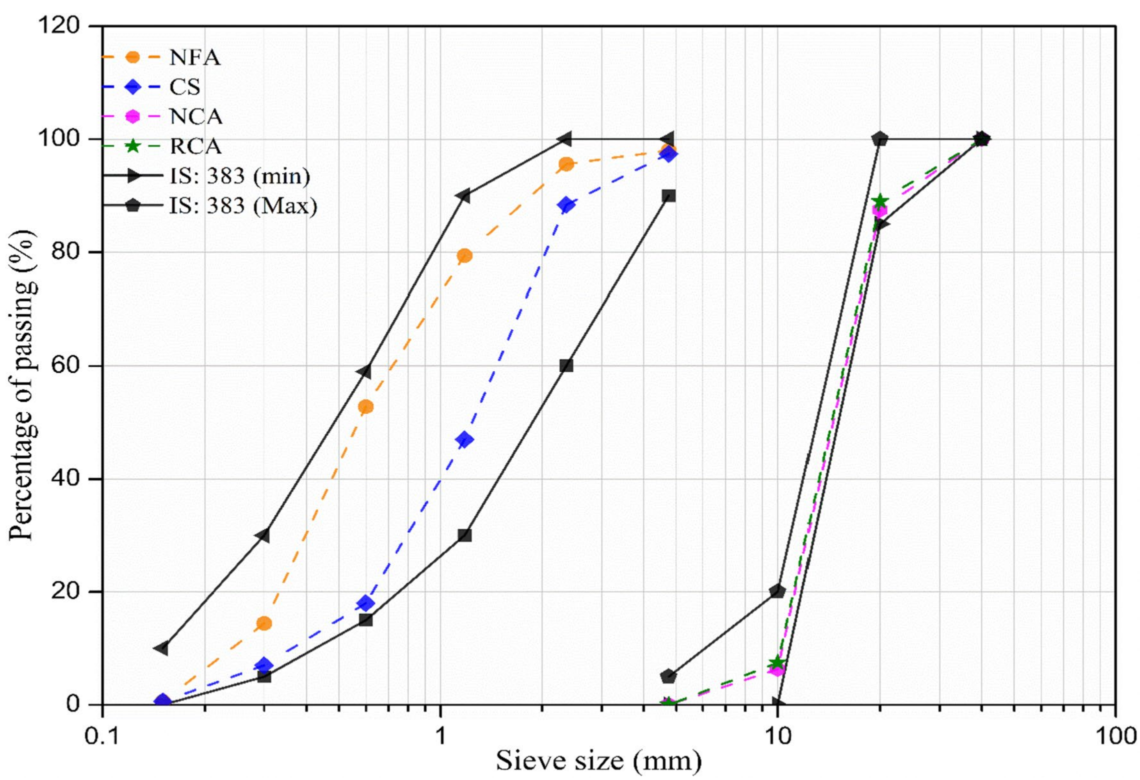


Fig. 2 Grading analysis of fine and coarse aggregate

control concrete (Ameri et al. 2021; Patnaik et al. 2020). A detrimental effect on self-compacting concrete was also observed when CS was incorporated as fine aggregate up to 40% (Gong and Ueda 2018). The strength of concrete was reduced by roughly 8% after exposure of 400 °C. The study's conflicting conclusions signifies the need for more investigation into concrete's fire-resistant qualities utilizing CS.

The novelty of the research work is to examine the combined effect of RCA and CS as a replacement of coarse aggregate and fine aggregate, respectively, on the mechanical and microstructural properties of concrete at high temperature exposures. Utilizing RCA and CS together

Table 3 Physical characteristics of aggregate

Properties	NFA	CS	NCA	RCA
Bulk density	1590 kg/m^3	1980 kg/m^3	2542 kg/m^3	2255 kg/m^3
Water absorption	0.81%	0.5	0.74%	4.0%
Specific gravity	2.65	3.62	2.56	2.72
Fineness modulus	3.0	3.8	6.34	7.2

as building materials could help the construction sector for creating more sustainable concrete and minimizes the loss of natural resources. As far as the author's knowledge, there are no studies discussing the residual performance of RAC at elevated temperatures using CS as fine aggregate till now. However, in earlier research works, the authors examined the impact of high temperatures on the residual behaviour of concrete using either CS as fine aggregate or RCA as coarse aggregate. In the current study, the percentage of replacement of coarse aggregate by RCA is made as one-third, i.e. 33%, 66% and 100% in the first series, whereas the concrete is prepared by 33% RCA with varying percentage (i.e. 20%, 40% and 60%) of copper slag as a replacement of natural fine aggregate in the second series. Since most of the investigations discovered that concrete made with 30% RCA replacement of NCA could accomplish the target strength and be comparable to control concrete, RCA replacement is fixed at one-third to improve comprehension and cover a wider range of particles. However, the replacement of RCA and CS is fixed as per the authors previous research work (Kumar et al. 2023) which examined the effectiveness of recycled aggregate-based self-compacting concrete by using varying proportion of CS for fine aggregate. All the mix proportions were exposed at different temperature levels of 30, 200, 400, 600 and 800 °C to assess their strength characteristics. In addition to this, the changes in microstructural behaviour at different temperature and the elemental composition of various mixes were discussed through scanning electron microscopy (SEM) and energy-dispersive X-ray analysis (EDAX) spectrograph.

Fig. 3 Muffle furnace

2 Materials and Methodology

2.1 Materials Used in the Study

2.1.1 Cement

The current investigation employed ordinary Portland cement (OPC) of 53 grade in accordance with IS: 12,269–1987 (IS-12269 1987). Various physical properties have been conducted in the laboratory as per BIS specification (IS:4031 Part 11; Part 4; Part 5; Part 6.) having specific gravity 3.14 with 6% fineness and 32% standard consistency. The details are presented in Table 1. The chemical composition of cement was obtained from X-ray fluorescence (XRF) test, and the results are presented in Table 2. The major compositions of cement are found to be CaO (60.83%) and SiO_2 (20.21%).

2.1.2 Coarse Aggregate

Crushed basalt stone of 20 mm size is considered as natural coarse aggregate (NCA) in the present study. Recycled

Table 4 Mix proportions of concrete

Mixtures	Control concrete	R33	R66	R100	R33CS20	R33CS40	R33CS60
Cement (kg/m^3)	393	393	393	393	393	393	393
NFA (kg/m^3)	865	865	865	865	692	519	346
CS (kg/m^3)	0	0	0	0	173	346	519
NCA (kg/m^3)	1200	804	408	0	804	804	804
RCA (kg/m^3)	0	396	792	1200	396	396	396
SP (%)	1	1	1	1	1	1	1
Water (kg/m^3)	177	177	177	177	177	177	177
Slump value	90	95	88	80	120	125	118

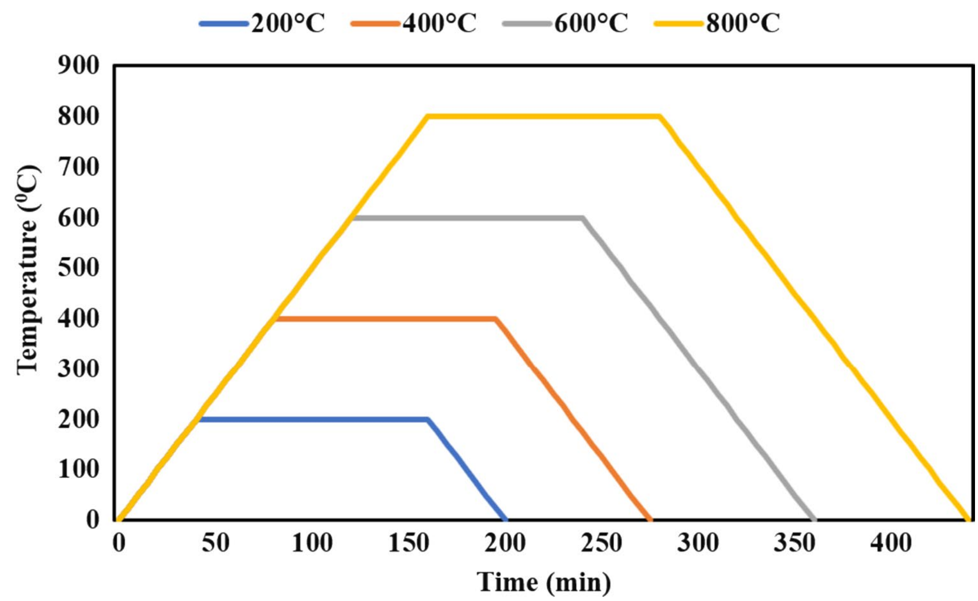


Fig. 4 Time–temperature curve for heating & cooling process

coarse aggregates (Fig. 1a) obtained from demolition of 10 years old petrol pump are used to replace the conventionally used coarse aggregates. Grading analysis of NCA and RCA has been done as per IS: 2386 (part-I) (IS:2386- Part I, 1963) and graphically represented in Fig. 2. Indicating that, both the aggregates are well graded and confirmed as per IS: 383 (IS:383 1970). RCA has been found to be finer as compared to NCA. Table 3 represents the physical properties of fine and coarse aggregates that are evaluated by performing various experiments as per standard code of practice (IS 2386-Part III 1963).

2.1.3 Fine Aggregate

Locally available sand is employed as natural fine aggregate (NFA) in the research work. Copper slag, as shown in Fig. 1, obtained from Hindustan Copper Limited (HCL), Jamshedpur, India, is used as fine aggregate. Gradation analysis of NFA and CS as represented in Fig. 2 is carried out in the laboratory and in accordance with IS: 2386 (part-I) and IS: 383, respectively. The nominal sizes of NFA and CS were found to lie in zone II and zone I, respectively. The physical characteristics of NFA and CS are determined in the laboratory according to standard code of practice (IS 2386-Part III 1963), and the results are tabulated in Table 1. For determining the chemical properties of NFA and CS, XRF test was conducted and the results are presented in Table 3. The XRF results showed that in copper slag, the iron content (57.26%) is more than that of NFA (4.66%) whereas the silica content of CS (32.9%) is less than NFA (84.45%).

2.1.4 Admixture

PCE 200 (Poly-Carboxylic Ether based) obtained from Asian Paints Ltd is used as admixture in the experimental work and is available in liquid form. The pH and specific gravity of admixture are found as 7.0 and 1.09 with nil chloride content.

2.2 Mixing and Curing

The mix design follows IS:10,262–2019 (IS 10262, 2019) guide lines for all the concrete mixes of grade M30. The mix parameters considered in this research field were, (i) recycled coarse aggregates with varying proportions (i.e. 0, 33, 66 and 100%) and (ii) copper slag to replace natural fine aggregate with varying proportions (i.e. 0, 20, 40 and 60%) in concrete mixture containing 33% RCA. The detailed mix proportions of various concrete mixtures along with the slump value of fresh concrete of each mix are presented in Table 4.

2.3 Heating Procedure

For evaluating residual mechanical properties of concrete, the 28 days matured concrete specimens were exposed to four different temperatures (200 °C, 400 °C, 600 °C and 800 °C). An auto-controlled electric muffle furnace (Fig. 3) was used for heating of the specimens at required temperature. A constant rate of heating 10 °C/min (Sedaghatdoost et al. 2019; Tung et al. 2023) was considered to attain the target temperature and also to ensure that the samples were sufficiently and uniformly heated. After that, the specimens were exposed for two

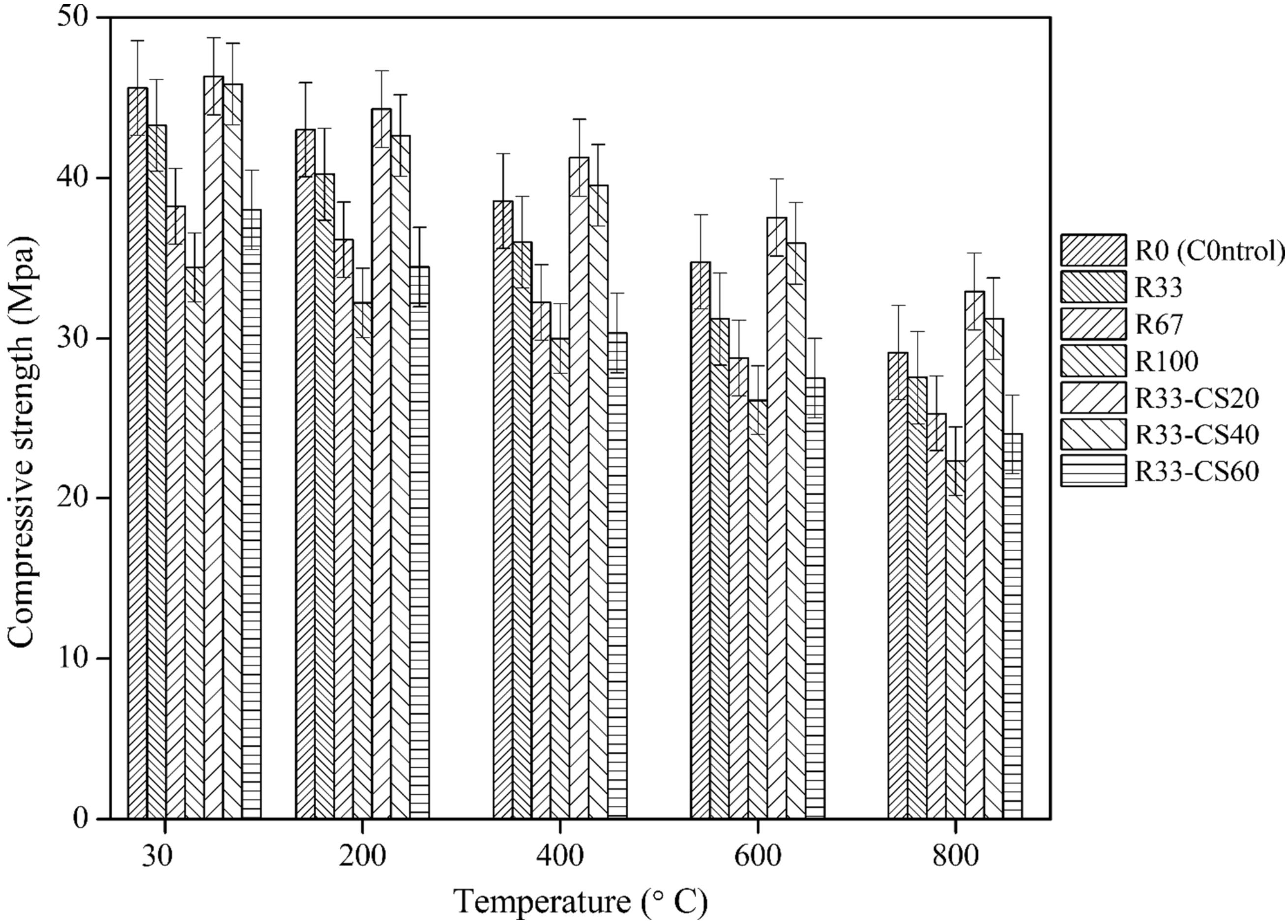
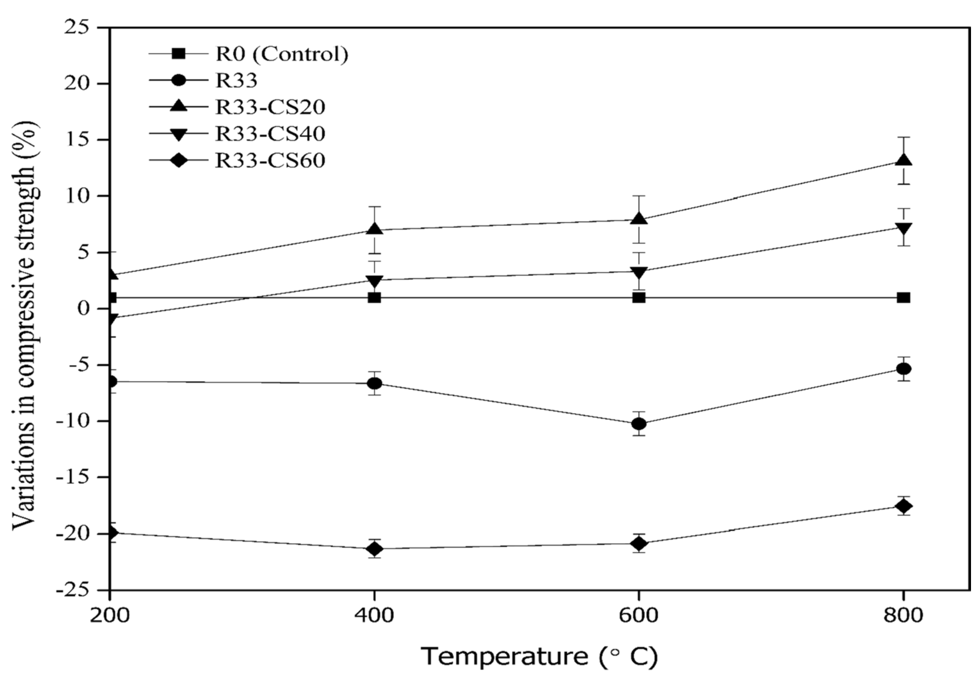


Fig. 5 Compressive strength of concrete mixtures exposed to various temperature

Fig. 6 Compressive strength variation of CS blended RAC over control mix exposed to various temperatures



hours at the desired temperature. The specimens were then undergoes various testing procedures to determine their residual strength properties after being exposed and cooled naturally. Figure 4 depicts the heating and cooling process of specimens at different temperature variations.

2.4 Mechanical Properties

2.4.1 Compressive Strength Test

To evaluate the compressive strength of different concrete mixtures, standard concrete cube specimens of 150 mm size were used as per IS: 516 (IS 516 1959). The specimens were tested in compression testing machine (CTM) having capacity of 3000 kN by applying loading rate of 14 N/mm^2/min until the failure occurs.

2.4.2 Split-Tensile Strength Test

For evaluating split tensile strength, cylindrical specimens of dimension 150 mm × 300 mm were used as per the provision of IS: 5816 (IS 5816–1999 1999). The test is carried out in CTM with loading rate of 1.2 N/mm^2/min.

2.4.3 Flexural Strength Test

Flexural strength of different concrete mixtures was evaluated in a similar manner according to IS:516 (IS 516 1959). The specimen of size (100 × 100 × 500) mm was placed between the two roller supports of flexural testing machine of 100 KN capacity with centre to centre spacing of 400 mm and applied the load gradually by two-point loading method with loading rate of 0.7 N/mm^2/min until failure occurs.

2.4.4 Ultrasonic Pulse Velocity (UPV) Test

The quality of hardened concrete of different cube specimens was evaluated by using ultrasonic pulse velocity (UPV) test after 28 days curing as per IS: 13,311(part-1) (IS 13311 (Part 1), 1992) before and after the exposure of temperature.

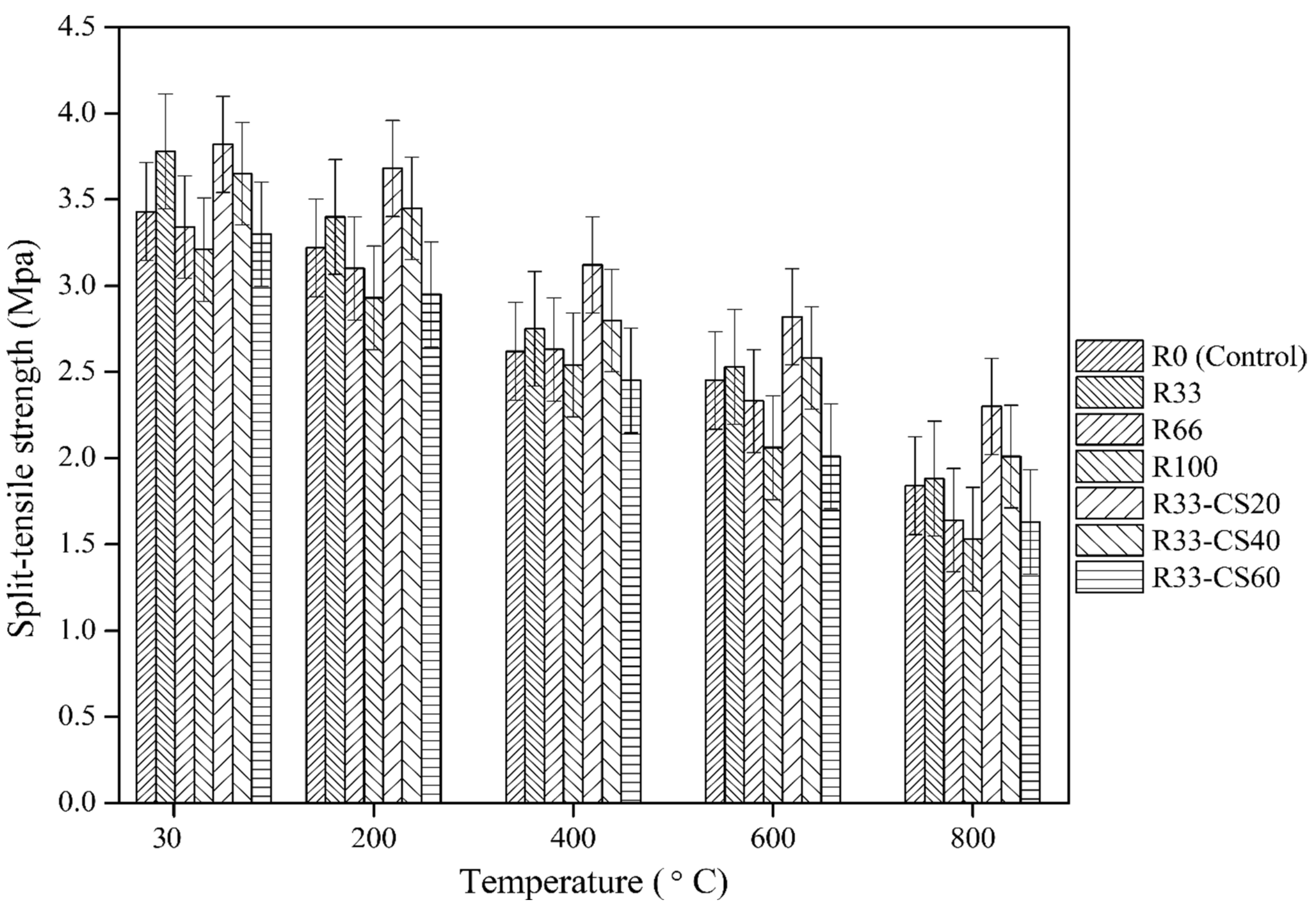


Fig. 7 Split tensile strength of concrete mixtures exposed to various temperatures

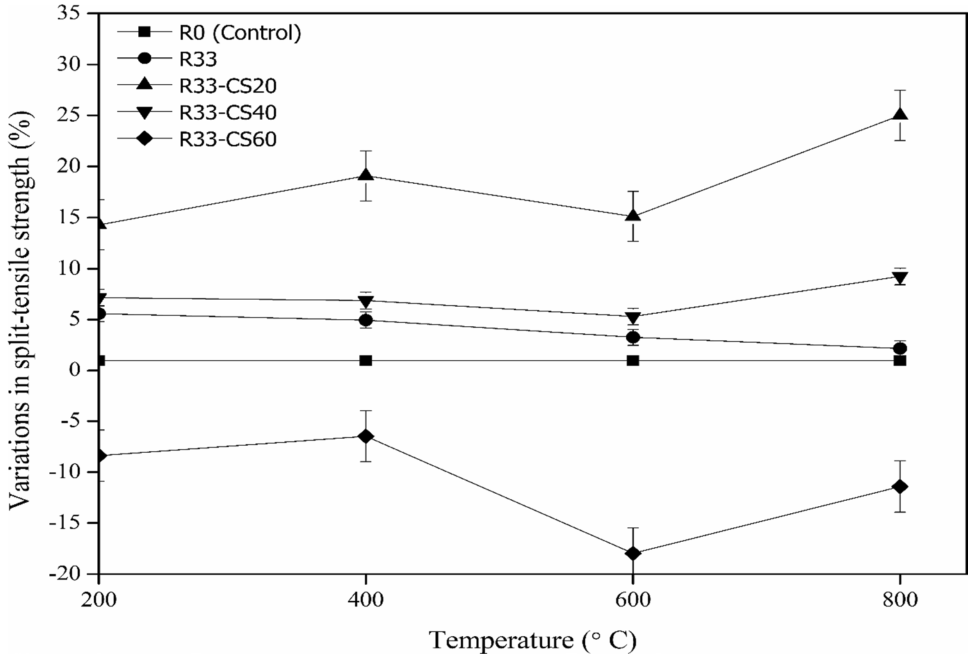


Fig. 8 Split-tensile strength Variations of CS blended RAC over control mix at elevated temperatures

3 Results and Discussion

3.1 Strength Characteristics

3.1.1 Compressive Strength Test

The test results of compressive strength of various RAC mixtures incorporating CS as fine aggregate after exposed to room and elevated temperatures are graphically represented in Fig. 5. It has been observed that at ambient temperature condition the compressive strength of concrete decreased with the increase in RCA content. It can be noted that the concrete made by 33% RCA showed minor variation in compressive strength, i.e. about 5% over control concrete. However, the strength of RAC drops significantly by 16% and 24%, respectively, with the addition of 66% and 100% RCA. Similar results were seen in a previous investigation as well (Salahuddin et al. 2019). The major causes of the strength reduction of RAC with a rise in RCA content include the presence of significant volume of mortar adhering to the surface of RCA, and lower density. Similar trend has been observed when the RAC mixes are exposed to higher temperature. Adding 100% RCA reduces the compressive strength of RAC by up to 30% when exposed to temperatures between 200 and 800 °C. However, residual compressive strength for concrete mixtures with 33% RCA showed a marginal reduction with respect to control mixture.

Similarly, with the inclusion of copper slag, the compressive strength of RAC with 33% RCA is increased in comparison with the control mix at 28 days of maturity. The strength is enhanced by 7.05% and 5.92% with addition of copper slag by 20% and 40%, respectively. However, the strength is reduced by 12% when copper slag is increased by another 60%. As copper slag smoothens the surface and decreases the cohesiveness of the mixture; its glassy structure could be the reason for this reduction. (Gupta and Siddique 2019). However, at elevated temperature up to 800 °C, the CS blended RAC mixes show decreased strength with respect to its initial strength. For instance, in the case of concrete specimens made using 33% RCA and 20% of copper slag, the compressive strength is dropped by up to 29% as compared to its initial strength with the rise of temperature exposure from 200 to 800 °C. This decrease in strength with increase in temperature might be due to an increased heat along with dehydration of ettringite. Additionally, it can be the result of chemical degradation at higher temperatures, that would form the porous structure and cause the microstructure to degrade (Ameri 2021). Figure 6 shows the variations of compressive strength between CS blended RAC over control mix at different exposure of temperatures. As compared to the control mix, the compressive strength of RAC with 33% RCA (R33-CS0 mix) decreased significantly as the exposed temperature increased from 200 to 600 °C. The reduction is about 6.44%, 6.61% and 10.21% at 200, 400 and 600 °C temperature, respectively. This may be due to the fact that, as the temperature level increases the specimen undergoes heavy water loss due to the evaporation of free water present inside the RAC matrix causing the formation of voids and cracks and reduced the strength of the RAC. However, because of the enhanced thermal expansion properties between the aggregates and cement matrix, the R33-CS0 mix exhibited

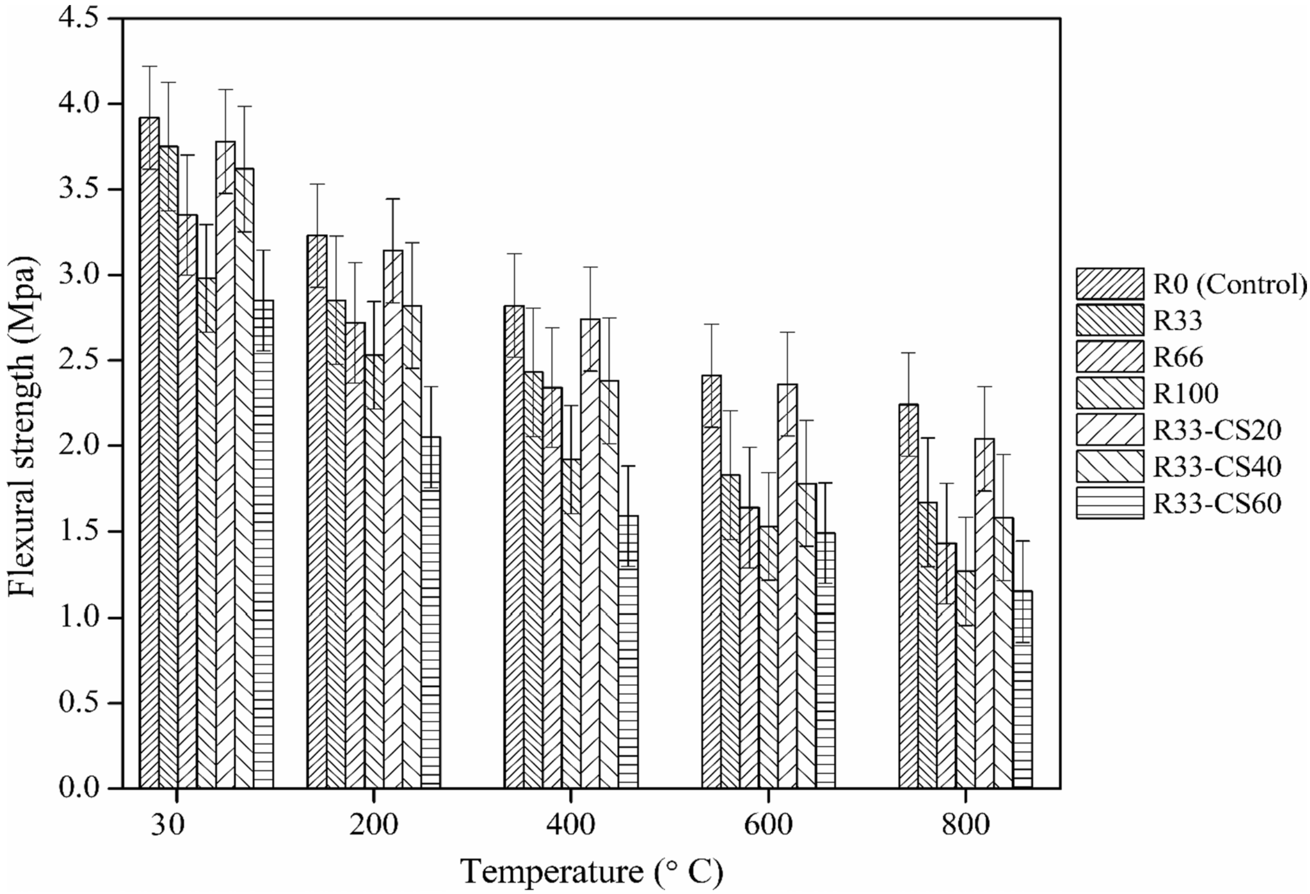


Fig. 9 Flexural strength of RAC mixtures at different temperature exposures

Fig. 10 Control concrete **a** at room temperature **b** at an exposure of 800 °C

minor variation in compressive strength (up to 5%) over control mix at the temperature exposure of 800 °C (Sarhat and Sherwood 2013). Furthermore, it is observed that with increased temperature the compressive strength of RAC mixes up to 40% CS incorporation as fine aggregate showed improved performance over the control mix. The strength increment of about 3%, 7%, 9% and 13%, respectively, is found over control mix with 20% CS addition. The increased strength is attributed to the less water absorption capacity and lower thermal expansion properties of CS particles than NFA, as a result formation of relatively less voids and cracks at higher temperature in comparison with control mix.

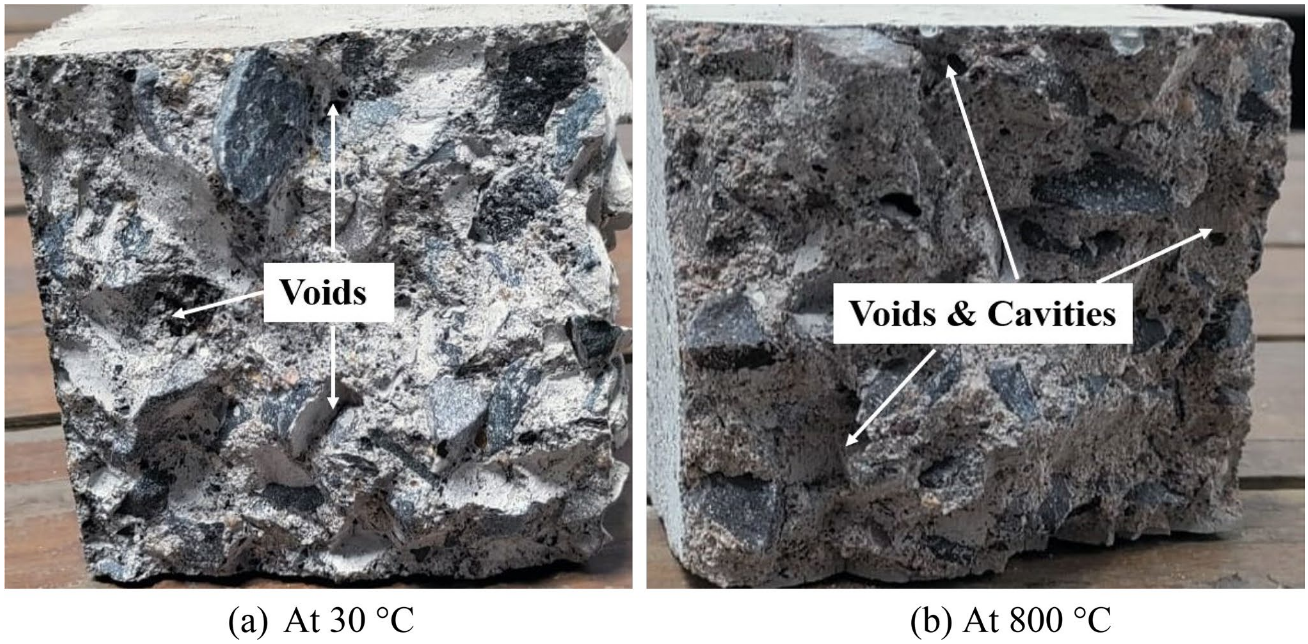


Fig. 11 Visual assessment of Control concrete after flexural failure

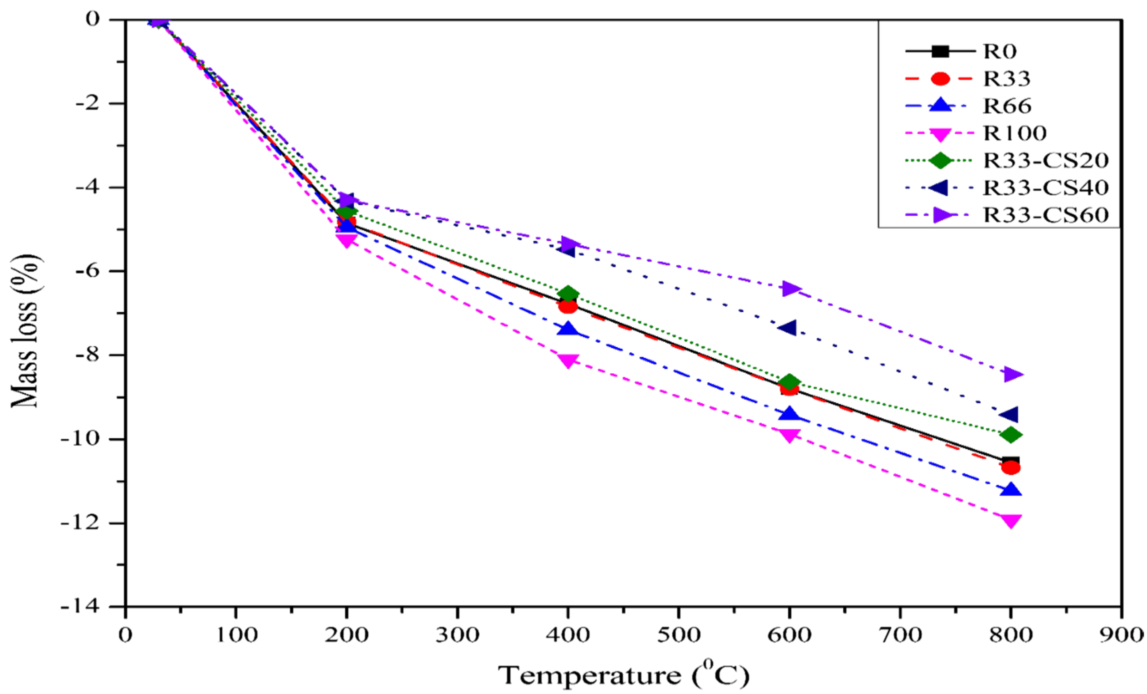


Fig. 12 Mass loss of concrete mixes at elevated temperature

3.1.2 Split-Tensile Strength Test

Figure 7 represents the results of split-tensile strength values after 28 days for various RAC mixtures incorporating CS as fine aggregate at the temperature exposure of 30–800 °C. All RAC mixes have shown a similar pattern of reducing split-tensile strength as rehydration takes place throughout the cooling down stage, and at higher temperatures, more pronounced volumetric changes are observed (Beatriz da Silva et al. 2020). However, the split-tensile strength of

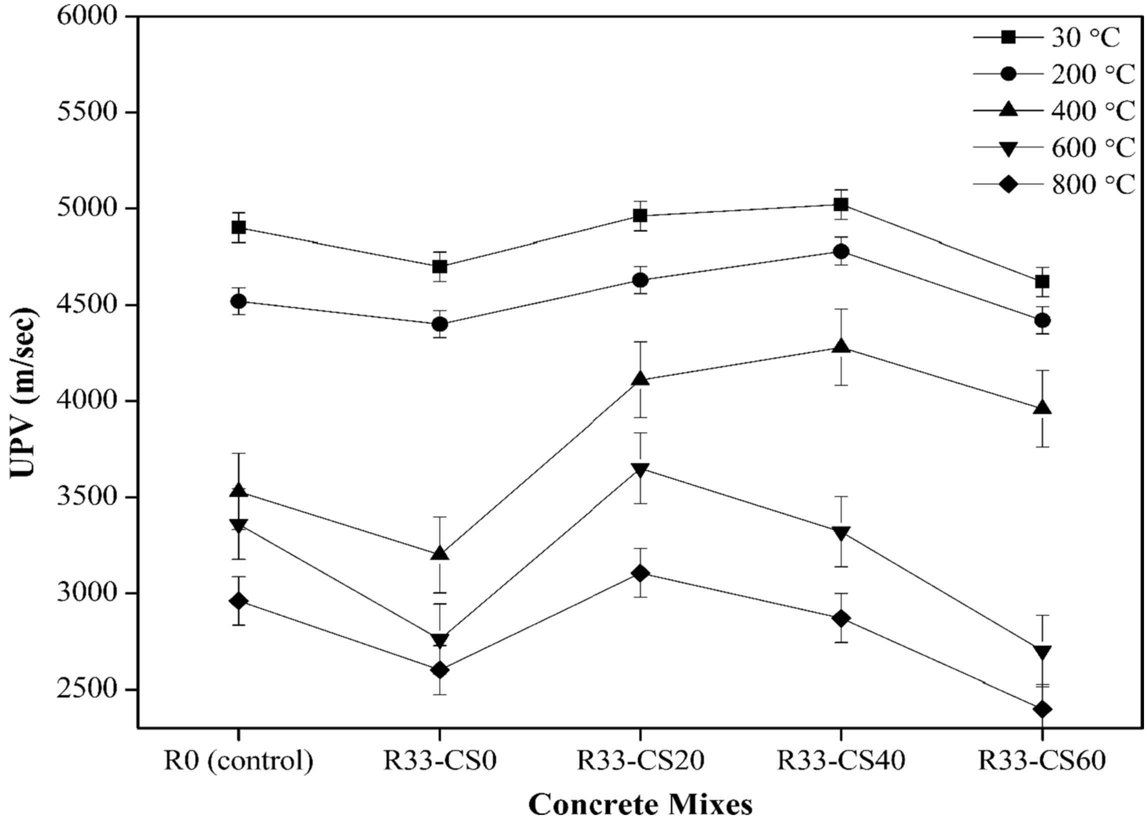


Fig. 13 UPV of concrete mixes at different temperature exposures

RAC containing 33% RCA (R33) is enhanced up to 10% at ambient condition and up to 5% over control mix at the temperature exposure from 200 to 800 °C. The increased strength attributed to the better bond between the aggregate and mortar developed from the ITZ performance and increased adhesion capacity of mortar to RCA surfaces (Oikonomou 2005). Furthermore, when CS was added to RAC under ambient conditions, its tensile strength increased to 11% when compared to the control mix. Figure 8 depicts the tensile strength variations between CS mixes and control mix at various exposure temperatures. Compared to other mixes, R33-CS20 mix achieved the maximum increment in tensile strength which is about 14.3%, 19%, 15.1% and 25% at 200, 400, 600, and 800 °C, respectively. Similarly, the tensile strength of R33-CS40 mix is improved from 7 to 9% with respect to control mix at the same temperature exposure.

The improved strength is explained by the lower thermal expansion properties of CS than fine aggregate, which inhibited the development of microcracks in the interfacial transition zone (ITZ). However, the tensile strength is further reduced as the CS content is increased to 60%. This is because of the increased specific weight of the CS particles that reduced its ability to absorb water.

3.1.3 Flexural Strength Test

The results of 28 days flexural strength of different RAC mixtures incorporating CS as fine aggregate exposed to temperatures of 30–800 °C were graphically plotted and are presented in Fig. 9. It is noticed that the flexural strength of the concrete mixtures significantly decreased at room temperature as well as after being exposed to the specified temperatures which was consistent with the values obtained from the compressive strength results. The strength of control mix was reduced by 18%, 28%, 38% and 43%, respectively, at the temperature exposure of 200, 400, 600 and 800 °C, respectively, with respect to the room temperature strength. The reduction is caused by the breaking down of hydration products and excessive moisture loss at higher temperature which led to the development of fractures at the specimen's surface as shown in Fig. 10b. Whereas, the specimen at room temperature observed no surface cracks (Fig. 10a).

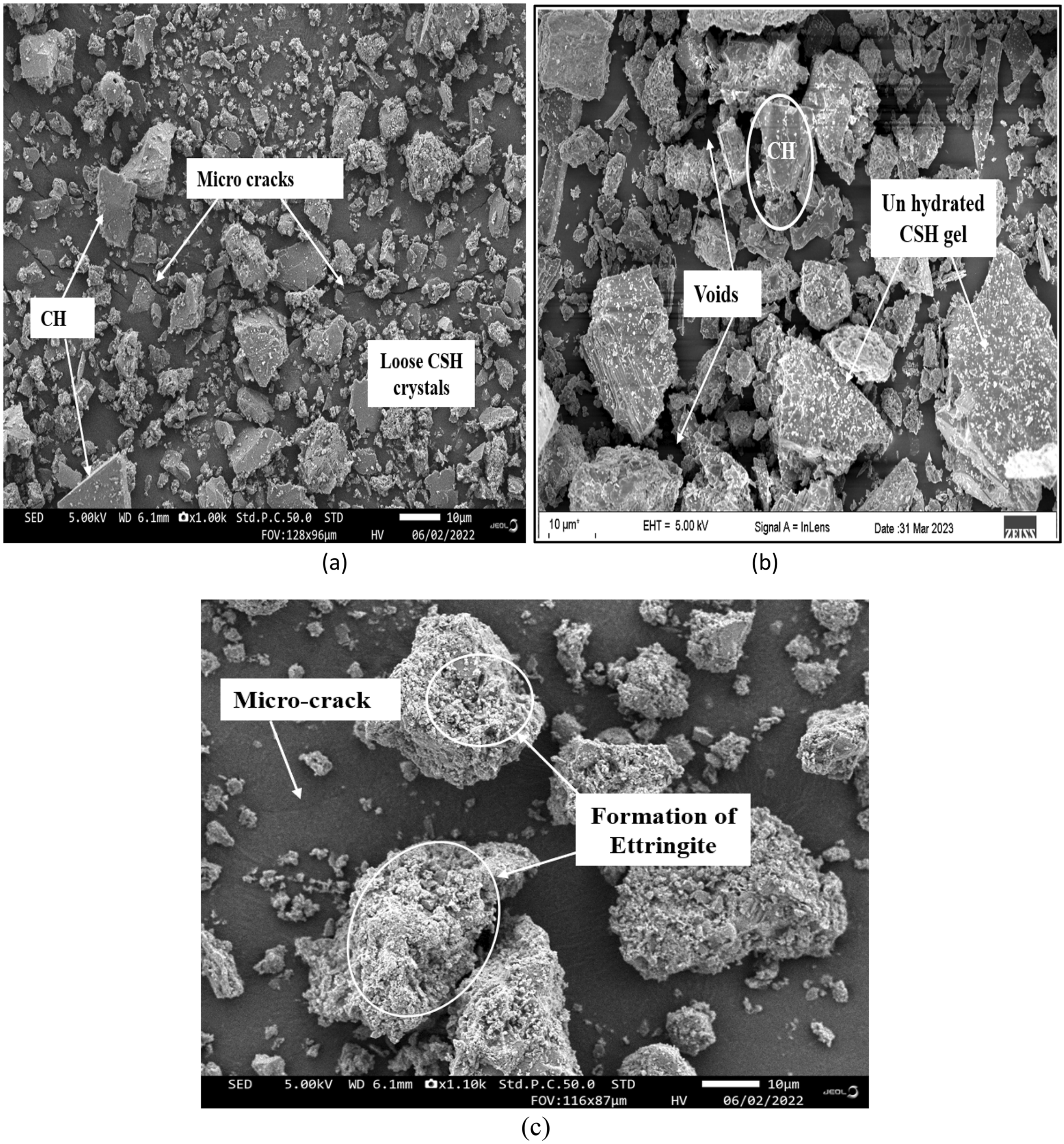


Fig. 14 SEM analysis of various concrete mixes exposed to room temperature **a** control mix **b** RAC mix **c** R33-CS20 mix

Similarly with the incorporation of RCA up to 100% the flexural strength was dropped up to 57% in comparison with the control concrete up to 800 °C. This was attributed to the high thermal expansion of RCA due to the non-uniform thermal pressures between NCA and RCA (Zhao et al. 2018). However, the strength was more pronounced when CS of varying proportions was incorporated to the RAC mix at elevated temperature. For instance, the mixture containing 33% RCA and 20% CS showed the least reduction in residual flexural strength with respect to the other mixes. The strength dropped by around 16%, 27%, 37%, and 46%, respectively, in comparison with the room temperature strength when the specimen exposed to 200, 400, 600, and 800 °C. The disintegration of calcium

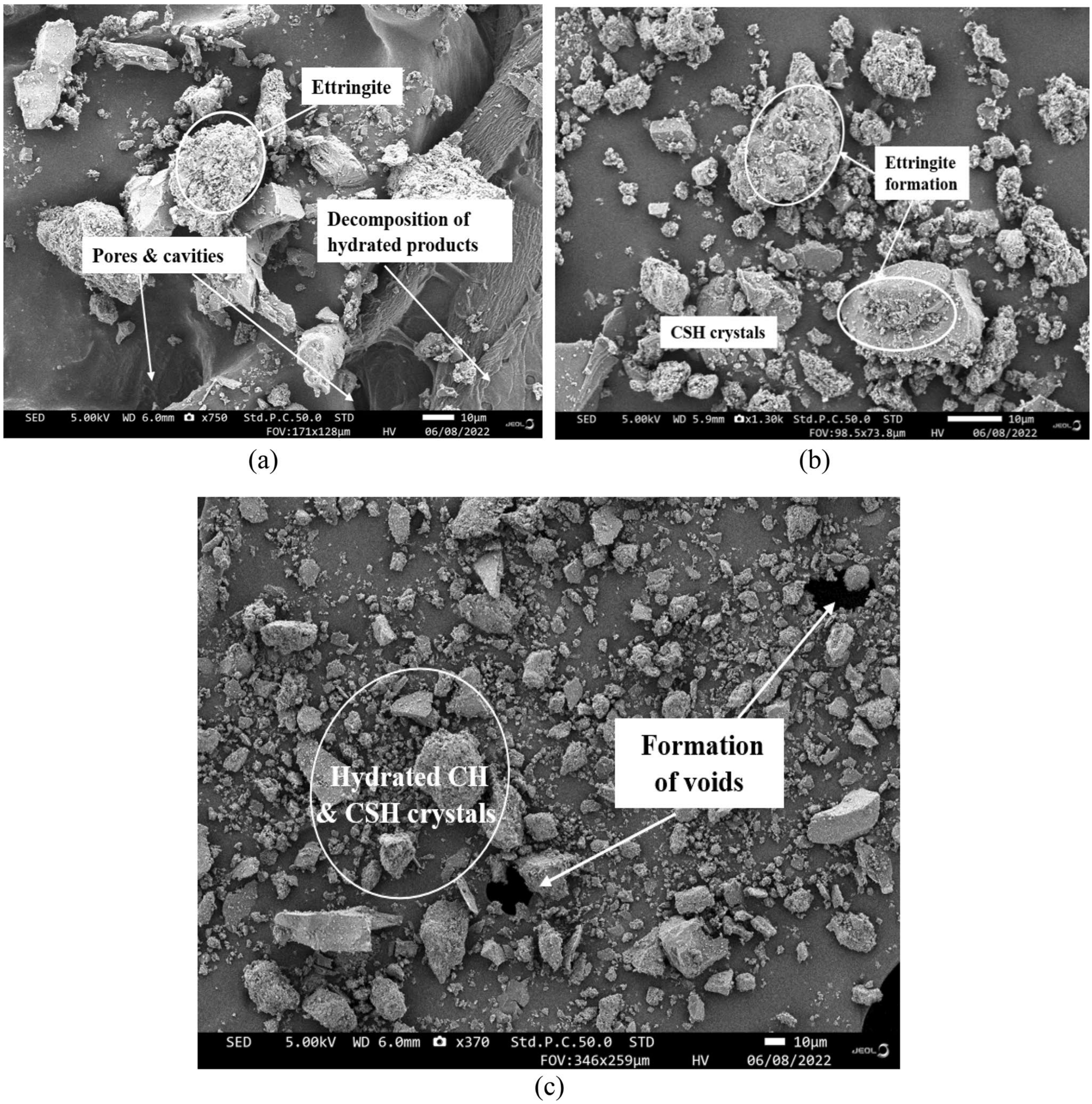


Fig. 15 SEM analysis of various concrete mixes after exposure of 800 °C **a** control mix **b** RAC mix **c** R33-CS20 mix

silicate hydrate (CSH) gel and the evaporation of free water weakened the chemical by forming the pores and micro-cracks inside the mix; as a result, strength loss was maximized at higher temperature. Figure 11a, b showed the cross section of the failure specimen at flexure before and after subjected to elevated temperature. Maximum number of pores and voids were developed when the specimens were exposed to higher temperature than the specimens at ambient condition. However, from Fig. 11, it was evident that the colour of the matrix was changed after being exposed to high temperatures, which indicated both physical and chemical changes to the paste.

3.2 Mass Loss

The mass loss of concrete sample of various mixtures was examined by taking weight before and after exposed to elevated temperature to determine the amount of water evaporated and pore structure deterioration. Figure 12 illustrates the mass loss of various concrete mixes at different exposed temperatures where the mass loss for all mixes has been found to be increasing with rise in temperature. From Fig. 12 it has been observed that at any given temperature the mass loss of RAC mixes is higher than that of the control specimen which is due to higher water absorbing capacity as well as greater adhered mortar surrounding the RCA surface. The rate of mass loss of RAC mixes became higher from 400 to 800 °C due to heavy water loss and rapid decomposition of hydrated products which ultimate reduced the strength of concrete. However, when compared to the control mix at various temperature conditions, the mass loss of RAC mixes decreased with an increase in CS concentration. For instance, by adding 40% CS as a substitution of fine aggregate to the RAC the reduction of mass loss was about 10%, 20%, 16% and 11%, respectively, over control and RAC mix at the temperature's ranges from 200 to 800 °C. The findings emphasized the advantages of CS on mass detainment of RAC under high exposure conditions. The smooth glassy texture of copper slag could reduce the stress induced at aggregate–binder interface and consequently decreased the frequency of microcracks and voids close to the aggregates. This made the concrete became more temperature resistant.

3.3 Ultra-Sonic Pulse Velocity Test (UPV)

The results of UPV of different concrete mixtures including control mix after being exposed to given temperature are presented graphically in Fig. 13. The tendency of decreasing UPV values in concrete mixes with rising temperatures is similar to that of improving compressive strength. This is because at higher temperature the relative density of concrete specimens becomes low and cracks were more pronounced (Salahuddin et al. 2019). However, with the addition of CS to RAC mix the UPV values increased significantly at higher temperature as compared to control concrete and RAC mix. It was increased up to 16% and 21% with the addition of 20% and 40% CS, respectively, over control concrete at the temperature up to 400 °C. The increased value of UPV is due to the higher density of CS than that of NFA. However, the temperature beyond 400 °C the UPV values remains decreased due to the increased porosity of CS aggregates and lower density of RCA than that of NCA (Table 1). According to IS: 1331–1992 part-1(IS 13311 (Part 1), 1992) the qualities of all the concrete mixes were found excellent (> 4500 m/s) at ambient temperature condition whereas the quality of concrete changes to good when exposed to higher temperature up to 400 °C and above 600 °C the quality of concrete became reduced (< 3000 m/s).

3.4 Microstructural Analysis

3.4.1 SEM Analysis

The morphology of control mix and RAC mixes was studied through SEM analysis before and after exposure of elevated temperature. In order to understand the microstructural alterations in the matrix before and after exposure of elevated temperature, comparisons were made between control and RAC mixes. The SEM analysis of control mix, R33 mix and R33 CS-20 mix at ambient temperature condition is shown in Fig. 14a–c. SEM image of control mix (Fig. 14a) indicates the appearance of micro-cracks in the paste and the un-hydrated crystals such as CSH and CH are dispersed inside the sample in a well-defined manner. From Fig. 14b, it was observed that the concrete paste exhibited a relatively less compact and crystalline microstructure in comparison with the control mix. The presence of voids in the paste indicates the higher porosity of RCA which led to lower the thermal conductivity of RAC than that of control mix (Laneyrie et al. 2016). The micrograph of R33-CS20 exhibited a dense and crystalline microstructure than that of control mix (Fig. 14c). The hydrated products were adequately spread over the matrix and created a strong connection with the aggregates. Some microcracks and the formation of needle-shaped structures were observed in the micrograph. The SEM analysis of control mix, RAC mix and R33-CS20 mix exposed to elevated temperature of 800 °C is presented from Fig. 15a–c. At the higher temperature, the decomposition of hydration products was more pronounced as shown in Fig. 15a, b. The voids and cracks are more prominent as the evaporation of free water reduced the mechanical strength of the mix [G.F Peng]. The morphology of R33-CS20 shown in Fig. 15c exhibited comparatively less voids and cracks in comparison with control and R33 mix. This might result from CS's poorer thermal expansion characteristics than NFA. In addition, as CS absorbs water at a slower rate than NFA, mixes containing CS enhanced the adhesion capacity of mortar to recycled aggregate surfaces and improved the performance of ITZ which led to a strong link between the mortar and aggregate. The results proved the increased compressive and tensile strengths of R33-CS20 mix over control mix at higher temperature.

3.4.2 EDAX Analysis

EDAX analysis was performed on cement matrix of crushed concrete sample after exposed to room and elevated temperature. EDAX was carried out by applying a gold coating to the specimens and X-ray radiation was continuously focused on the specific area of the specimens to determine the elemental compositions. The peaks of the elements are shown on the ordinate of the micrograph by the specific spot of the samples observed from the EDAX spectroscopy. The elemental compositions of control, R33 and R33-CS20 mixtures before exposure to higher temperature are presented from Fig. 16a–c. The major elements found in EDAX spectroscopy are O, K, Na, Fe, Mg, Ca, Si, Al, and S. The presence of Ca and Si in the mixtures confirmed the development of CSH gel. Figure 16a shows a significant peak of Si compared to Ca. Figure 16a shows a significant peak of Si compared to Ca, since the control concrete is made entirely of sand that is high in silica. However, peaks of Ca and Si confirmed the accumulation of C–S–H gel in R33 mix as shown in Fig. 16b. Peaks of Al and S also provided additional evidence that calcium alumino-sulphates were developed in RAC mix and the formation of ettringite. As observed from Fig. 16c, at 20% CS substitution in RAC mix, the peak of Ca was higher than Si with the formation of dense homogeneous CSH layer than that of control mix. The peak intensity of Fe in the EDAX attributed to the presence of iron in significant amounts in the composition of CS.

The EDAX analysis of control mix, RCA mix and R33-CS20 mix after exposure of 800 °C temperature is presented from Fig. 17a–c. The common elemental peaks observed in the micrograph were O, K, Mg, Al, Fe, Ca, Si and L. From Fig. 17a, b, it was observed that at higher temperature the peaks of Ca and Si were at same level as compared to the peaks of Ca and Si observed at room temperature which confirmed the accumulation of dense and compact C–S–H crystals which was decomposed rapidly due to the vaporization of free water. The presence of Al also confirmed the formation of ettringite in the matrix. Further, with the incorporation of CS in RAC mix (R33-CS20), the peak of Ca was increased and higher than Si as shown in Fig. 17c with respect to the room temperature. The development of CSH gel in the mixture was further validated by the presence of Si and Ca.

4 Statistical Modelling

To assess the statistical relation between different properties of CS blended RAC, linear regression analysis was employed on experimental data by considering the effect of temperature ranging from 30 to 800 °C.

4.1 Statistical Relation Between Compressive Strength and Split-Tensile Strength

The regression technique used to estimate split-tensile strength of different mixtures using compressive strength results at different temperature exposures is shown in Fig. 18. The correlation between split-tensile and compressive strength as observed from Fig. 18 was

$$y = 0.47\sqrt{\mathrm{CS}} \quad (1)$$

where y = split tensile strength (STS), and CS is the compressive strength of CS blended RAC.

From Eq. (2), it is indicated that a strong direct correlation was established between the split-tensile and compressive strengths of CS blended RAC with correlation coefficient 0.978.

4.2 Statistical Relation Between Compressive Strength and UPV

Figure 19 showed the relationship between the compressive strength and UPV of different concrete mixes at different temperature exposures. A linear correlation was observed between compressive strength and UPV, with a regression coefficient of 0.80 and the equation formed for predicting the UPV of CS blended RAC is given by

$$y = 119.12x - 558.7 \quad (2)$$

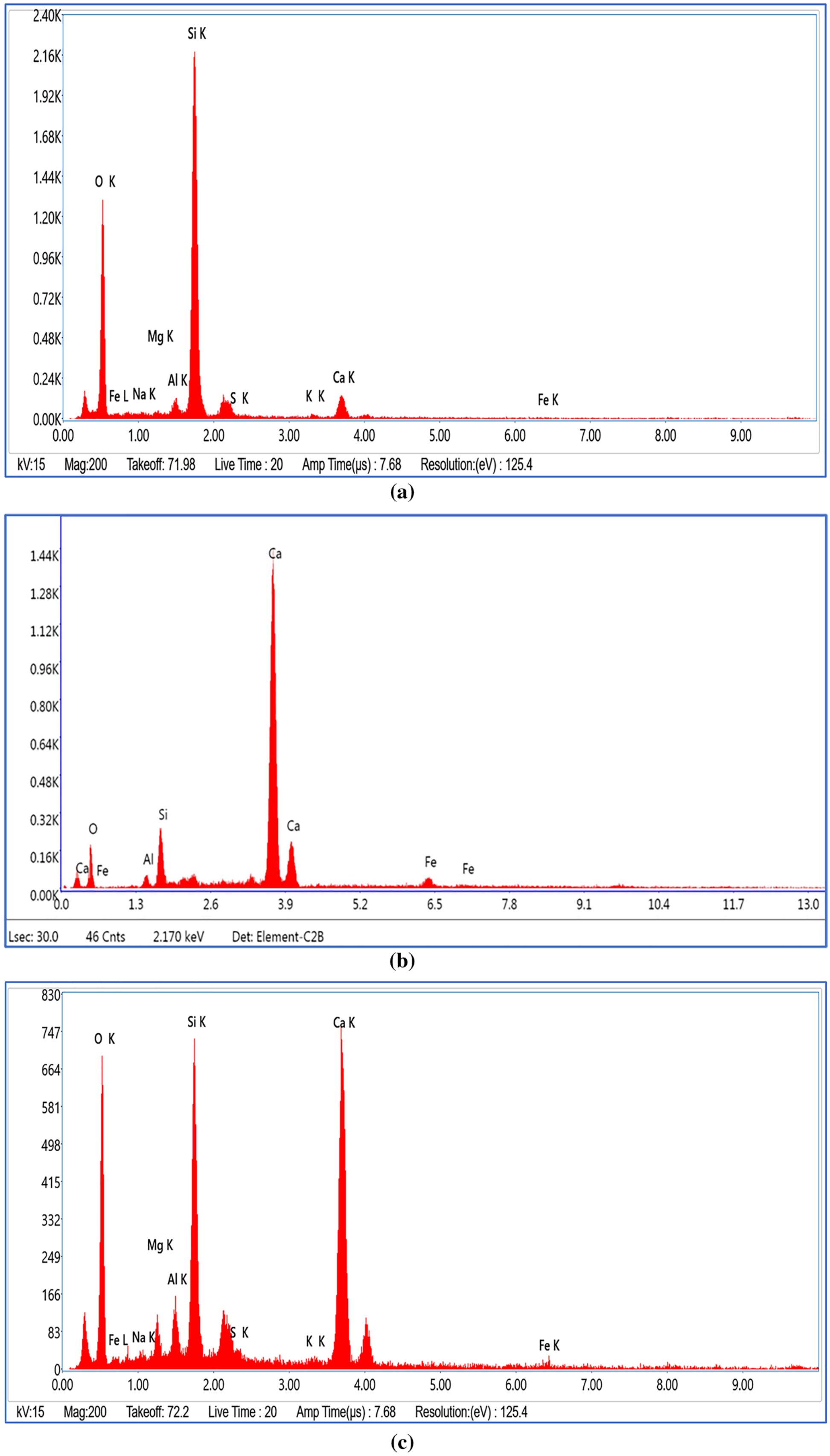
Equation (2) indicated that the UPV values of all mixes were decreased with the decrease in compressive strength which validated the experimental result so obtained.

5 Conclusion

The present study evaluated the impact of using copper slag as a fine aggregate on the characteristics of RAC at elevated temperatures. Furthermore, mechanical and microstructural behaviour of various concrete mixtures before and after exposure of different temperatures was assessed. The main conclusions of the study are;

1. The residual mechanical qualities of the concrete mixtures were deteriorated with the increased temperature due to the chemical decomposition of hydrated products resulting cracks and voids in the concrete matrix.
2. The rate of deterioration of mechanical properties of RAC was decreased by adding up to 40% copper slag as a replacement of fine aggregate at any given temperature due to its lower water absorption and thermal expansion properties than NFA.
3. In comparison with RAC and control mix, CS blended with 33% RCA maintained a higher residual compressive and split-tensile strength. The mix R33-CS20 attained

Fig. 16 **a** EDAX analysis of control mix at room temperature. **b** EDAX analysis of R33 mix at room temperature. **c** EDAX analysis of R33-CS20 at room temperature



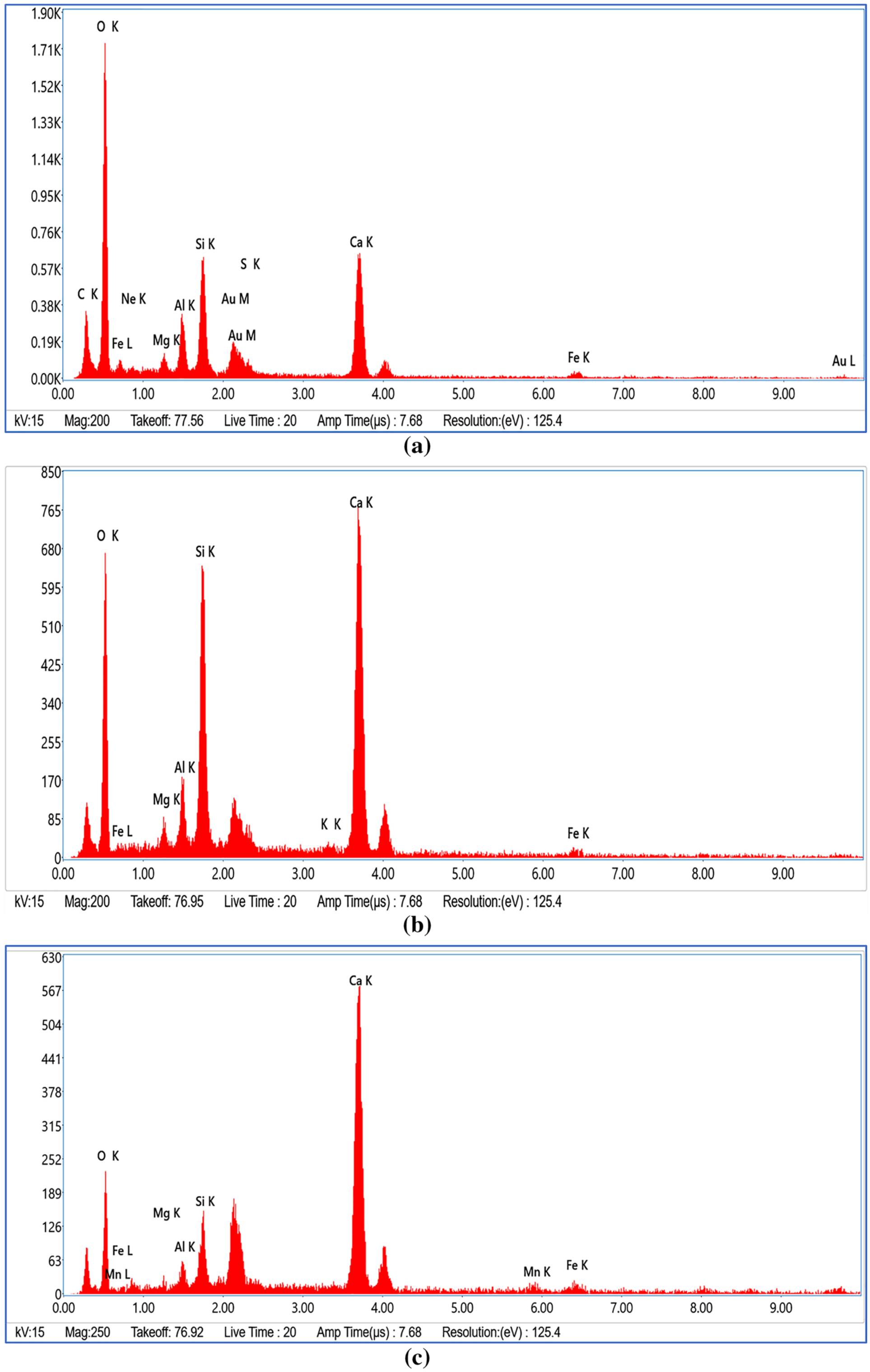


Fig. 17 **a** EDAX analysis of control mix after exposure of 800 °C. **b** EDAX analysis of R33 mix after exposure of 800 °C. **c** EDAX analysis of R33-CS20 mix after exposure of 800 °C

the highest compressive (up to 13%) and tensile (up to 25%) strength over the control mix.

4. The recycled aggregate concrete made with 33% RCA and 20% CS attained the maximum compressive, tensile, and flexural strength properties at the temperature exposure up to 800 °C.
5. Inclusion of CS reduced the mass loss of RAC up to 20% at over control mix because of lower thermal expansion qualities of CS than NFA.

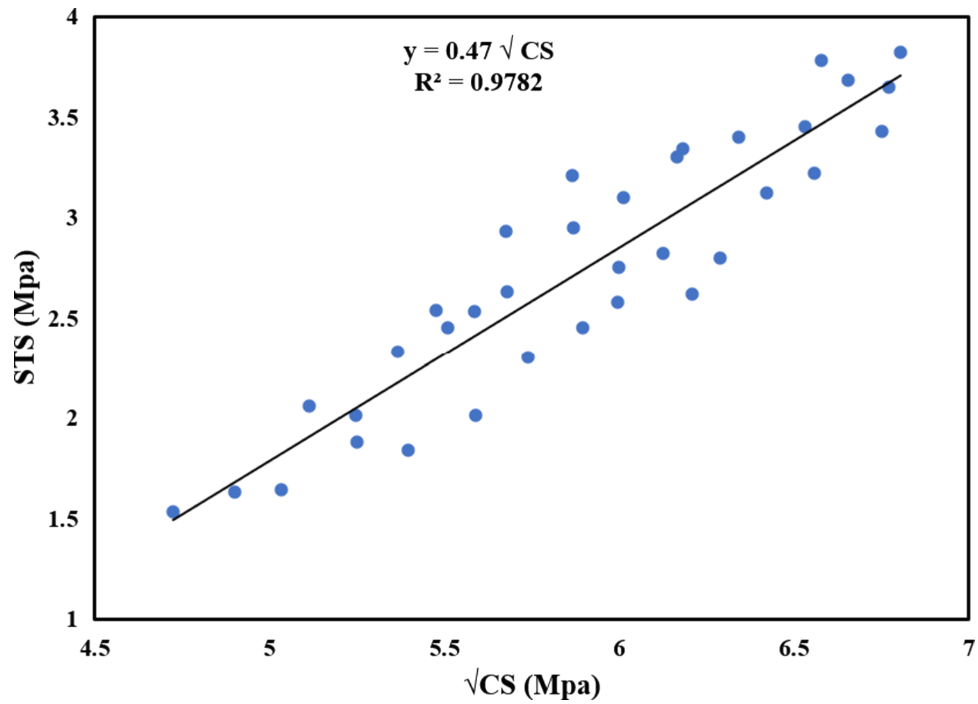


Fig. 18 Regression analysis of compressive and split tensile strength

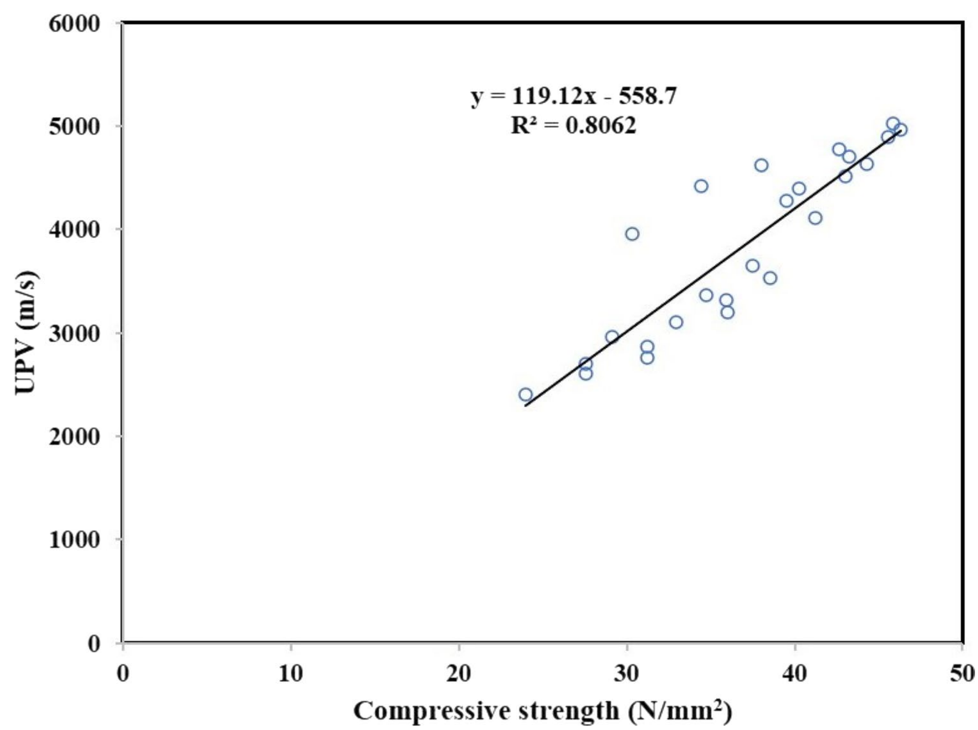


Fig. 19 Regression analysis of compressive strength and UPV

6. Results of UPV test exhibited similar trend of variation to that of compressive strength at elevated temperatures with regression coefficient of 0.80. The quality of hardened concrete improved up to 16% and 32%, respectively, over the control and RAC mix (R33) when CS up to 20% was used as fine aggregate.
7. According to the SEM analysis, the CS blended RAC mix formed a comparatively strong bond between aggregate and matrix than control mix. Incorporation of CS up to

40% reduced the formation of voids within the matrix and improved its strength at elevated temperatures.
8. The primary peaks of Ca, Si, and O were seen in the EDAX analysis of the control, RAC, and CS mixes, which confirmed the existence of CSH gel in the paste. The presence of sulphur and aluminium in the mix confirmed the production of ettringite in the RAC and control mixes.

In general, the addition of copper slag up to 40% as a replacement of fine aggregate improved the mechanical performance of RAC which established the greater fire resistant to concrete. Additionally, the present study promotes the sustainable development in the construction industry by using these waste materials as a replacement of virgin materials to protect the natural resources and minimizes environmental and waste disposal challenges. Additionally, more experimental research may be conducted by replacing cement with suitable mineral admixtures to the CS-based recycled aggregate concrete to improve mechanical and durability properties of RAC. Further, the economic and environmental benefit of concrete containing RCA and CS may be investigated.

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Declarations

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