Investigation of Post Fire Mechanical Performance of Recycled Aggregate Concrete Containing Ground Granulated Blast Furnace Slag

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Abstract. Structures made from recycled aggregate concrete are exposed to high temperatures during fire scenarios which degrade their mechanical properties. Hence, this study investigated the residual mechanical properties of recycled aggregate concrete (RAC) containing ground granulated blast furnace slag (GGBS) after exposure to elevated temperatures. 21 experimental runs for design mix of RAC considering recycled coarse aggregate (RCA) replacement of natural coarse aggregate at 50, 75, and 100%, GGBS replacement of cement at 0, 20, 40, and 60% and water to binder ratio at 0.4 and 0.5 levels were used. The residual mechanical properties of RAC including compressive strength, splitting tensile strength, and elastic modulus were determined through laboratory experimental tests at room temperature (about 25°C) and after exposure to elevated temperatures of 200, 400, 600, and 800°C. Experimental results showed that residual mechanical properties of RAC decreased with increasing temperatures but their resistance to degradation was significantly enhanced with the addition of GGBS at 40% GGBS content. The novel model developed for the prediction of residual compressive strength of RAC has high prediction accuracy based on the performance metrics used to evaluate the model performance. The model has p-values less than 0.0001, a high R^2 value of 0.9781, a low root mean square error (RMSE) of 1.456 and mean absolute percentage error (MAPE) of 0.2287. Overall, the study contributed immensely to the knowledge of RAC as a sustainable alternative to normal concrete in areas prone to exposure to high temperatures which will significantly aid the effective fire safety design of structural members produced with recycled aggregate concrete.

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1 Introduction

The use of recycled concrete aggregate (RCA) as aggregate in concrete production is one of the ways being adopted to mitigate the environmental depletion arising from sourcing natural aggregate for concrete production [1], and solving waste disposal challenges posed by large amounts of construction and demolition waste [2]. However, RCA's high water absorption, high porosity and low strength arising from micro-cracks and porous attached old cement paste contribute to reduced strength in recycled aggregate concrete (RAC). Ground granulated blast furnace slag (GGBS) has been added to RAC mix constituent to enhance its strength and reduce the amount of cement used in the mix [3-4].

The exposure of recycled aggregate concrete structures to high temperatures during fire scenarios degrades their mechanical properties [5-6]. A key fire safety design requirement according to European standard, EN 1992-1-2 [7] is that the load bearing capacity of concrete exposed to high temperature due to fire can be assumed. Researchers are recently more concerned with evaluating concrete residual mechanical properties which are usually carried out by subjecting concrete samples to elevated high temperatures in a controlled furnace to simulate the effect of high temperatures in real building fire conditions [8-10]. These mechanical properties mainly include compressive strength, tensile strength, and modulus of elasticity which change substantially with the degree of exposed temperature [10].

The reliability of continuous usage of concrete exposed to high temperatures depends on its post fire residual strength performance. The use of RCA and GGBS in concrete mix is on an increasing trend [11-12]. Hence, it is important to assess and understand the mechanical strength performance of RAC containing GGBS after exposure to elevated temperatures. Moreover, the development of a prediction model that can accurately estimate post fire compressive strength of RAC containing GGBS will not only help save time that may have been expended on carrying out experimental work but also contribute significantly to the design of structural members produced with recycled aggregate concrete subjected to high temperatures.

2 Methodology

2.1 Material Collection and Characterisation

RCA used in this study was obtained from crushed reinforced concrete beams used for flexural strength tests. The particle size of RCA after crushing ranges from 5 - 22 mm with a nominal maximum size of 22 mm. Ordinary Portland cement (Type I) and GGBS of grade S95 were used as binders. The GGBS has a specific gravity of 2.8, fineness (Blaine) of 5000 cm^2/g and 28 days strength activity index of 96. Natural coarse aggregates and fine aggregates (river sand) were obtained from a construction site in Ho Chi Minh City as a representative of the common natural aggregate types used for construction works in Vietnam. Laboratory tests were carried out to determine the physicomechanical properties of aggregates: RCA has dry rodded density (1450kg/m^3), specific gravity (2.45) and water absorption (4.41%); Natural coarse aggregate has dry rodded density (1580kg/m^3), specific gravity (2.75) and water absorption (1.22%). The maximum aggregate size of aggregate used is 22 mm.

2.2 Preparation of recycled aggregate concrete specimens

The mix constituent for 21 experimental runs of RAC containing GGBS was developed. RCA was used to replace natural aggregates at 50, 75, and 100% levels. GGBS replacement levels of cement were at 0, 20,40 and 60%. The water binder ratio used for the mix is 0.4 and 0.5. The proportions of aggregates and binder quantities in kg/m^3 were estimated following ACI 211.1-91 [13] standard for normal strength concrete. 420 samples were prepared from the 21 experimental runs, 210 were tested for compressive strength and modulus of elasticity, and the remaining 210 samples were tested for splitting tensile strength. The average of two samples results obtained for the same mix design that is exposed to the same temperature was recorded as the final value.

2.2.1 Thermal loading on RAC specimens

The automatic controlled electric furnace with a heating capacity of 1000℃ was used to heat RAC specimens. The specimens were placed in the furnace and heated to targeted temperatures of 200, 400, 600, and 800℃. The furnace temperature was maintained for 2 hours after heating specimens to targeted temperature to coordinate the furnace temperature with that of the core of RAC specimens. Thereafter, the furnace was turned off and its door opened for the specimens to cool down to ambient temperature.

2.3 Mechanical strength testing of RAC

Compressive strength, splitting tensile strength, and modulus of elasticity tests were carried out on RAC specimens after they had been subjected to targeted elevated temperatures. The specimens were tested after being stored at ambient temperature for 7 days to ensure the core of specimens cooled down to room temperature [14]. A 1000 kN UTEST Universal testing machine (UTM-6100.SVD2) was used for the compressive strength test following ASTM C39 [15] standard, splitting tensile strength following ASTM C496 [16] standard, and modulus of elasticity test following ASTM C469 [17] standard.

The tested residual mechanical strength of RAC containing GGBS was analysed based on their absolute residual strength values and relative residual strength values. The residual compressive strength of RAC is the retained compressive strength in a specimen after being subjected to high temperature. The relative residual compressive strength value was estimated using Equation 1. The same approach was used for estimating relative residual splitting tensile strength and modulus of elasticity.

$$\text{RAC} = \frac{compressive\ strength\ retained\ after\ exposure\ to\ high\ temperature\ (f^{T}{}_{c})}{compressive\ strength\ at\ room\ temperature\ (f_c)} \times 100 \qquad (1)$$

2.4 Development of prediction model

Response surface methodology was adopted to develop prediction model for RAC residual compressive strength based on experimental results. Steps for model development in Design-Expert 12.0 software were followed to develop the prediction model. The parameters for the 105 data points of residual compressive strength of RAC obtained from experimental results were randomly partitioned to 70% and 30% for training and validation purposes respectively. The developed model was validated by applying it for the prediction of residual compressive strength of collected experimental data for RAC specimens exposed to elevated temperatures from previous studies. Furthermore, the developed model performance was evaluated using different Statistical performance metrics including coefficient of determination (R^2), root mean square error (RMSE), and mean absolute percentage error (MAPE).

3 Result and Discussion

3.1 Workability of RAC containing GGBS

The slump values obtained for RAC-GGBS mixes with varying replacement levels of NCA with RCA, w/b ratios and GGBS replacements are presented in Figure 1. As expected, the slump value of RAC-GGBS increased with w/b ratio level. The addition of GGBS was observed to enhance the workability of RAC mixes, increasing GGBS replacement level from 20 to 40% leads to about 22, 14, and 6% higher slump values in RAC containing 50,75, and 100% RCA content respectively. An increased slump value in RAC mix due to the addition of GGBS is connected to better particle dispersion of GGBS compared to OPC [18]. Also, GGBS helps in filling up spaces within concrete aggregates resulting in less internal friction among concrete components and more flowable concrete [19]. It can be seen that the workability of RAC mixtures decreased with increasing RCA content. This can be attributed to the higher water absorption capacity of RCA due to their porous structure with opened cracks and the adhered attached mortar on RCA surface [20, 21]. The mean slump value of RAC containing 50, 75 and 100% RCA content was estimated as 70, 62 and 50mm respectively.

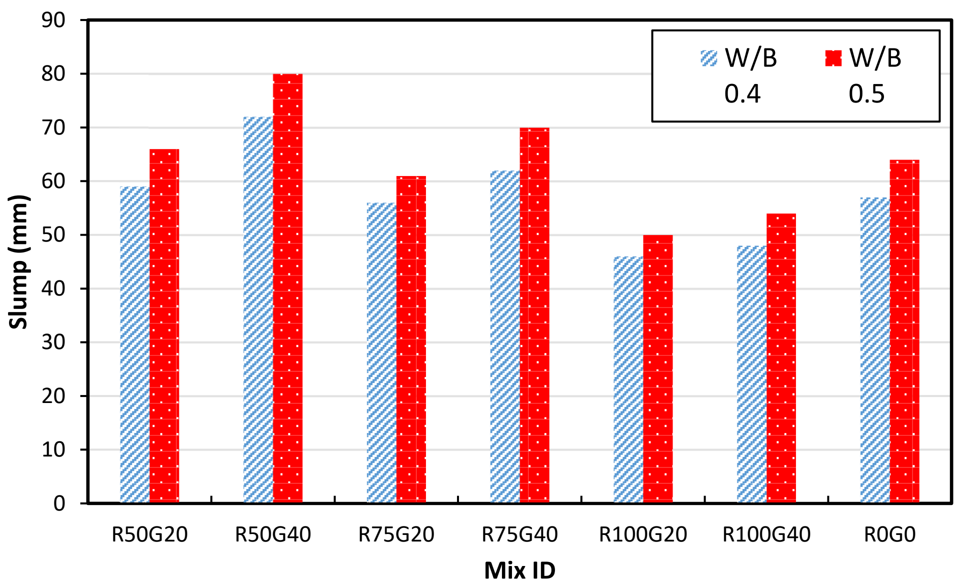

Fig. 1. Comparison of slump value of RAC mixes at different w/b ratio

3.2 Residual compressive strength of RAC

Figure 2 shows the influence of RCA content and GGBS content on the residual compressive strength of RAC. The relative residual compressive strength of RAC with 100% RCA (R100G0) was lower at an initial elevated temperature of 200 °C compared to RAC with 50 and 75 % RCA content but has higher relative strength at higher elevated temperatures. This is because higher non-uniform thermal stresses generated between natural aggregate and RCA at elevated temperatures resulted in faster compressive strength deterioration in RAC with 50% and 75% RCA content [22]. The addition of GGBS to RAC clearly enhanced its resistance to deterioration of compressive strength at elevated temperatures. The pozzolanic reaction between cement and GGBS aids more hydration process [23] leading to more thermally stabilized Calcium silicate hydrate (C-S-H) gel formation and less Calcium hydroxide ($Ca(OH)_2$) crystals formation. More thermally stabilized C-S-H gel formed in RAC-GGBS improved bonding between aggregates and cement paste and lesser C-S-H decomposition during exposure to high temperatures, thereby contributing to enhanced resistance to residual compressive strength deterioration. Shumuye [24] found out that normal concrete cast from 30% - 50% slag replacement have more well-structured C-S-H gels and those with 30% slag showed better fire resistance to deterioration of mechanical properties compared to the other concrete groups 50 and 70% slag content. Experimental results in this study have shown that 40 % GGBS has higher resistance to strength deterioration at initial temperatures up to 600 °C while the addition of 20 % GGBS showed relatively better resistance to strength deterioration after exposure to 800 °C temperature.

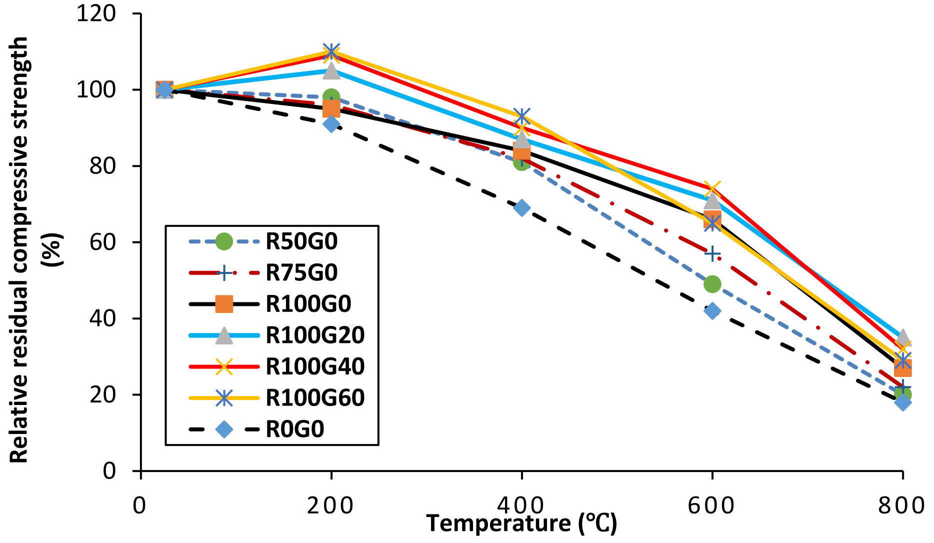

Fig. 2. Relative residual compressive strength of RAC with temperature

3.2.1 Effect of w/b ratio on residual compressive strength

The residual compressive strength of RAC containing GGBS specimens mixed with 0.4 w/b ratio was higher than their equivalent sample with 0.5 w/b ratio. A possible reason could be due to higher cement and GGBS contents in 0.4 w/b ratio mix which enhanced hydration process. Zega [25] and Khalifa [26] observed that an increased w/b ratio aggravates the rate of strength degradation in concrete exposed to high temperatures. The regression analysis for RAC-GGBS compressive strength degradation level with temperature is compared with that of the control sample in this study (R0G0) and Euro code 2, EN 1992-1-2 [7] residual compressive strength reduction factors in **Figure 3**. RAC samples containing GGBS showed a lower strength degradation rate compared to control samples and EN 1992-1-2 code compressive strength reduction factors for normal concrete exposed to high temperatures.

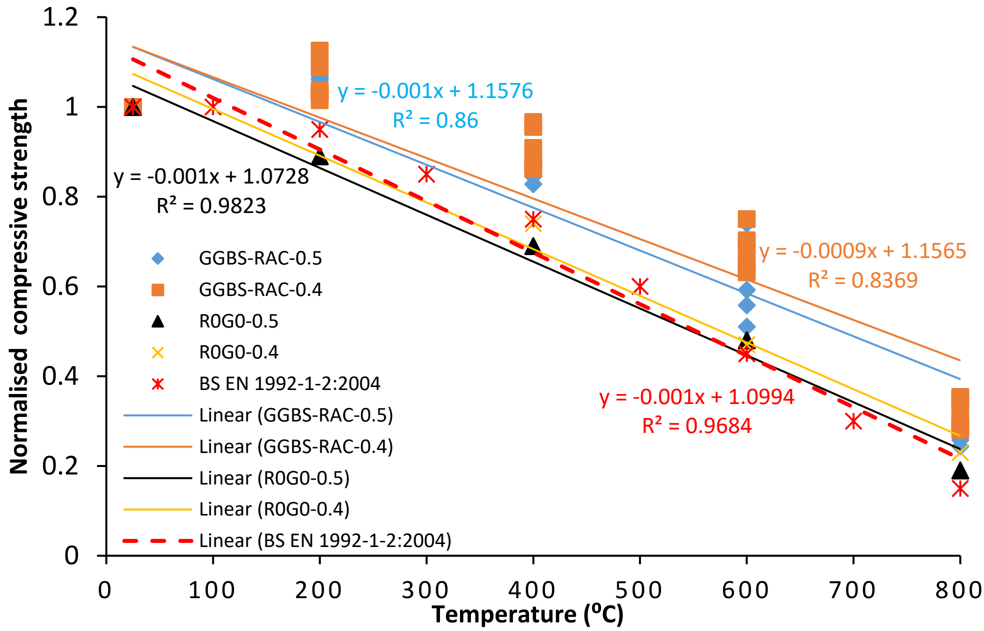

Fig. 3. Strength degradation of RAC exposed to elevated temperature compared with code strength reduction factor for normal concrete.

3.3 Residual splitting tensile strength of RAC

Figure 4 shows the retained residual splitting tensile strength of RAC samples at varying amounts of RCA and GGBS contents. The splitting tensile strength of RAC decreases with rising temperature. This can be attributed to the dehydration and decomposition of the hydration products resulting in less bonding at ITZ [27-28]. There was a positive effect of the addition of GGBS on RAC splitting tensile strength. RAC containing 40% GGBS (R100G40) has higher residual splitting tensile strengths of 10.9, 23.1, 21.2, 34.1, and 54.2% after exposure to 25, 200, 400, 600, and 800°C temperatures respectively when compared to RAC sample without GGBS (R100G0) exposed to same temperature level. The bond strength between recycled aggregate and new cement paste at the interfacial transition zone is enhanced with the addition of GGBS, leading to enhanced resistance to deterioration of splitting tensile strength of RAC-GGBS subjected to high temperatures [29-30].

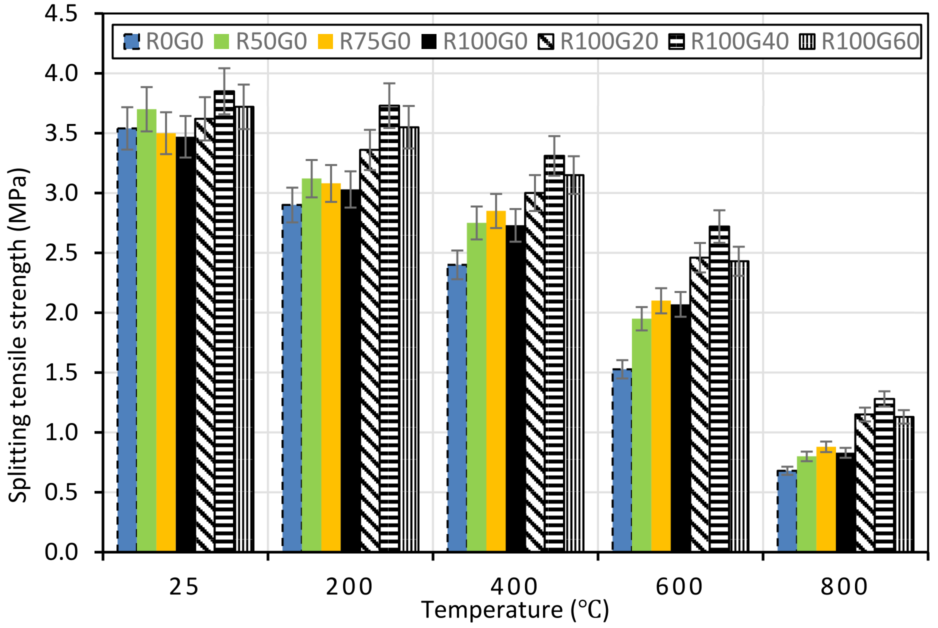

Fig. 4. Residual splitting tensile strength of RAC samples at varying GGBS replacement levels

3.3.1 Effect of w/b ratio on the splitting tensile strength of RAC

Figure 5 shows the retained splitting tensile strength in fully replaced RAC mixed with 0.4 and 0.5 w/b. Increased w/b ratio resulted in decreased retained splitting tensile strength of RAC with or without GGBS. Higher internal moisture evaporation in RAC samples mixed with 0.5 w/b ratio caused the compactness of the cement mortar to loosen, consequently weakening the ITZ and reducing RAC residual splitting tensile strength [28]. There is a clear margin between the retained splitting tensile strength of specimens with 0.4 and 0.5 w/b ratio at room temperature and up to 400°C temperature, However, this gap starts to diminish gradually after 400°C. Specimens with 0.4 and 0.5 retained somewhat the same value of splitting tensile strength after exposure to maximum 800°C temperature indicating that the effect of change in w/b ratio on splitting tensile strength of RAC-GGBS is less significant at higher exposed temperature levels. The evaporation of absorbed and chemically bound water in RAC specimens takes place under 400°C [31]. Hence, there is less contribution of different w/b ratios on deterioration of splitting tensile strength at temperatures above 400°C.

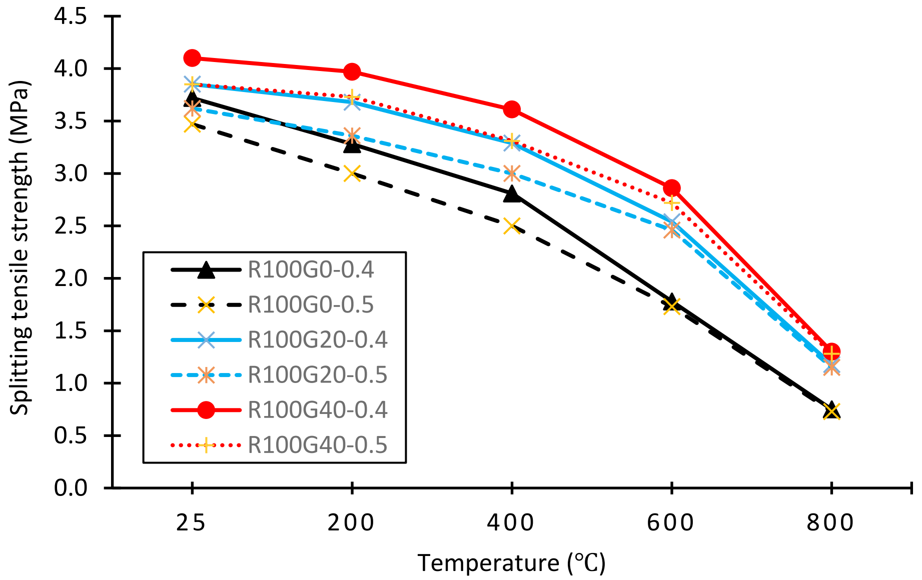

Fig. 5. Degradation of residual splitting tensile strength of RAC at different w/b ratio

3.4 Residual modulus of elasticity of RAC

Control sample made of natural aggregate has the highest modulus of elasticity at room temperature and up to 400°C temperature compared to RAC samples. The porosity of RCA and high deformation of attached mortal on RCA surface are responsible for the low residual modulus of elasticity in RAC [32-33]. More than 50% of RAC modulus of elasticity was lost after 400°C temperature which is due to alteration in the microstructure of RAC. The content of $Ca(OH)_2$ starts to decrease, dehydration and decomposition of the C-S-H gel emerge and thermal crackings are fully developed in RAC after exposure to 400 temperature which makes RAC specimens more porous with a drastic reduction in their stiffness [34]. For RAC containing GGBS, the rate of degradation of modulus of elasticity was less compared to RAC without GGBS indicating enhanced resistance to deterioration of modulus of elasticity of RAC exposed to elevated temperatures. RAC containing 40% GGBS (R100G40) has a higher residual modulus of elasticity of 11.9, 25.9, 36.4, 54.5, and 92.3% after exposure to 25, 200, 400, 600, and 800°C temperatures respectively when compared to RAC sample without GGBS (R100G0) exposed to same temperature level. The degree of hydration of cement paste is faster due to the pozzolanic reaction of GGBS and cement resulting in decreased porosity of cement paste which positively influenced the modulus of elasticity of RAC [35]. The positive impact of the addition of GGBS on RAC became more pronounced at higher exposed temperatures as GGBS helps to retarded the formation of macro and micro-cracks in RAC specimens subjected to elevated temperature [36].

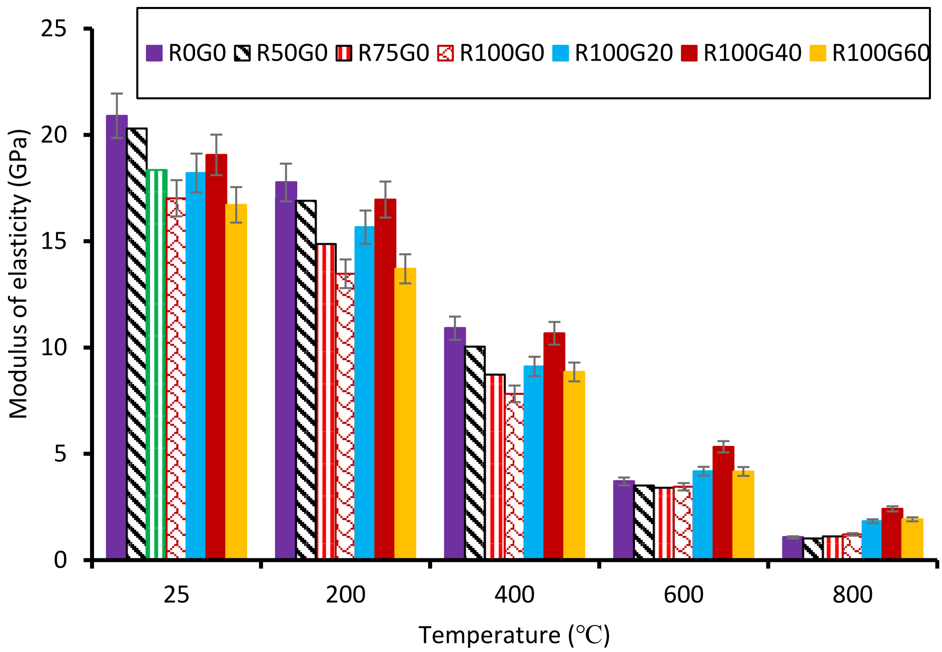

Fig. 6. Residual modulus of elasticity RAC-GGBS exposed to different elevated temperatures

3.5 Prediction model for RAC residual compressive strength

The developed prediction model fit RAC residual compressive strength as presented in **equation 2** was established to be significant on the result of ANOVA analysis. The model has large F-values of 377.33 and p-values less than 0.0001 indicating model significance [37-38] The p-values of all model terms, A, B, C, D, E, AB, AE, BC, DE, B^2, and E^2 are less than 0.0001 indicating the model terms have significant effects on the model output. The predicted R^2 value of 0.9781 implies good performance and high accuracy of the model. The adequate precision of the model is 66.64 which is greater than 4 required for a good model fit [39-40]. **Figure 7 (a)** and **(b)** show the scatter plot for model-predicted and actual experimental values, and the response surface plot of the developed model respectively.

$$f'_c = 23.03 - 1.94B^2 - 4.93E^2 + 0.59AB + 1.0AE - 0.27BC - 2.31DE + 0.624A + 0.582B - 0.517C + 4.6D - 10.21E \quad (2)$$

where: f'_c is the residual compressive strength of concrete (output), and variable, A is RCA replacement, B is GGBS replacement, C is the w/b ratio, D is the compressive strength of concrete at room temperature, and E is the exposed temperature level

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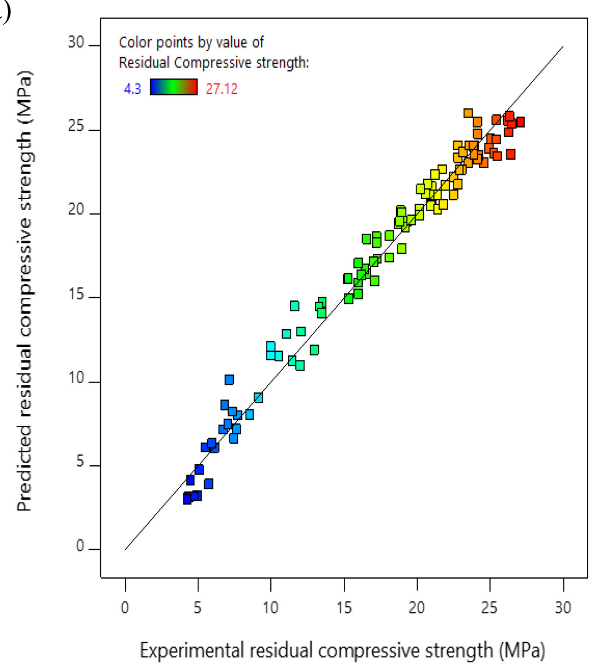
(a)



(b)

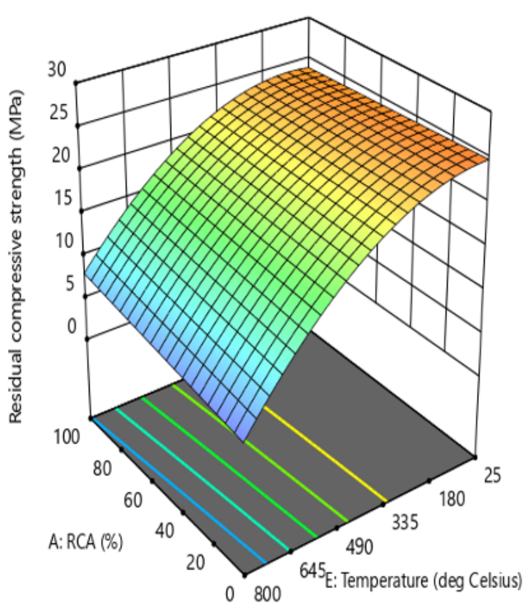


Fig. 7. (a) Scatter plot for model predicted vs actual values of RAC residual compressive strength (b) Response surface for RAC residual compressive strength exposed to elevated temperatures

3.5.1 Evaluation of model performance

Statistical performance metrics including coefficient of determination (R^2), absolute error, mean absolute percentage error (MAPE), relative error, and root mean square error (RMSE) were used to assess the developed model by applying it to collected experimental results of RAC exposed to elevated temperature from literature. The error margin in the model predicted values and actual experimental values were used to evaluate each performance metric according to equations 4.13 to 4.16. The results of the developed prediction model performance metrics are presented in **Table 1.** The model has a high R^2 value of 0.9781, a low root mean square error (RMSE) of 1.456 and a low mean absolute percentage error (MAPE) of 0.2287 indicating good model performance in predicting the residual compressive strength of RAC-GGBS exposed to elevated temperature. Similar metrics were used for the evaluation of performance of models developed for predicting residual mechanical properties of concrete exposed to high temperatures in previous published studies [41][42].

Table 1. Performance metrics for the predicted model

Performance indicators	Values
R^2	0.9781
Absolute error (MPa)	< 2.0
Relative error (%)	-27.9 to 22
MAPE	0.2287
RMSE	1.456

4 Conclusion

The workability of RAC is improved with the GGBS addition and RAC containing GGBS showed better post fire mechanical strength performance compared to RAC without GGBS. The resistance to degradation of RAC residual mechanical properties is enhanced more at 40% GGBS and RAC specimen mixed with 0.4 w/b ratio retained higher residual strength than when mixed with 0.5 w/b. Generally, the degradation of residual mechanical strength of RAC is dependent on the content levels of RCA, GGBS and w/b ratio used in the mix. Furthermore, experimental results revealed that lower exposed temperatures up to 400℃ do not constitute a major threat to the post fire mechanical performance of RAC blended with GGBS unlike the severe residual strength degradation observed in normal concrete and RAC without GGBS addition at these lower elevated temperatures. The novel model developed in this study has high prediction accuracy, model predicted values well fit the actual experimental output with low errors, indicating high reliability of the developed model.

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