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Thermal studies on recycled aggregate concrete modified with carbonated and bio-deposited recycled aggregates

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Abstract

Several research studies have been conducted to investigate the hardened and durability characteristics of the normal aggregate concrete (NAC) and recycled aggregate concrete (RAC). Similarly, few studies have been done to examine the thermal behaviour of the NAC and RAC. However, the influence of elevated temperature on the RAC with treated recycled coarse aggregate (RCA) in the concrete still needs to be investigated. This study presents the comparative discussion on the thermal performance of NAC, RAC, carbonated recycled aggregate concrete (CRAC) and bio-deposited recycled aggregate concrete (BRAC) at various elevated temperatures of 25, 200, 500 and 800°C. The investigation involves the determination of residual compressive strength, tensile strength, elastic modulus and thermal conductivity with a series of concrete mixtures under elevated temperatures. The optimal residual strength was observed at 500°C, beyond exposure of it causes a reduction in the strength. The residual strength of NAC, RAC, CRAC and BRAC at optimal temperature was reduced by 30.10%, 7.06%, and 31.02%. The equivalence of the thermal expansion coefficient of RCA with cement paste improves the residual response of RAC, and higher porosity of RCA decreases the thermal conductivity of the RAC by 43.06% compared to control concrete. Furthermore, no concrete samples crumbled at 800°C, but the residual properties tend to decrease for all mixes.

Keywords: Recycled aggregate, Carbonation, Bio-deposition, Elevated temperature, Residual strength

1. Introduction

The construction and demolition (C&D) wastes are the result of the demolition of old buildings, retrofitting and repairing works in the construction [1]. The quantity of C&D waste generation increases, resulting in dumping in landfill and thus creating disposal problems. Meanwhile, the requirement for aggregates in concrete construction is increasingly alarming the scarcity of resources and in search for suitable alternative materials. The constituents of C&D wastes include concrete, steel, brick, tiles, wood etc., among which recycling the concrete fractions to aggregates will be a viable solution to the aforementioned problem. This approach would resolve the disposal problems, conserve the natural resource and overcome the scarcity problems in the construction.

Aggregates are the inert component that comprises nearly 70% of the concrete volume. The thermal characteristics of the concrete mostly rely on the aggregate behaviour when exposed to elevated temperatures [2]. The aggregates rich in silica, such as gravel, sand and quartzite, exhibit strength loss even at 300°C and becomes crystalline at 500°C resulting in significant volume change. This significant volumetric change of silica-rich aggregates deteriorates the concrete upon its usage when subjected to elevated temperature [2]. The concrete deteriorates upon exposure to an elevated temperature due to variations in the thermal characteristics of cement paste with RCA. This induces stresses in the interfacial transition zone (ITZ), resulting in cracking in the RAC. Therefore, choosing less siliceous aggregates is essential to ensure thermal stability even at higher temperatures.

Extensive research has been carried out with the river gravel on the thermal behaviour of the concrete. In addition, few researches have been carried out with fine and coarse recycled aggregate in the concrete and have significant interest worldwide. This research infers that the coefficient of thermal expansion of adhered mortar on recycled coarse aggregate (RCA) is equivalent to cement paste resulting in better thermal resistance in RAC than NAC. Sarhat and Sherwood [2] exposed NAC and RAC to the elevated temperature of 250, 500 and 750°C and observed no disintegration till 750°C and better response was observed with RAC as the factor of thermal expansion of cement paste is equivalent to adhered mortar on the RCA. Zhu et al. [3] investigated the thermal conductivity of RAC and RAC blocks with RCA and waste brick slag and observed that thermal conductivity decreases with increased RCA content and decreased RCA density. Laneyrie et al. [4] exposed normal and high-performance RAC with industrial and laboratory RCA to 750°C and observed higher mass loss in RAC due to its higher moisture content and exhibited 20% lesser thermal conductivity than conventional concrete. The study also suggested that pre-treatment to RCA, either to remove or coat the adhered mortar, might improve

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the thermal performance of RAC. Khaliq and Taimur [5] exposed normal and high strength concrete with RCA to elevated temperatures ranging from 23°C to 800°C and observed an 11% reduction in the strength than NAC and strength retention at a residual temperature between 200°C and 600°C. It is also observed that there is a 16% higher strain in RAC than NAC owing to its ductile nature resulting from increased temperature and micro-structure cracking. Salahuddin et al. [6] replaced 20% of cement with glass powder, rice husk ash and marble powder for the mix with 100% of RCA and subjected to raised temperatures of 25°C, 200°C, 400°C and 600°C. The study reported no spalling of RAC when bare to elevated temperature, and the residual strength was equivalent to control concrete at elevated temperature. Wang et al. [7] exposed RAC with both fine and coarse RCA to elevated temperature and observed a residual temperature of 400°C with a decrease in strength of 26%; however, when exposed to 800°C, the strength was reduced by 72%. The dehydration of cement paste and crack formation due to the variance in the thermal expansion of cement paste and RCA causes a reduction in strength. Similarly, Zhao et al. 2020 [8] investigated the failure of RAC upon exposure to raised temperature and observed diagonal crack formation till 600°C; however, diagonal cracks were not predominant, but vertical cracks were significant in the middle at 800°C. The reduction in the strength was up to 87% at 800°C, but the strength reduction was minimal within the temperature range between 200°C to 400°C. Silva et al. [9] compared the thermal characteristics of normal and high-strength RAC at elevated temperature and observed a 48.5% and 47.3% decrease in strength for normal and high-strength RAC upon exposure to 650°C; however, the strength tend to increase by 14.6% and 3.98% upon exposure to 150°C owing to the stimulation of anhydrous cement particles in the concrete mixture. Kazmi et al. [10] exposed the pre-treated RCA to elevated temperature and inferred that the thermal conductivity of RAC is 27% lesser than NAC; however, pre-treated RAC showed a further decrease in thermal conductivity. The pre-treatment techniques tend to reduce the pore size, which is integral for thermal conductivity, and eventually, it reduces the mixes with pre-treated RCA. Chen et al. [11] studied the fracture behaviour of RAC exposed to elevated temperature and observed that initial fracture toughness and unstable fracture toughness of RAC reduces with rise in the elevated temperature and remain residual in the temperature range of 200°C to 300°C. Correspondingly, the ductility of RAC was inferior compared to NAC. Zhao et al. [12] exposed RAC slabs to elevated temperature for 90 mins, observed that an increase in RCA decreases the temperature in slabs, and found that the temperature at ribs is much lower than soffit. Feng et al. [13] used sea water (SW) and sea-sand (SS) to manufacture RAC and observed that use of SWSS reduced the flowability compared to NAC and RAC. The strength of SWSSRAC is higher compared to RAC but lower than NAC at longer curing periods. Wardeh et al. [14] observed that more visible cracks are observed in RAC than NAC upon loading, however the cracks opening is of same magnitude for both NAC and RAC. Also, the shear strength of RAC was less compared to NAC. Akkouri et al. [15] investigated the thermophysical characteristics with PET as fine aggregate and observed that optimizing mix with 20% of PET reduced thermal conductivity by 46.81% and thermal diffusivity by 27.34%. The workability increased to 370 mm with addition of PET and the strength tend to decrease. Amin et al. [16] exposed RAC with hybridized carbon nanofiber and steel fiber with RCA and observed that use of 0.5% of carbon nanofiber with 50% of RCA show strength enhancement by 8% and highest strength of 172 MPa was achieved with 2% of steel fiber. Arafa et al. [17] impregnated RAC with 0, 30, 60 and 100% of RCA in Mg_2SO_4 and observed that the strength was reduced by 11%, 21%, 20% and 21% with 6% of Mg_2SO_4 and 13%, 22%, 23% and 24% with 6% of Mg_2SO_4 at 28 days compared to CC. The review of a series of literature indicates a better response of RAC to elevated temperature owing to the equivalent coefficient of thermal expansion of cement mortar with RCA, however to the author's knowledge, the response of pre-treated RCA on the thermal behaviour of RAC has not been studied diversely yet. Also, volume change due to differences in temperature induce stresses and cracks in RAC. Such phenomenon necessitated the investigation on the behavior of RAC under various elevated temperatures. Conversely, the poor quality of RCA reduced its use in real-time applications and thus researches focus on pre-treatment to RCA. This research focuses on the pre-treatment of RCA with microbes and carbonation and the investigation of the bio-deposited RCA (BRCA) and carbonated RCA (CRCA) on the thermal behaviour of the RAC upon exposure to elevated temperature.

2. Materials and methods

2.1 Raw materials

Ordinary portland cement (Type I) with equivalent properties as specified in ASTM C-150 [18] was used. Table 1 shows the physical properties of the cement. The river sand equivalent to 2.36 mm size and river gravel equivalent to 10 mm and 20 mm sizes was used as natural fine aggregate (NFA) and natural coarse aggregate (NCA) in the concrete. In addition, recycled coarse aggregate (RCA) derived from the concrete fractions of the demolished buildings with a size equivalent to NCA, was used. The NCA was replaced with 30%, 50% and 100% of RCA by its volume. All these aggregates were surface saturated prior to their usage in concrete mix to ensure better workability. The NCA and RCA gradation curves are shown in Figure 1, and an equivalent gradient was observed to ensure effective packing. The visual and micrographs of the RCA are shown in Figure 2. The visual and micrographs evident the smearance of cement particles on the RCA. The XRD composition of the RCA is shown in Figure 3, wherein the calcite compound is predominant rather than silica owing to the adhered mortar on the RCA.

Table 1 Physical properties of cement

Properties	Obtained values
Initial setting time (mins)	28
Final setting time (mins)	540
Specific surface (m^2/kg)	270
Consistency (%)	28

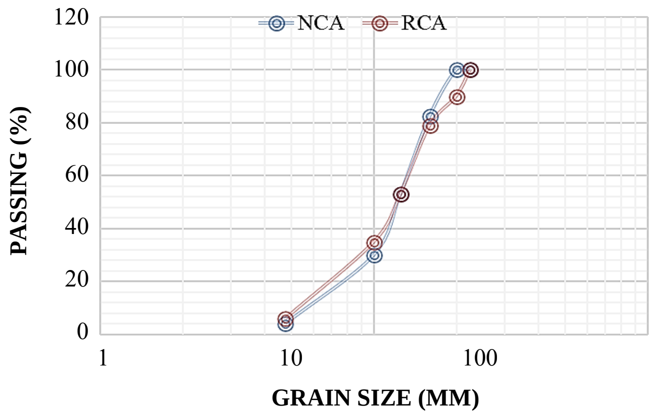
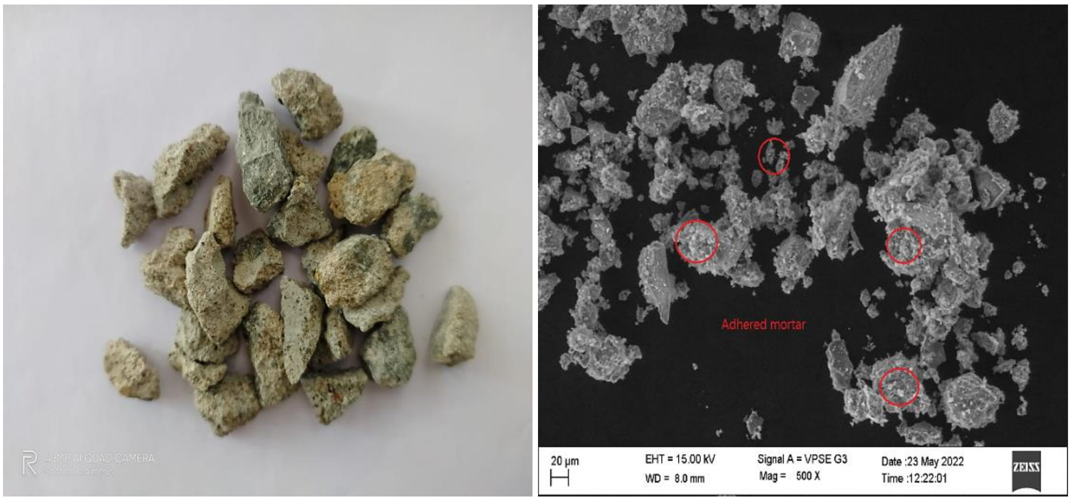


Figure 1 Gradation curves



(a) (b)

Figure 2 RCA (a) Visual (b) Micrograph

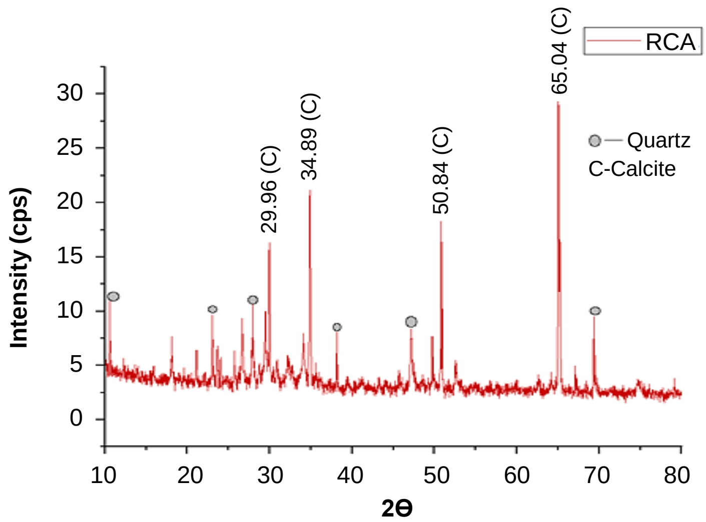


Figure 3 XRD of RCA

2.2 Treatments to RCA

The strains of *Bacillus subtilis* were obtained and cultured in an Agar Medium consisting of 0.5% peptone, 0.3% beef extract and 0.5% NaCl. To prepare the agar medium, 30 g of agar concentrate was dissolved in 1000 ml of distilled water. The mixture is heated during stirring to allow the complete dissolution of the agar precipitate. It is then autoclaved at 120°C for 15 minutes and cooled. The cooled mixture is then transferred to Petri plates and kept undisturbed to congeal. The strains of *Bacillus subtilis* were added along agar medium, incubated at 37°C and shaken at 175 rpm for 48 hours [19, 20]. The grown culture is diluted and spread out on agar plates to calculate the cell count and obtained 7 x 10^5 cells/ml. Figure 4 shows the culture solution of *Bacillus Subtilis*, which is used for bio-deposition treatment.

Figure 4 Culture solution of *Bacillus Subtilis*

The bio-deposition to RCA was performed under laboratory conditions, wherein the collected RCA was surface saturated and air-dried to reach SSD condition. It is then saturated in the cultured solution for 24 hours. The RCA was removed from the cultured solution and immersed in the bio-deposition medium for 72 hours. After 72 hours, the RCA was removed, surface washed and dried at room temperature to produce bio-deposited recycled coarse aggregate (BRCA).

In carbonation treatment, the RCA was treated with locally available CO_2 (99.5% purity) in the fabricated carbonation set up at 20°C with an R.H. of 60%, as shown in Figure 5. The carbonation chamber with RCA was subjected to 0.4 MPa pressure for 24 hours. It is then allowed to cool at room temperature and used as carbonated recycled coarse aggregate (CRCA) [21, 22].

Figure 5 Carbonation treatment to RCA

2.3 Material properties

The collected aggregates were tested for their physical properties [23], and the results are given in Table 2. It could be inferred that the RCA properties was inferior compared to NCA. The increased perviousness of RCA ensuing from the adhered mortar is the predominant factor affecting the RCA quality [24, 25], as it could be well reflected with 86% higher water absorption in RCA compared to NCA. Also, the adherence of mortar in the RCA reduces the specific gravity of RCA by 13.5% and increases the crushing index by 19.10% compared to NCA. So, the RCA was treated with microbes and CO_2 to produce BRCA and CRCA. It could be observed that the water absorption of BRCA was 75.38% less compared to RCA, and the specific gravity of BRCA was enhanced by 4.8% compared to RCA. The microbial treatment to RCA induces the $CaCO_3$ precipitation through interaction with $Ca(OH)_2$ on the RCA [19, 20]. The precipitated calcium carbonate seals up the porous surface of RCA and improves its properties. The specific gravity of CRCA was enhanced by 5.92%, and the water absorption of CRCA was decreased by 79.12% when compared with RCA. A similar mechanism of $CaCO_3$ production was observed in the carbonation treatment, and that seals the RCA pores and improves its properties [21, 22]. However, in all cases, RCA, BRCA and CRCA properties were inferior compared to NCA.

Table 2 Properties of aggregates

S. No	Properties	Aggregates			
		NCA	RCA	BRCA	CRCA
1	Specific Gravity	2.71	2.38	2.50	2.53
2	Water absorption (%)	1.13	6.42	1.58	1.34
3	Crushing index (%)	20.40	25.24	22.14	21.73

2.4 Concrete mixture

A total of six different concrete mixes with NCA, RCA, BRCA and CRCA were manufactured, and details of the mix are shown in Table 3. Mix 1 was prepared with 100% of NCA to achieve a target strength of M30 grade concrete, mixes 2, 3 and 4 were prepared with 30%, 50% and 100% of RCA, mix 5 was prepared with 100% of BRCA and mix 6 was prepared with 100% of CRCA. Mix 1 was chosen as a reference mix to evaluate the thermal characteristics of the RAC upon exposure to elevated temperature. The concrete mix proportions are determined as per IS 102626 (2009), with a w/c ratio of 0.45. For each mix, 48 cylinders were cast to evaluate the residual properties at the corresponding curing period. The cast cylinders were set for 24 hours at room temperature. The specimens were then demoulded and cured at room temperature for 28 days and were tested at 28 days to evaluate the concrete response to elevated temperature.

Table 3 Concrete mix proportions

Mix ID	Mix combination	(Kg/m^3)					
		Cement	NFA	NCA	RCA	BRCA	CRCA
Mix 1	R-0	413	799	1029	-	-	-
Mix 2	R-30	413	799	720.3	308.7	-	-
Mix 3	R-50	413	799	514.5	514.5	-	-
Mix 4	R-100	413	799	-	1029	-	-
Mix 5	BR-100	413	799	-	-	1029	-
Mix 6	CR-100	413	799	-	-	-	1029

2.5 Concrete testing

After curing, the concrete specimens were exposed to 25, 200, 500 and 800°C elevated temperatures for 1 hour and allowed to cool under laboratory temperature (Figure 6). The fluctuations in the temperature were measured with thermocouples provided in the middle of the furnace. A 2000 kN capacity UTM was used to evaluate the residual mechanical properties such as compressive strength (CST), tensile strength (TST) and static elastic modulus (SM) as per ASTM standards. The cylinders were axially loaded at 0.2 MP/s for CST, and the cylinders were loaded in the transverse direction at 0.05 MPa/s for TST. To determine SM, two LVDTs are attached to both sides of the cylinder, and the specimens are loaded at a rate of 0.2 MP/s. The relationship between stress and stress was plotted digitally, and the secant elastic modulus was determined. The thermal conductivity of concrete was determined with a thermal conductivity meter [15, 26]. After 28 days of curing, the cylinders were dried in a hot air oven at 50°C and allowed to cool down to a room temperature of 25°C [2]. The top and bottom surfaces of the specimens were cleaned and smoothened, a voltage difference of 1V was applied, and the thermal conductivity of the RAC was measured. The results of all tests were validated with the average of three specimens.

Figure 6 Specimens subjected to elevated temperature

3. Results and discussions

3.1 Density

The variation in the properties of the control mixes (M1 to M6) at 25°C significantly shows the decrease in the mechanical properties owing to an increase in the replacement of RCA. Figure 7 shows the variation in the densities of the RAC upon exposure to room temperature. It is found that increase in the RCA reduces the density of the RAC. The density of R-30, R-50 and R-50 mixes was reduced by 7.05%, 11.05% and 15.68%. The reduction in the density is attributed to the incidence of adhered mortar on it [24, 25]. However, the density of BR-100 and CR-100 was 6% and 7% more compared to R-0 owing to the treatments to densify the micro-pores in the adhered mortar with $CaCO_3$ on the RCA.

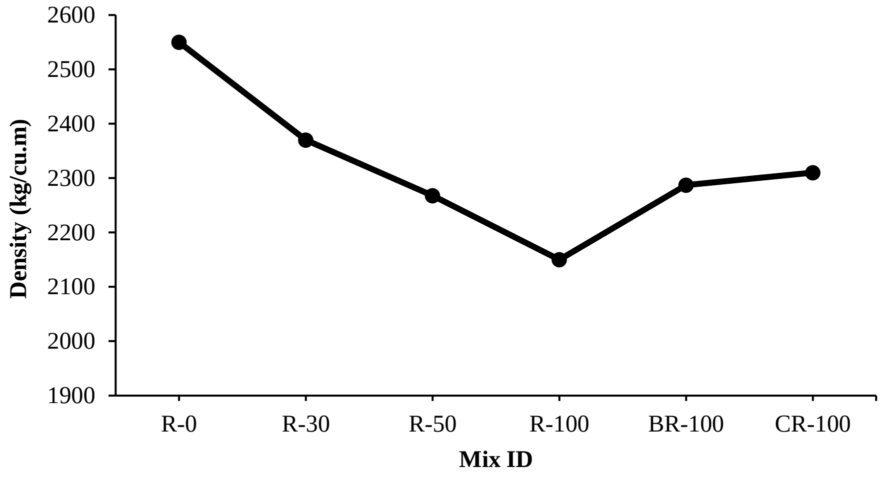


Figure 7 Density of the mix at room temperature

3.2 Compressive strength

Figure 8 shows the variation in the CST of the RAC upon exposure to room temperature. The replacement of RCA was optimized to 30%, beyond which it causes decreases in the mechanical properties. The CST of R-50 and R-100 was reduced by 10.32% and 17.87% compared to R-0. Similarly, the TST of R-50 and R-100 was reduced by 4.32% and 7.49% compared to R-0, and the SM of R-50 and R-100 was 5.29% and 9.37% lower than R-0 at 28 days. The reduction in the mechanical properties is due to the smearance of cement particles in the RCA that weakens the interfacial zone in the concrete [24, 25]. However, the CST of BR-100 and CR-100 was reduced by only 3.34% and 2.01%; the TST of BR-100 and CR-100 was reduced by only 1.34% and 0.81%, and the SM of BR-100 and CR-100 was reduced by 1.68% and 1.04% compared to R-0 at 28 days. Through bio-deposition and carbonation, the $CaCO_3$ deposits on the RCA surface, improving the quality of RCA, and thus, the strength improvement in RAC was observed [25, 27]. It is well known that NAC possesses one ITZ between the cement matrix and NCA that acts as an efficient zone of load transfer. The RAC possess two ITZ owing to the smearance of the cement mortar attached to it. The first ITZ is amid RCA and the new matrix (strong link), and the second ITZ is between the old mortar attached to RCA and the newly prepared mortar (weak link). During loading, the weakest link exhibits increased crack formation from the weak mortar adhered to the RCA. However, bio-deposition and carbonation treatment to RCA stiffens the weak mortar in the latter ITZ and improves the strength of the RAC [28, 29].

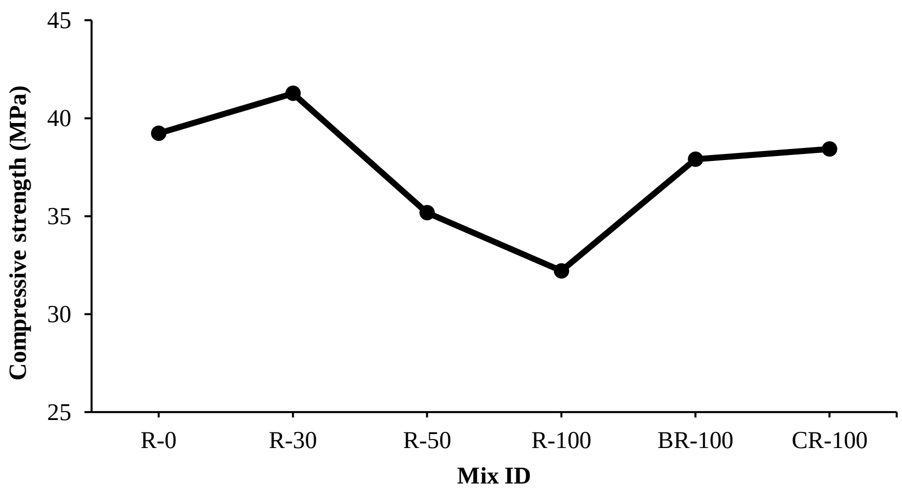


Figure 8 Compressive strength of the mix at room temperature

The behaviour of the concrete mix after exposed to elevated temperature is characterized by the residual CST, TST and SM at certain ages. Figure 9 shows the variation in the CST of the mixes upon exposure to elevated temperature. It is inferred that the strength of the mixes was reduced with the rise in the elevated temperature. The percentage decrease in the CST was more in NAC than RAC and similar trends were observed in the TST and SM. The residual compressive strength with RCA was achieved between 200°C to 500°C. The decrease in CST of R-0 at 200°C, 500°C and 800°C was 19.12%, 30.01% and 64.02%, whereas the decrease in the CST of R-100 at 200°C, 500°C and 800°C was 16.14%, 7.76% and 49.98%. It could be observed that the minimum decrease in the CST was observed with R-100 than R-0 upon exposure to elevated temperature. Also, the drop in the compressive strength was minimum in R-100 mixture between 200°C to 500°C ensuing the residual temperature range. The improvement in the thermal behaviour of RAC at elevated temperature is ascribed to the equivalent coefficient of thermal expansion of adhered mortar on the RCA with the new cement paste [2, 6, 8]. However, the decrease in the CST of BR-100 at 200°C, 500°C and 800°C was 18.06%, 31.02% and 64.15% and decrease in the CST of CR-100 at 200°C, 500°C and 800°C was 18.60%, 29.63%, 63.51%. The bio-deposition treatment and carbonation treatment to RCA does not show any significant enhancement in the thermal characteristics of the RAC. The treatment methods tend to coat the adhered mortar with $CaCO_3$ that eventually affects the equivalency of coefficient of thermal expansion amid the RCA and new cement paste [9, 10].

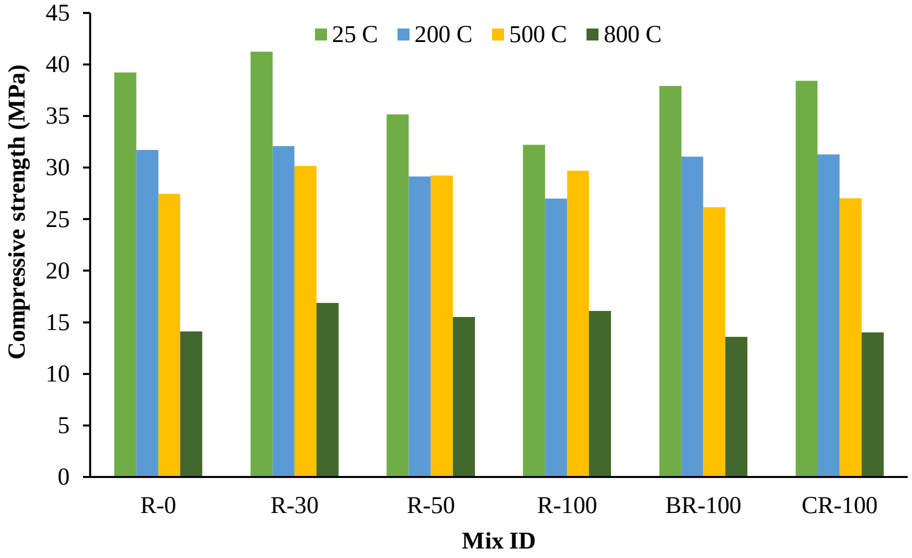


Figure 9 Compressive strength of the concrete mix at elevated temperature

3.3 Tensile strength

Figure 10 shows the variation in the TST of the mixes upon exposure to elevated temperature. The trend of variation in the TST is equivalent to the CST; however, the percentage of variation in the TST differs from the CST. The decrease in TST is minimum compared to CST at elevated temperatures. The decrease in the TST of R-0 at 200°C, 500°C and 800°C was 8.13%, 13.30% and 33.54%, and the decrease in the TST of R-100 at 200°C, 500°C and 800°C was 6.80%, 3.18% and 24.20%. The decrease in the TST of BR-100 at 200°C, 500°C and 800°C was 7.66%, 13.80% and 33.65%, and the decrease in the TST of CR-100 at 200°C, 500°C and 800°C was 7.90%, 13.11% and 33.19% [16, 17, 25].

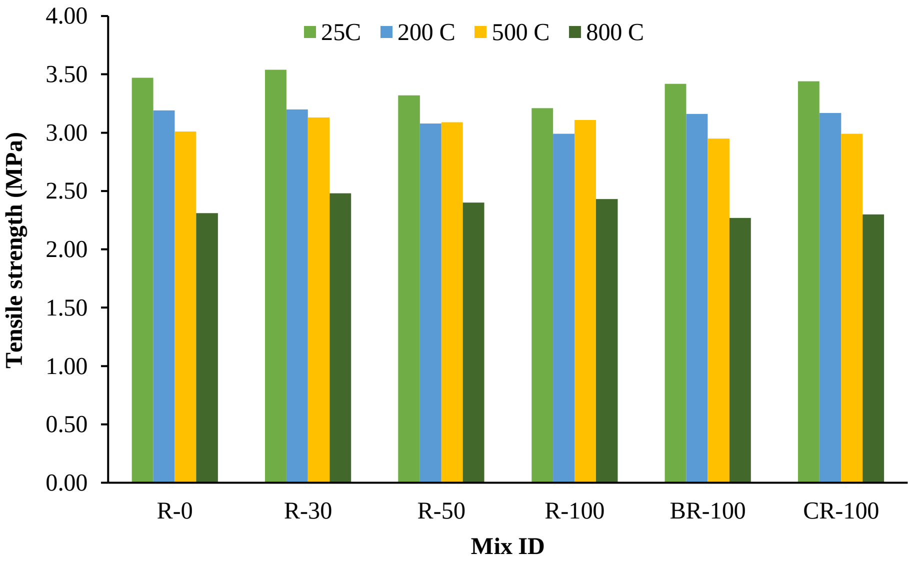


Figure 10 Tensile strength of the concrete mix at elevated temperature

3.4 Static modulus

Figure 11 shows the variation in the SM of the mixes upon exposure to elevated temperature. The decrease in the SM of R-0 at 200°C, 500°C and 800°C was 10.06%, 16.34% and 40.01%, and the decrease in the SM of R-100 at 200°C, 500°C and 800°C was 8.42%, 3.95% and 29.27%. The equivalent coefficient of thermal expansion between the RCA and new cement mortar improves the stiffness and reduces the drop in the SM of the RAC at elevated temperatures. The decrease in the SM of BR-100 at 200°C, 500°C and 800°C was 9.48%, 16.94% and 40.12%, and the decrease in the SM of CR-100 at 200°C, 500°C and 800°C was 9.78%, 16.11% and 39.59% [10, 11, 16].

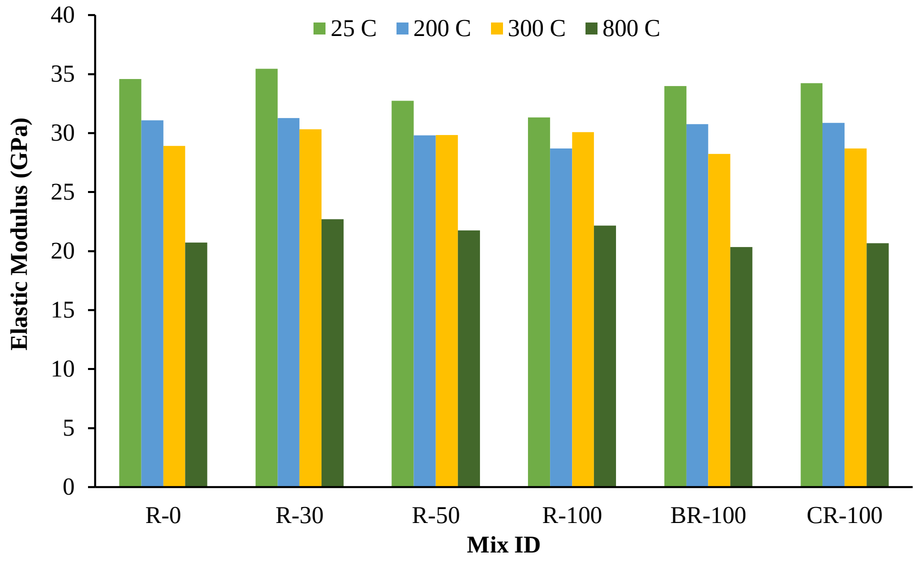


Figure 11 Elastic Modulus of the concrete mix at elevated temperatures

3.5 Thermal conductivity

Figure 12 shows the thermal conductivity of different mixes. The thermal conductivity of the RAC decreases with an increase in the replacement of RCA. The thermal conductivity of the R-0 and R-100 mix was 1.37 W/mK and 0.78 W/mK, and the thermal conductivity of the R-100 mix was 43.06% less compared to R-0. Similarly, the thermal conductivity of the R-30 and R-50 mix was 10.21% and 16.05% less than R-0. The higher perviousness of RCA ensuing from the adhered mortar affects the thermal conductivity of the RAC [30, 31]. The mechanical properties of BR-100 and CR-100 mixes were improving due to treatment techniques. In addition, it is essential to ensure the thermal insulation properties of the RAC. The thermal conductivity of BR-100 and CR-100 was 26.67% and 33.04% more compared to R-100 and only 23.35% and 16.05% lesser than R-0. The formation of $CaCO_3$ due to carbonation and bio-deposition techniques blocks the voids on the RCA and thus reducing the porosity and affecting the thermal conductivity of the concrete [15, 16].

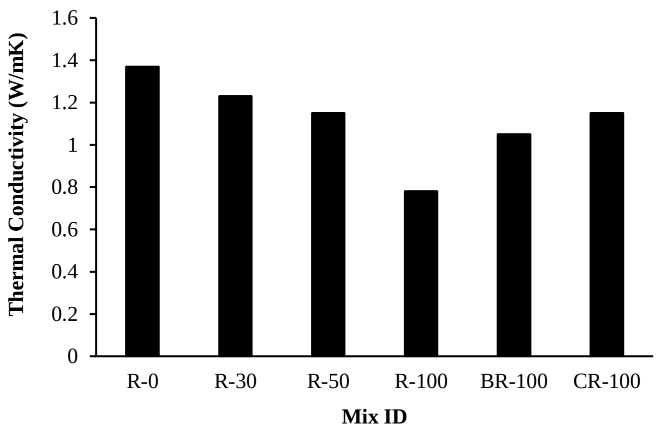
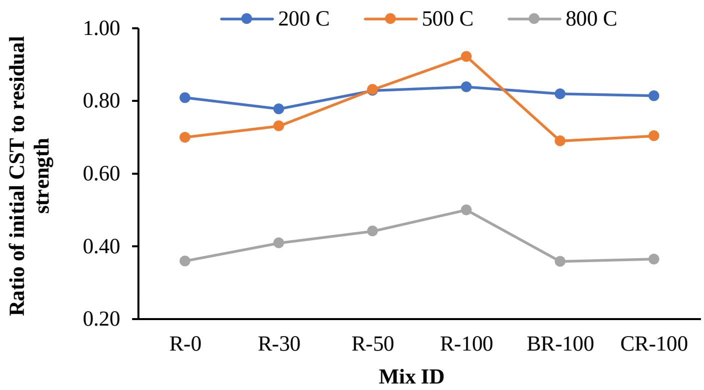


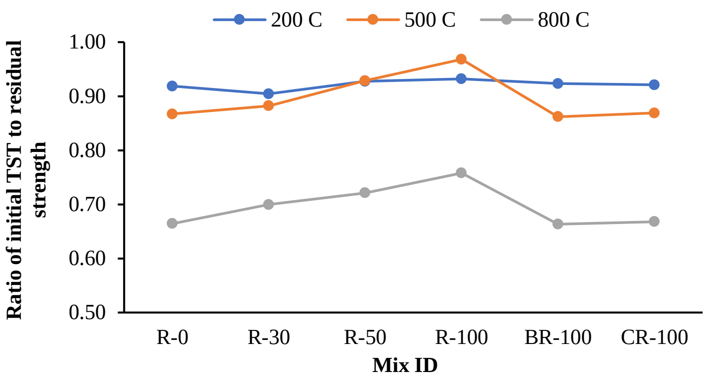
Figure 12 Thermal conductivity of the concrete mix

3.6 Effect on levels of replacement

Concerning replacement levels, an increase in the replacement of RCA decreases the mechanical properties at 25°C owing to its highly porous nature. However, upon exposure to elevated temperature, an increase in the RCA shows better resistance to thermal effect owing to the thermal coefficient equivalency resulting from the adhered mortar. Figure 13 shows the variation in the ratio of initial to residual mechanical properties with different percentages of RCA at various elevated temperatures. The increase in the RCA eventually improves the residual properties. However, the improvement may be minimum at 200°C but increases at 500°C and 800°C. Similarly, the R-50 and R-100 mixes respond better to elevated temperatures than the R-30 mix. Similar behaviour concerning replacement level was observed with TST and SM at various elevated temperatures. Since the higher perviousness of RCA is the critical factor that decides the strength of RAC, it is essential to ensure surface saturation in RCA before its application in concrete. After curing, the concrete samples should be completely dried at room temperature before exposing them to elevated temperatures. This is because exposing wet concrete specimens to elevated temperature will induce steam in the voids of the concrete and deteriorates the concrete at an early stage [8, 9, 11].



(a)



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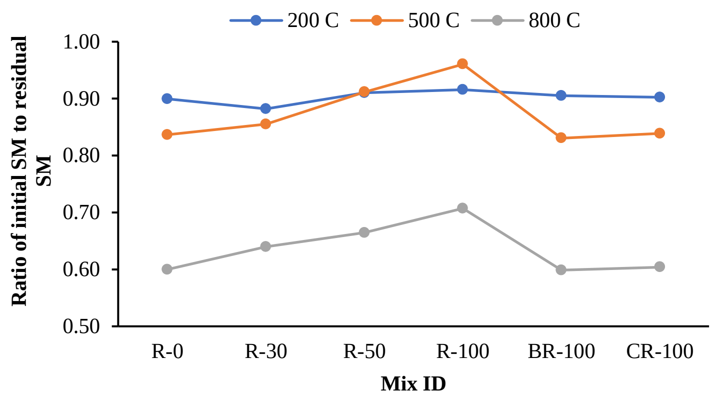

(c)

Figure 13 Ratios of initial mechanical properties to residual properties (a) Compressive strength (b) Tensile strength (c) Elastic Modulus

4. Conclusions

The experimental investigation on the influence of the elevated temperature on the behaviour of different RCA was performed, and the conclusions were derived as follows:

1. The increase in RCA replacement decreases the RAC's mechanical properties owing to the higher perviousness ensuing as of the adhered mortar.
2. The residual temperature of RAC was observed between 200°C to 500°C, and an increase in the RCA improves the residual response of the RAC.
3. The bio-deposition and carbonation treatments to RCA do not show any significant improvement in the thermal properties of the RAC.
4. The thermal conductivity of RAC decreases with the increase in the replacement of the RCA. The thermal conductivity of the R-100 mix was 43.06% less compared to R-0, while the thermal conductivity of BR-100 and CR-100 was 26.67% and 33.04% more compared to R-100. Such concrete with good thermal resistance can be well suited in the construction of refractories, chimney, underground mining operations etc. with sustainable approach.

5. Acknowledgement

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