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PREDICTING THE COMPRESSIVE STRENGTH OF CONCRETE CONTAINING CRUMB RUBBER AND RECYCLED AGGREGATE USING RESPONSE SURFACE METHODOLOGY

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ABSTRACT: The reuse of construction demolition waste and rubber waste has been a key challenge in recent decades due to the decrease in natural material resources and the huge amounts of abundantly available waste. When recycled aggregates (RCA) and crumb rubber (RBR) are used together as partial substitutions for coarse and fine aggregates, respectively, in concrete, it leads to a decrease in the compressive strength when compared to natural aggregate concrete, so it is needed to construct models that can predict the strength before using them. In this paper, response surface methodology was utilized to develop predictive models for the influence of the combined incorporation of RCA and RBR in concrete on the compressive strength. The predictions were based on the results of 100 various concrete mixes obtained from previous works and from the literature. The variables included w/c ratio (0.39 and 0.5), RBR replacement (0% to 40%), levels of RCA replacement (0% to 100%), and durations of 7 and 28 days. The compressive strength was taken as a response. All models and their terms were validated using various statistical tests. The results showed that linear and quadratic models and their terms were significant, and can be utilized for the prediction of the compressive strength with less error.

Keywords: Recycled aggregate; Crumb rubber; Concrete; Compressive strength; Prediction; Response surface methodology

1. INTRODUCTION

The disposal of waste tires as well as construction materials and concrete from demolished buildings has become a concern. Concrete from demolished buildings and used tires are two examples of typical waste materials in the construction and automotive industries, respectively. To reduce their harmful effects on the environment, scrap tire rubber and recycled aggregate have been used to replace aggregates in concrete from a sustainable perspective. Reusing scrap tires and construction demolition waste effectively is important and necessary for saving energy and protecting the environment [1].

Many studies have been conducted to investigate the effect of incorporating crumb rubber (RBR) as a replacement for sand in concrete on the concrete's performance. The increase in the crumb rubber level has reduced the mechanical properties of concrete containing RBR [2–6], but it has increased the resistance to cracks when compared to concrete without RBR [7].

Full substitution of sand in concrete with RBR has decreased the concrete's compressive strength by 93% [8], while 15% fine aggregate replacement in concrete with RBR has decreased the concrete's compressive strength by 50% [9]. The decrease in the mechanical properties of concrete containing RBR is due to the poor adhesion at the rubber aggregate's boundaries. Rubber particles pre-treated with sodium hydroxide (NaOH) enhanced rubberized concrete's tensile and bonding strengths [7, 10].

Numerous environmental concerns, such as the enormous amounts of construction and demolition waste, the paucity of suitable disposal locations, and the depletion of natural resources, have stimulated the substitution of natural coarse aggregate in concrete with construction and demolition waste. The evaluation of recycled aggregates' physical and mechanical characteristics is essential for producing structural concrete [11, 12]. The utilization of recycled aggregates in construction increases the range of reusable materials in the construction sector. If the intended final product quality is attained, the use of recycled aggregates reduces the volume of waste [13]. The strength of recycled aggregates (RCA) is less than that of natural aggregate because it has hardened cement paste on its surface, a higher porosity, and a water absorption of three to five times that of natural aggregate [14, 15]. Adding RCA to concrete reduces its mechanical properties and shortens its lifespan [16–20]. One possible alternative to the traditional method of disposing of scrap rubber and the massive volumes of demolition waste is to recycle crumb rubber and RCA in concrete production as partial substitutes for fine and coarse aggregates, respectively.

Numerous models have been proposed to predict the mechanical properties of concrete containing various replacements for fine and coarse aggregates. Multiple regression analysis and artificial neural networks were used to model the behavior of recycled aggregates in concrete [21]. The multivariate regression analysis has been used to develop prediction models for the effect of incorporating natural pozzolan as partial substitutions for cement and sand in cement mortars containing silica fume [22] on the compressive strength.

Response surface methodology (RSM) provides statistically proven predictive models for process optimization [23]. RSM is effective when multiple factors affect performance or responses. Non-linear response surfaces can be experimentally interpreted using RSM. RSM is a valuable statistical tool for designing experiments, model development, evaluation of variable impacts and optimal condition search [24–26]. RSM fits numerous parameters that vary simultaneously to quadratic function.

The purpose of this research is to apply RSM to analyze and predict the impact of partial substitution of fine and coarse aggregates in concrete with RBR and RCA, respectively, on the concrete's compressive strength. Linear and quadratic prediction models were developed using RSM based on data on the compressive strength of modified concrete by RBR and RCA at 7 and 28 days obtained from previous works and from the literature [27, 28]. The models were built using various conditions for fine aggregate replacement with RBR and coarse aggregate replacement with RCA as variables. The response was compressive strength. Statistical tests were used to determine the significance of the models and their terms.

2. RESEARCH SIGNIFICANCE

The research focuses on reusing construction demolition waste and rubber waste as partial replacements for aggregates in concrete, assisting in the disposal of large amounts of waste materials, and producing environmentally friendly construction material. Response Surface Methodology was employed to develop predictive models for the compressive strength of concrete given the w/c ratio and the replacement levels of natural coarse and fine aggregates in concrete with RCA and crumb rubber, respectively. The findings of this study could be used as a guide to predict the effect of combined incorporation of RCA and crumb rubber in concrete on the compressive strength.

3. MATERIALS AND METHODS

3.1 Materials

The experimental data used in this study was obtained from previous works and from the literature [27, 28]. The experimental data consists of two parts. The first part consists of 50 average compressive strengths of 150-mm-cubic specimens after 28 days. The specimens contain crumb rubber and RCA at replacement levels of (0, 5, 10, and 20%) and (0, 25, 50, and 100%), respectively. The second part consists of 50 average compressive strengths of 100-mm-cubic specimens after 7 and 28 days. The specimens contain crumb rubber and RCA at replacement levels of (0, 10, 20, 30, and 40%) and (0, 25, 50, 75, and 100%), respectively.

Table 1 illustrates the properties of used materials in the utilized experimental data.

Table 1 Material properties of ingredients [27, 28]

Ingredients		[27]	[28]
Fine aggregate		Natural sand	River sand
	SG	2.5	2.51
	FM	2.17	3.07
	WA	1.8%	1.37%
Coarse aggregate		Natural aggregate	Crushed gravel
	MA	25.5mm	10 mm
	SG	2.7	2.58
	CRV	15.19%	20%
	WA	0.8%.	1.26%
Cement		OPC type I with	CEM II/B-V
	SG	3.15	3.15
RCA	MA	25.5 mm	10 mm
	SG	2.5	2.54
	CRV	25.3%	23%
	WA	4.17%.	7.09%
Crumb rubber (RBR)	SG	0.9	0.973
	WA	0.3%	8.46%
	FM	4.38	2.78
W/C ratio		0.5	0.39

SG: specific gravity; FM: fineness modulus; WA: water absorption; CRV: crushing value; MA: maximum aggregate size.

By grinding scrap tire rubber, crumb rubber was obtained. Fig. 1 shows the particle size distributions of natural fine aggregate (NFA) and crumb rubber. The gradations of the natural coarse aggregate (NCA) and RCA are shown in Fig. 2. The proportions of control mixes for the used experimental data were shown in Table 2.

Table 2 Control mix ingredients (kg/m^3) [27, 28]

Reference	Cement	Water	Coarse Aggregate	Fine aggregate
[27]	400	200	1132	629
[28]	589	230	996	572

In order to increase the adherence of the rubber/cement interface, rubber particles have been pre-treated. Chemical treatment with a NaOH solution removes the zinc stearate coatings that develop on the rubber surface of tires [29]. A porous and rough surface that may increase cohesion between cement and rubber is created when additives on the rubber's surface are dissolved by the NaOH solution and left behind [30].

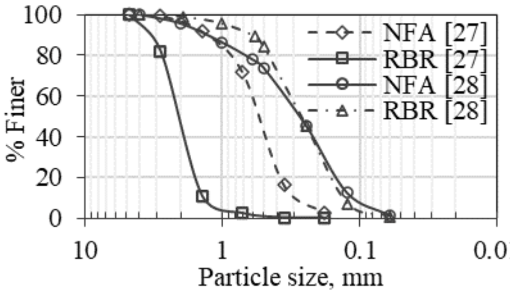


Fig. 1 Fine aggregate and RBR Gradations [27, 28]

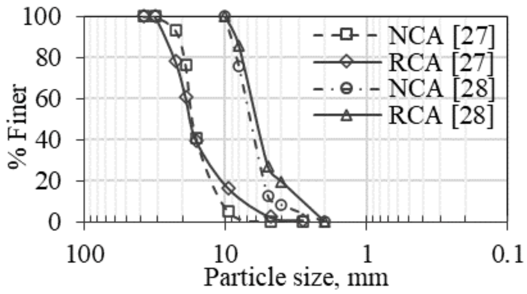


Fig. 2 Gradations of NCA and RCA [27, 28]

3.2 Response Surface Methodology

In most cases, an RSM model could be a full quadratic equation or a reduced form of this equation. The form of the second-order model is as follows:

$$Y = \beta_o + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \beta_{ii} x_i^2 + \sum_{i \neq j=1}^{n} \beta_{ij} x_i x_{ij} + \varepsilon \quad (1)$$

Where; β_o is the fixed response; β_i, β_{ii} and β_{ij} are the linear, quadratic and interaction regression terms, respectively; x_i is the level of the independent variable; n is the number of variables; ε is the error.

Statistical analyses, including the F-test, the lack-of-fit test, the p-value, and others, were used to evaluate the effectiveness of the developed models. The determination coefficient (R^2), shows how good a model is. The used variables were: 1) the level of replacement of natural coarse aggregate with RCA; 2) the level of replacement of fine aggregate with crumb rubber (RBR); 3) the water/cement ratio (w/c); and 4) the curing duration (AGE). Table 3 illustrates the ranges of all used variables. The response is the compressive strength of concrete (Fc).

Table 3 Variables ranges

Variable	Units	Low	High
RCA	%	0	100
RBR	%	0	40
W/C ratio	--	0.39	0.5
AGE	day	7	28

4. RESULTS AND DISCUSSIONS

4.1 Compressive Strength

Figs. 3 and 4 show the 3D plots for the compressive strength of cubic specimens used in the development of the predictive models.

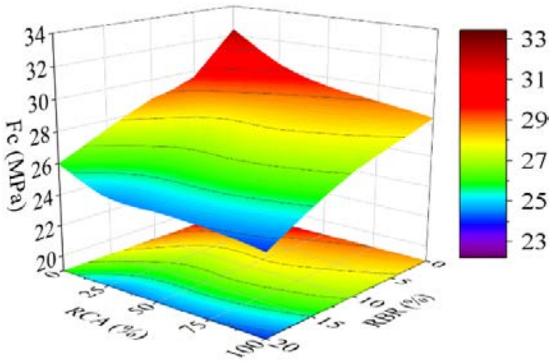
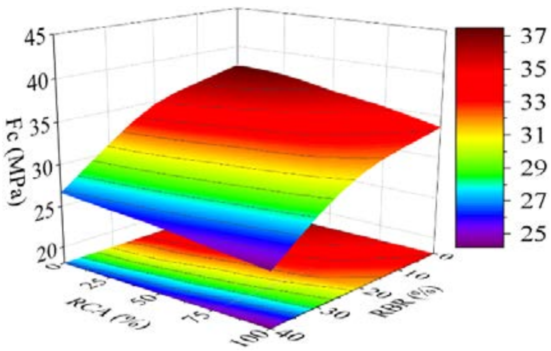
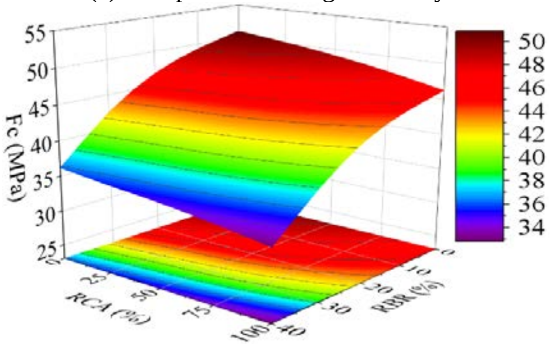


Fig. 3 Compressive strength at 28 days [27]



(a) Compressive strength at 7 days.



(b) Compressive strength at 28 days.

Fig. 4 Compressive strength of concrete [28]

4.2 Analysis of Variance

The analysis of variance (ANOVA) for all linear and quadratic responses and their terms are illustrated in Table 4. The F-values for the linear and quadratic strength models were 710.46 and 674.30, indicating the significance of both models. The two models have p-values lower than 0.05 indicating the significance of both models. For the linear strength model, the significant terms were RCA, RBR, W/C ratio, and AGE. For the quadratic strength model, the significant terms were RCA, RBR, W/C ratio, AGE, RCA×RBR, RCA×W/C, RBR×AGE, and RBR^2.

The linear and quadratic strength models' lack of fit F-values were 1.38 and 0.30, respectively, indicating that the lack of fit is not significant in comparison to the pure error, which is desirable. The Lack of Fit p-values for linear and quadratic strength models were 0.1484 and 1, indicating that there was a 14.84% and 100% chance, respectively, that a Lack of Fit F-value this large might occur due to noise. This means that the quadratic model fits the data better than the linear one.

The values of R^2 for the linear and quadratic strength models were 96.77% and 98.54%, respectively, which means each model is a good fit. The predicted R^2 of the linear and quadratic strength models were 96.37% and 98.30%, respectively. The adjusted R^2 of the linear and quadratic strength models were 96.63% and 98.39%, respectively. The differences between the predicted and adjusted R^2 were less than 0.2 for both models, indicating reasonable agreement among them.

In measuring the model's performance, adequate precision was also used. It compares the range of predicted values at the design point to the average prediction error. The adequate accuracy values of the models in this investigation were 92.744 and 94.695 for linear and quadratic strength models, respectively. The models can be utilized to navigate the design space because all precision values obtained were more than 4. A coefficient of variation, abbreviated CV, is a technique for measuring how widely distributed values are in a dataset in relation to the mean. The lower the CV, the smaller the standard deviation from the mean. The standard deviations for the linear and quadratic strength models are 1.35 and 0.9323, respectively; the values are lower compared to the mean, indicating a strong fit and low prediction error.

The linear and quadratic responses and the interaction between their terms for the compressive strength are shown in Eq. (2) and Eq. (3), respectively.

$$\boldsymbol{Fc = 106.914 - 0.0311RCA - 0.2971RBR - 189.48\left(\frac{w}{c}\right) + 0.70163AGE} \quad (2)$$

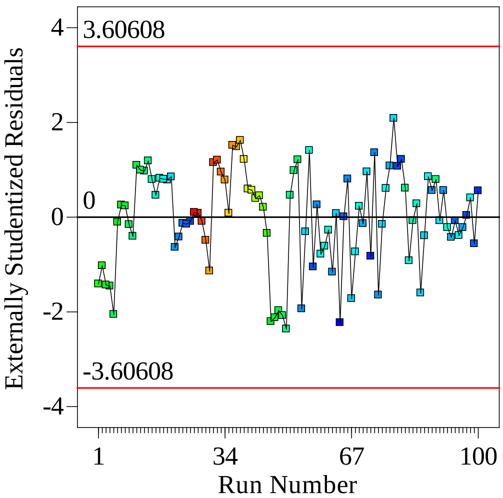
$$\boldsymbol{Fc = 108.439 - 0.1182RCA + 0.23757RBR - 199.81\left(\frac{w}{c}\right) + 0.81796AGE - 0.0064RBR^2 + 0.00056RCA \times RBR + 0.17581RCA \times \left(\frac{w}{c}\right) - 0.4955RBR \times \left(\frac{w}{c}\right) - 0.0058RBR \times AGE} \quad (3)$$

Table 4 ANOVA results

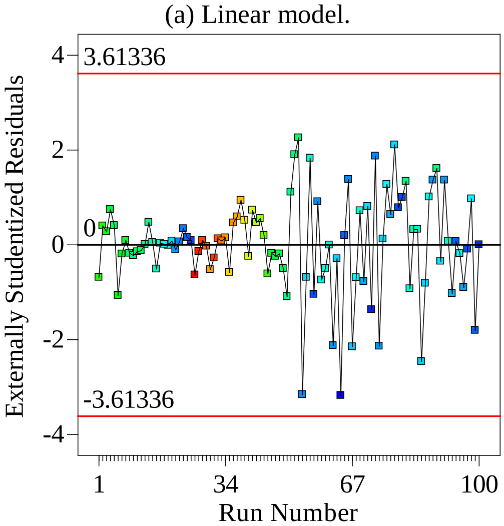
Model	Source	Sum of Squares	df	Mean Square	F-value	p-value		Fit Statistics	
Linear strength model	Model	5179.87	4	1294.97	710.46	< 0.0001	significant	SD	1.35
	A-RCA	126.89	1	126.89	69.62	< 0.0001		Mean	32.82
	B-RBR	1171.8	1	1171.8	642.89	< 0.0001		CV %	4.11
	C-W/C ratio	5061.38	1	5061.38	2776.84	< 0.0001		R^2	0.9677
	D-AGE	1641.64	1	1641.64	900.66	< 0.0001		AR	0.9663
	Residual	173.16	95	1.82				PR	0.9637
	Lack of Fit	118.46	58	2.04	1.38	0.1484	not significant	AP	92.7442
	Pure Error	54.7	37	1.48					
	Cor Total	5353.03	99						
Quadratic strength model	Model	5274.8	9	586.09	674.3	< 0.0001	significant	SD	0.9323
	A-RCA	81.9	1	81.9	94.22	< 0.0001		Mean	32.82
	B-RBR	423.72	1	423.72	487.49	< 0.0001		CV %	2.84
	C-W/C ratio	2916.74	1	2916.74	3355.71	< 0.0001		R^2	0.9854
	D-AGE	1641.64	1	1641.64	1888.71	< 0.0001		AR	0.9839
	AB	5.26	1	5.26	6.05	0.0158		PR	0.983
	AC	8.09	1	8.09	9.31	0.003		AP	94.6949
	BC	3.11	1	3.11	3.57	0.0619			
	BD	22.56	1	22.56	25.96	< 0.0001			
	B^2	61.56	1	61.56	70.83	< 0.0001			
	Residual	78.23	90	0.8692					
	Lack of Fit	23.53	53	0.4439	0.3003	1	not significant		
	Pure Error	54.7	37	1.48					
	Cor Total	5353.03	99						

SD: standard deviation; CV: coefficient of variation; AR: adjusted R^2; PR: predicted R^2; AP: adequate precision.

Fig. 5 shows the relationship between studentized residuals and run numbers for linear and quadratic strength models. In both cases, residuals appear to be uniformly distributed around zero. The predicted versus actual compressive strengths for linear and quadratic strength models are shown in Fig. 6. It demonstrated a correlation between the magnitude of the predicted strength and the experimental results in both cases. The 2D and 3D plots shown in Figs. 7, 8, and 9 show that increasing the RCA, RBR, or W/C ratio decreases the compressive strength.



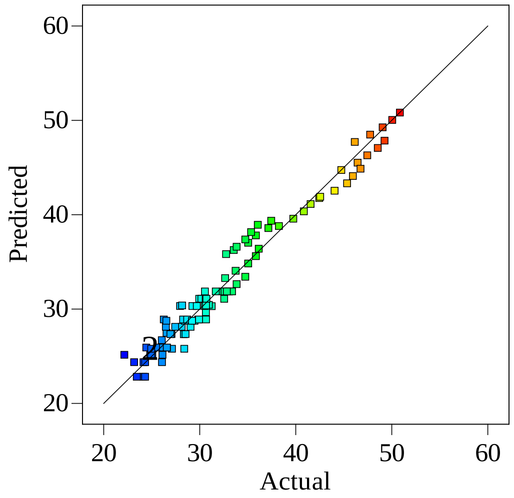
(a) Linear model.



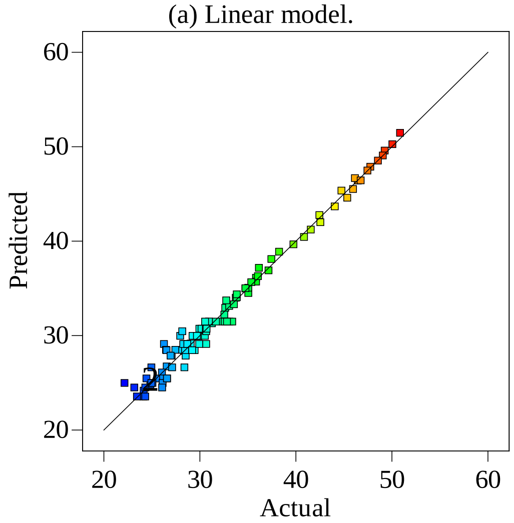
(b) Quadratic model.

Fig. 5 Studentized residuals versus run number

The W/C ratio has the highest bad impact on the compressive strength, the surfaces have steep slope as shown in Fig. 8(c) and Fig. 9(c). The RBR replacement has the greatest influence on the compressive strength when compared to the RCA replacement effect. The RBR effect's curvilinear surface (Fig. 8(a-c) and Fig. 9(a-c)) is consistent with the developed quadratic model for the compressive strength.



(a) Linear model.



(b) Quadratic model.

Fig. 6 Predicted versus actual compressive strength

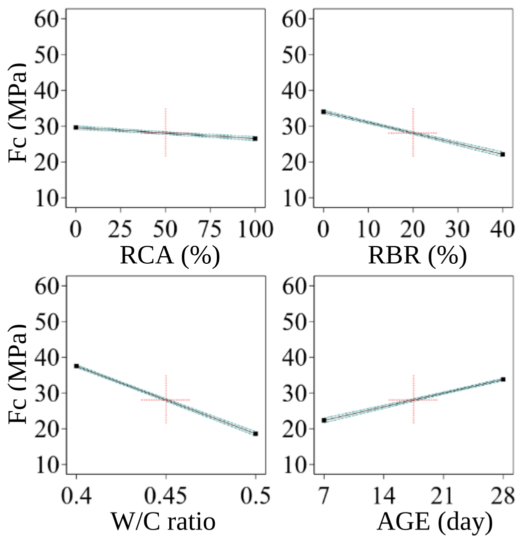


Fig. 7 2D plots for Linear strength model

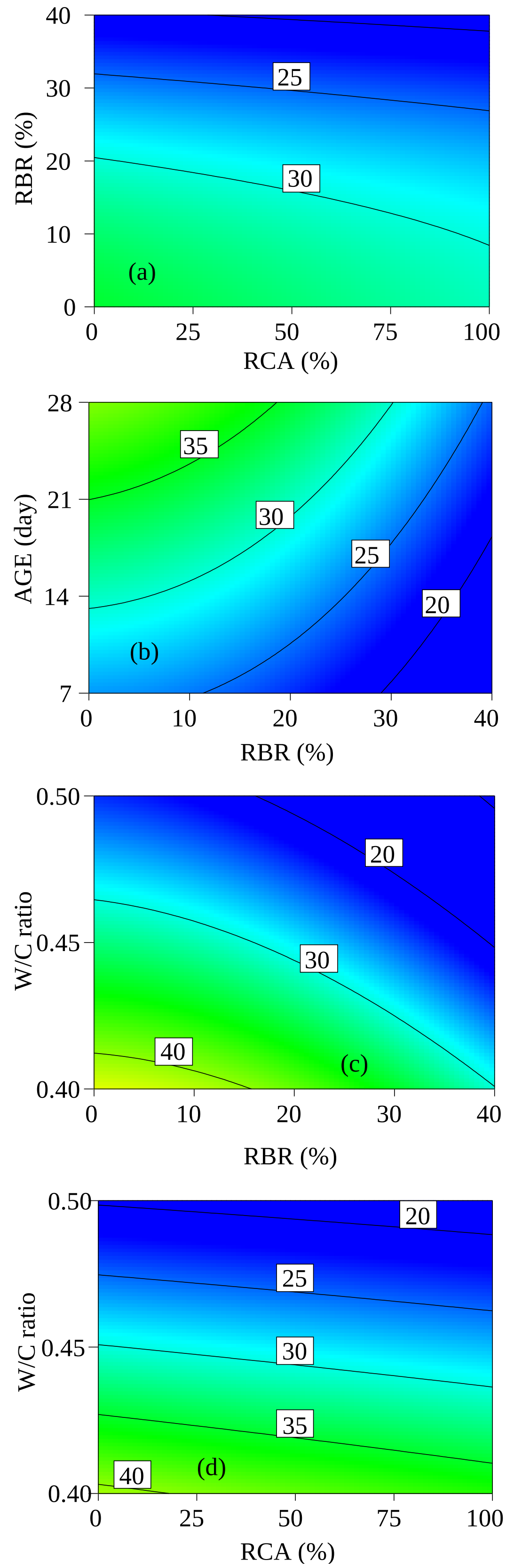


Fig. 8 2D plots for quadratic strength model

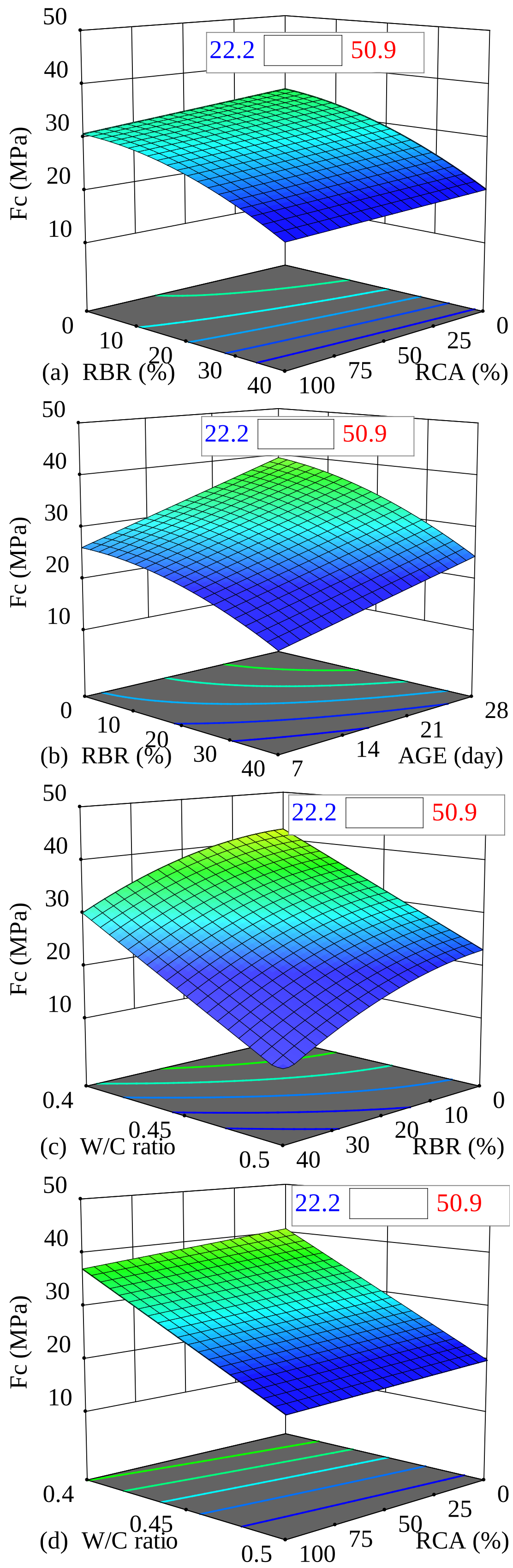


Fig. 9 3D plots for quadratic strength model

5. CONCLUSIONS

The impact of incorporating RBR and RCA as partial substitutions for fine and coarse aggregate at various replacement levels, respectively, in concrete was modeled using response surface methodology on 100 test results of the compressive strength of concrete cubes at 7 and 28 days. The constructed models were linear and quadratic. The following are the conclusions:

- The combined incorporation of RCA and crumb rubber in concrete reduced the concrete's compressive strength.
- Replacing 100% NCA with RCA has reduced the compressive strength by about 12%.
- Replacing fine aggregate with more than 20% is not recommended for structural concrete.
- RSM is an effective approach for modeling the effect of incorporation of RCA and crumb rubber in concrete on the compressive strength.
- All of the linear and quadratic models that were made had significance (p) values that were closer to zero, which means that the models were statistically significant, with levels of confidence greater than 95%, and can be used for the prediction of the compressive strength.
- The greatest value of the determination coefficient (R^2) of the strength models was 98.54% for the quadratic strength models.
- Based on the applied statistical tests, the quadratic model achieved a good correlation estimation level for the concrete compressive strength, with better data fit and lesser estimation error. W/C ratio and % RBR have the most significant effects on concrete's compressive strength.

6. ACKNOWLEDGMENTS

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