AUT Journal of Civil Engineering

AUT J. Civil Eng., 5(2) (2021) 301-310
DOI: 10.22060/ajce.2021.18634.5689

Response Surface Methodology Modelling to Study the Influence of Recycled Aggregates on Some Mechanical Properties of Recycled Concrete

H. Salehi[1], N. Biglarijoo[2*] , H. Barkhordari[1]

[1] Department of Civil and Mechanical Engineering, Khatam Ol Anbia University, Tehran, Iran.
[2] Civil and Environmental Engineering Faculty, Khaje Nasir Toosi University of Technology, Tehran, Iran.

ABSTRACT: Recycling is introduced as one of the most significant approaches in waste management practices. Various studies have concentrated on the influence of recycled concrete aggregate in concrete; however, no specific model has been suggested to predict the behavior of parent concrete. In this paper, response surface methodology coupled with the central composite design was used to design tests and model characteristics of recycled concrete. Effective factors in experimental work included compressive strength (f_c) of parent concrete, and substitution rate of parent concrete while compressive strength (f_c), tensile strength (f_t), and water absorption of recycled concrete were objective responses. Statistical analysis suggested that models were adequate with an acceptable correlation coefficient (above 0.80). Perturbation and response surface plots revealed that f_c and f_t of recycled concrete heavily depended on the f_c of parent concrete. For parent concretes with fc of 19 MPa and 85% substitution rate, the f_c and f_t values of recycled concrete were 31.6 MPa and 2.89 MPa while these values for parent concrete with fc of 36 MPa and 85% substitution rate were 42.1 and 3.7 MPa. In fact, as the f_c of parent concrete enhanced, f_c and f_t of produced concretes increased. However, in case the f_c of parent concretes increased, water absorption of recycled concrete decreased. The lowest water absorption of recycled concrete was 3.2%, which belonged to f_c of 36 MPa and 15% substitution whereas the highest water absorption was observed for the parent concrete with f_c of 19 and 85% substation rate.

Review History:

Received: Jun. 24, 2020
Revised: Jul. 30, 2020
Accepted: Oct. 26, 2021
Available Online: Oct. 29, 2021

Keywords:

RCA
Modelling
Waste
Properties
Concrete.

1- Introduction

As a prevalent concern in recent years, managing waste materials has become a focus of attention in different nations. Generally, waste materials refer to three principle items: wastewater, solid waste, and air emission. Municipal solid waste materials include a noticeable part of solid waste amongst which the portion of construction and demolition waste (CDW) is noticeable. As a good example, in North America, construction waste and debris consist of about 25-45% of the waste stream, depending on the region, while Construction Materials Recycling Association (CMRA) estimates that only 25% of this quantity is recycled [1]. Additionally, 85% of solid waste materials generated in Jordan come under the category of building construction waste [2]. One feasible strategy for several CDW materials (concrete, glass, masonry scrap and rubble, asphalt, ceiling tiles, and ceramic and glass tiles) is to be encapsulated in the concrete matrix [3]. Besides the construction and building industry, some catastrophic disasters such as war, flood, hurricane, and earthquake could contribute to the production of municipal solid waste. Among the aforementioned waste materials, concrete seems to be a potential recyclable material as it occupies a large proportion of demolition. Shi and Xu reported that 100 million tons of waste concrete are generated annually in China, which forms one-third of universal CDW waste [4]. Unfortunately, a large amount of CDW debris is normally dumped in landfills while they have the potential to be recycled [5, 6].

Concrete is so popular in the construction industry that most projects take advantage of this useful material. There is no doubt that this material requires a considerable amount of natural sources of aggregates [7]. The exploitation of these natural sources is assumed as a potential environmental threat. One practical solution to this global concern is to use waste materials as recycled aggregates in a concrete mixture [8]. Recycled concretes possess some specific properties, which dictate the importance of careful studies. The performance of recycled concrete aggregate (RCA) relies on the adhered mortar of the aggregates, which normally results in lower abrasion resistance, higher porosity, and higher water absorption compared to natural aggregates [9-12]. The increase in water absorption in recycled concretes could reach up to 25% in 20 percent replacement for coarse aggregates. Such concretes are typically more porous which contributes to lighter hardened as well as less durable concretes [13, 14]. These recycled concretes are normally 1 percent lighter for each 10 percent of substitution. Some of the previous researches have proved that compressive, tensile, and flexural strengths of concrete made with RCA decreased considerably

*Corresponding author's email: nader.biglary@gmail.com

Table 1. Compressive strengths of parent concretes.

Concrete Code	A	B	C	D	E
Compressive Strength (MPa)	19.0	21.5	28.0	33.0	36.0

with the addition of recycled concrete aggregates [10, 15, 16]. For instance, around 10 percent of reduction was observed in compressive and tensile strength of concretes containing 20% recycled concrete. However, others have indicated that the performance of recycled concrete depends heavily on the mechanical properties of parent concrete and may improve the mechanical properties of concrete. Some researchers have shown that producing concretes with compressive strength of 40-70 Mpa with recycled concrete aggregates is possible using an adequate amount of superplasticizer whereas other studies dictate the negative impact of these aggregates on concrete [17, 18].

Modeling the characteristics of concrete can assist researchers to prevent running unnecessary laboratory studies and present a better view of the concrete performance. When it comes to investigating different variables and the interaction between them, response surface methodology (RSM) seems to be a reliable tool for both process design and modeling with minimum possible test numbers [19]. RSM is a widely used mathematical and statistical approach for modeling and analyzing a process in which the goal response is influenced by various variables and the aim of this method is to optimize the responses [20]. To predict a first-degree acceptable polynomial model, a factorial test or a fractional factorial design could be applied. Nonetheless, a more complex design such as a central composite design (CCD) can be implemented for a second-degree polynomial model.

Despite the immense contributions of the above researches, to our knowledge, there is still no particular model or simulation for the influence of parent concrete on mechanical properties of recycled concrete. In fact, previous studies have investigated the influence of parent concrete on recycled concrete experimentally whereas no model is proposed to consider the impact of parent concrete strength and replacement levels of recycled aggregates. Therefore, this paper will address a part of this knowledge gap by: i) running experimental studies concentrating on the impact of RCA on the properties of concrete; ii) modeling the influence of parent concretes on compressive strength, tensile strength, and water absorption of recycled concrete.

2- Materials and Methods

2- 1- Experimental Procedure

To have a wide range of compressive strengths, five distinctive parent concretes were derived from laboratory specimens. This wide range of strength (from 19 to 36 MPa) enables us to consider the influence of parent concrete as a partial replacement of natural aggregates. These parent concretes were crushed and sieved in the laboratory. Table 1 shows the results of compressive strengths of parent concrete codes, namely: A, B, C, D, and E. To scrutinize the impact of RCA on the properties of concrete, 13 concrete mixtures were prepared. RCA was partially replaced at 15, 25, 50, 75, and 85 percent (by weight) with natural coarse aggregate. Table 2 depicts the chemical and physical properties of the type I cement. Workability was examined by conducting a slump test on the fresh concrete to maintain acceptable workability (according to ASTM C143) whereas compressive strength (according to ASTM C39), splitting tensile strength (according to ASTM C496), and water absorption (according to BS 1881) tests were done on hardened concrete specimens after 28 days. The slump test was done taking advantage of a metal mould in the shape of a conical frustum that is open at both ends and has been handled. The cone was put on a hard surface that was not absorbent. Then, this cone was filled with fresh concrete in three distinct stages. At the end of the third stage, the concrete was struck off flush with the top of the mould. The mould was lifted, in order not to disturb the concrete cone. The slump value was the distance from the top of the slumped concrete to the level of the top of the slump cone. Moreover, the compressive strength was done by dividing the maximum possible load applied to the specimen during the test by the cross-sectional area. Water absorption of specimens was calculated by immersing the specimens and then measuring the increase in mass as a percentage of dry mass after 24 h. To run the splitting tensile strength test, bearing

Table 2. Chemical and physical properties cement.

Property	%
Silicon dioxide (SiO_2)	21.41%
Aluminum oxide (Al_2O_3)	4.88%
Iron oxide (Fe_2O_3)	3.82%
Calcium oxide (CaO)	63.69%
Magnesium oxide (MgO)	1.56%
Sulfur trioxide (SO_3)	2.36%
Potassium oxide (K_2O)	0.65%
Sodium oxide (Na_2O)	0.47%
Loss on ignition	1.95%
Tricalcium aluminate (C_3A)	6.47%

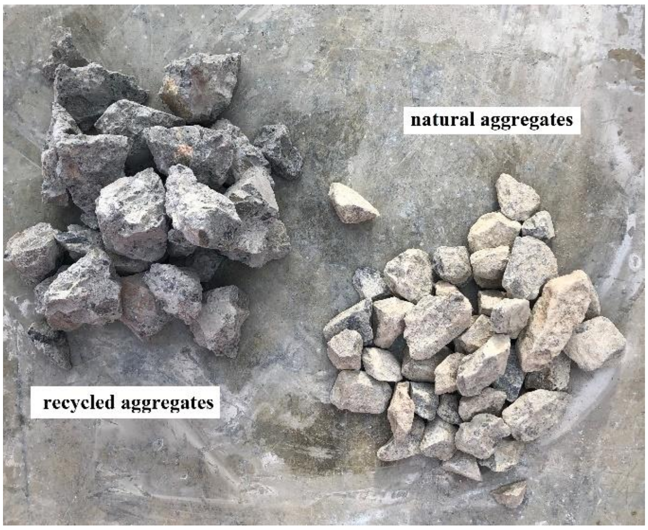

Fig. 1. Natural aggregates and recycled aggregates.

blocks were installed first. Then, the load was applied and the maximum load was recorded. The splitting tensile strength was measured using the equation of $T = \frac{2P}{\pi LD}$, where:

T = tensile strength; P= maximum applied load; L = average sample length; D= sample diameter.

The maximum size of the coarse aggregates in all mixes was restricted to 19 mm. Fig. 1 illustrates the difference between natural coarse aggregates and recycled coarse aggregates. Physical characteristics of the natural and recycled aggregates are depicted in Table 3. The grading of natural fine aggregates (NFA), natural coarse aggregates (NCA), and recycled coarse aggregates (RCA) are presented in Table 4. A high-range water reducer (HRWR) was also used to maintain the workability of the concrete mixtures at a slump value of 100 mm. The amount of water was fixed at 180 kg/m^3.

2- 2- Experimental design and statistical model

The Design Expert Software (version7.0.0) was applied for the experiment design and data analysis. Response Surface Methodology (RSM) can help to set up experiments with the minimum possible number of tests. In this research paper, central composite design along with response surface methodology was used to evaluate two major factors. Using CCD, the number of required tests is minimized while Design-Expert facilitates statistical analyses regarding sensitivity analysis, and modeling relations [21]. In this paper, parent concrete strength (X_1), and substitution rate of parent concrete (X_2) are considered as major factors. Three distinctive properties including compressive strength, tensile strength, and water absorption are responses. Table 5 shows the levels of a factor in this method.

In this paper, the experimental design consists of (a) four runs of the two-level factorial design, (b) four runs at the star points, and (c) one center point and its four replicates to determine the experimental error and any possible effects of curvature in the response surfaces. This test design may lead to the repetition of some experiments which seems necessary for better responses in the effects of curvature. Each response variable could be described by the quadratic model, which is shown as follows [22]:

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i<j} \beta_{ij} X_i X_j + e(X_1, X_2, ..., X_k) \quad (1)$$

where Y is the response variable, Xi is the coded value related to factor i (here between 1 and 3), β_0 is the intercept term (a constant that corresponds to the response when X_j is zero for each factor), β_i is the coefficient of the linear effects of factors on the response variable, β_{ij} is the coefficient of the interactions between factors and β_{ii} can be interpreted as the curve 'shape' parameters accounting for quadratic influences

Table 3. Physical properties of natural and recycled aggregates.

Aggregate	Specific Gravity (SSD)	Water Absorption (%)
NFA	2.51	0.87
NCA	2.63	0.43
RCA (A)	2.44	4.45
RCA (B)	2.42	4.35
RCA (C)	2.48	3.65
RCA (D)	2.53	3.30
RCA (E)	2.62	3.30

(SSD: Saturated Surface Dry)

Table 4. Natural and coarse aggregates grading.

Sieve Size (mm)	Passing Percent (%)						
	RCA (A)	RCA (B)	RCA (C)	RCA (D)	RCA (E)	NCA	NFA
19	100	100	100	100	100	100	100
12.5	45	55	40	47	50	60	100
9.5	12	22	5	10	15	25	100
6.35	3	6	2	4	6	7	95
4.75	0	0	0	0	0	3	87
2.36	0	0	0	0	0	1.5	65
1.18	0	0	0	0	0	1	38
0.6	0	0	0	0	0	0	18
0.3	0	0	0	0	0	0	4
0.15	0	0	0	0	0	0	1.5
0.075	0	0	0	0	0	0	0.5

Table 5. Factor levels for the experiment.

Experimental variable (unit)	Symbol	Coded values				
		-1.41	-1	0	+1	+1.41
parent concrete strength (MPa)	X_1	19	21.5	28	33.5	36
Substitution rate (%)	X_2	15	25	50	75	85

of the factors [21]. The coefficient of determination (R^2) and the adjusted R^2 was implemented in ANOVA (Design Expert Software) to scrutinize the variance analysis and the fitting quality of the proposed model. Moreover, F-test was used for the evaluation of the significance of linear and quadratic terms. Based on the P-value gained in ANOVA analysis with a 95% confidence level, the final subset of variables was selected. Additionally, the Design-Expert software presented three-dimensional response plots and their related contour plots.

3- Results and Discussion

3- 1- Experimental results

After crushing and sieving parent concretes, recycled concretes were prepared by substituting the recycled aggregated with natural aggregates. The workability of fresh concrete was measured according to ASTM C 143 and all specimens were molded with an acceptable slump value around 100 mm. All specimens were examined after 28 days to provide hardened properties of concrete including compressive strength (f_c), tensile strength (f_t), and water absorption. Since experimental tests were run according to the test design suggested by central composite design (CCD), all following judgments are done based on the results achieved in this test design. Table 6 shows the variable factors (X_1 to X_2) which stand for f_c of parent concrete and substitution rate, respectively, and observed responses (Y_1 to Y_3) which stand for f_c, f_t, and water absorption of recycled concrete, respectively in this research. Fig. 2 shows how effective factors (X_1 and X_2) influence responses including f_c (Y_1), f_t (Y_2), and water absorption (Y_3), respectively.

The compressive strength of recycled concrete heavily depended on the mechanical properties of parent concrete and the rate of substitution. For parent concretes with f_c of 19 MPa and substitution rate of 50%, the compressive strength (f_c) and tensile strength (f_t) of recycled concrete were 27.0 and 2.5 MPa, respectively. However, when the compressive strength of the parent concrete increased to 36 MPa (with the same percentage of substitution), f_c and f_t of recycled concrete reached 37.8 and 3.4 MPa, respectively. This represents the significant role of compressive strength of parent concrete. The value of increase for both f_c and f_t is nearly 40% which seems considerable.

Table 6. Test Design and observed values of the CCD.

RUN	Coded Values		Real Values		Responses		
	X_1 (MPa)	X_2 (%)	X_1 (MPa)	X_2 (%)	Y_1 (MPa)	Y_2 (MPa)	Y_3 (%)
1	-1.0	+1.0	21.5	75	30.0	2.9	7.5
2	0.0	-1.4	28.0	15	26.0	2.8	4.3
3	0.0	0.0	28.0	50	26.5	2.8	7.1
4	0.0	+1.4	28.0	85	30.0	3.0	7.6
5	+1.0	-1.0	33.5	25	31.8	3.1	5.2
6	+1.0	+1.0	33.5	75	33.5	3.2	5.8
7	0.0	0.0	28.0	50	26.0	2.7	7.1
8	-1.4	0.0	19.0	50	27.0	2.5	7.6
9	0.0	0.0	28.0	50	26.3	2.7	7.1
10	+1.4	0.0	36.0	50	37.8	3.4	5.2
11	0.0	0.0	28.0	50	25.8	2.8	7.1
12	0.0	0.0	28.0	50	25.7	2.7	7.1
13	-1.0	-1.0	21.5	25	32.4	3.0	6.8

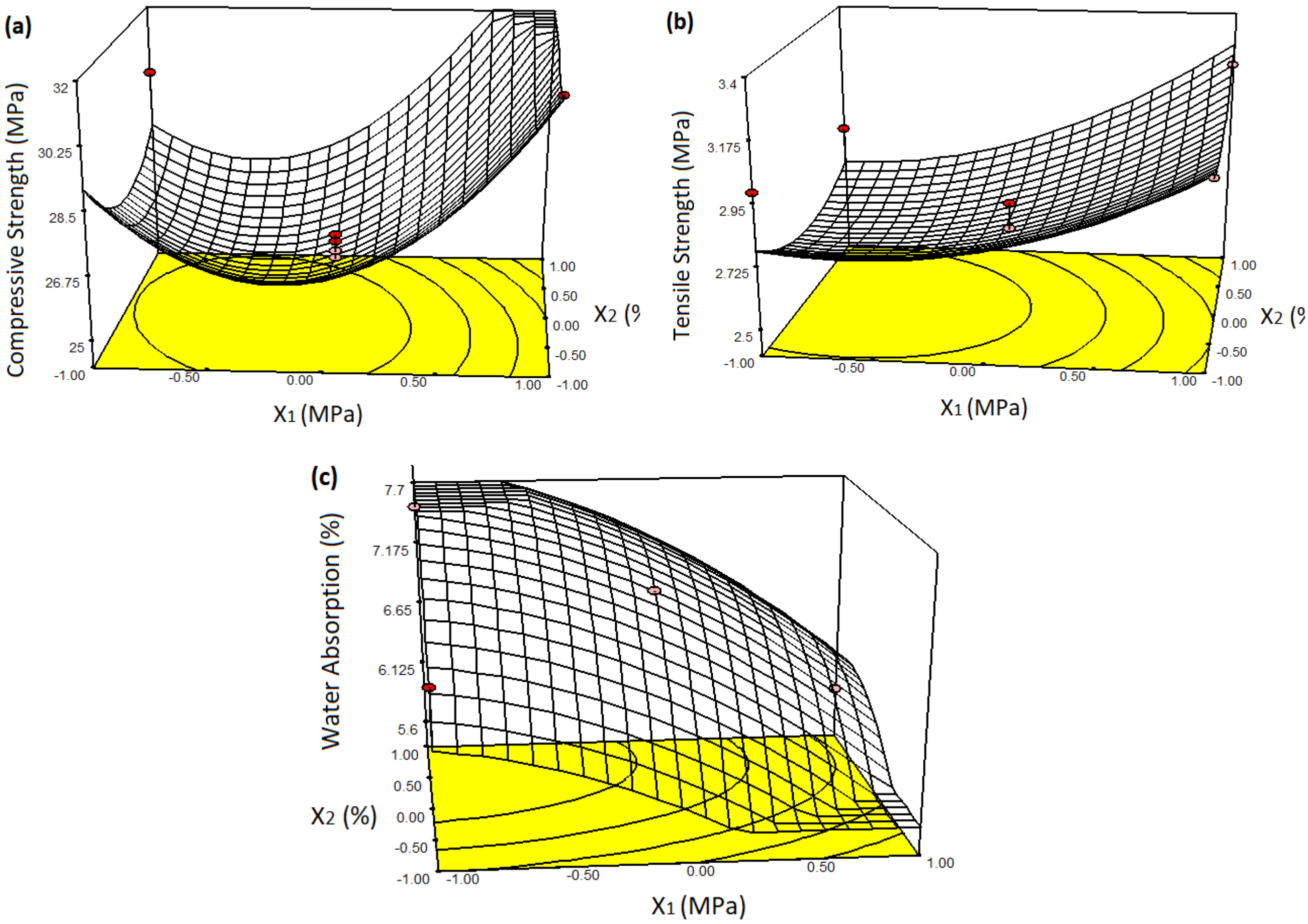

Fig. 2. 3D surface plots for Y1 to Y3.

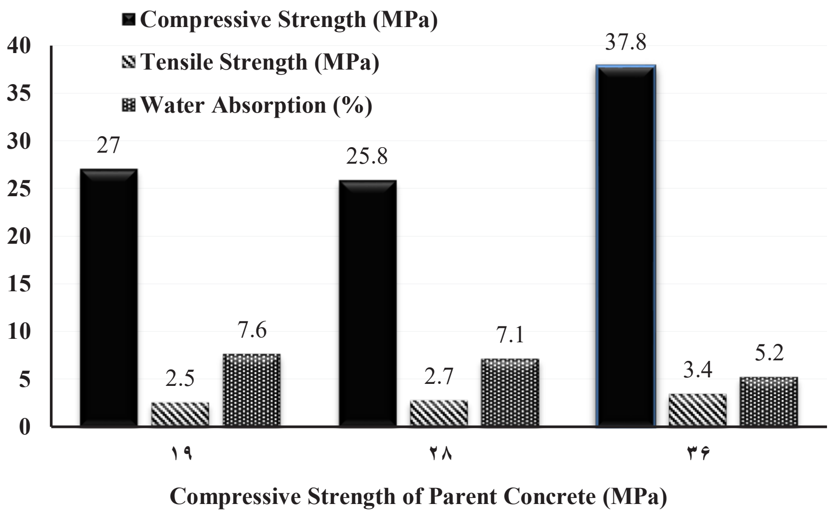

Fig. 3. Impact of parent concrete on different responses.

On the other hand, when the f_c of parent concrete is lower than 22 MPa, the increase in the percentage of substitution rate decreased the compressive strength of recycled concrete. For example, for parent concretes with f_c of 21.5 MPa, when the substitution rate increased from 25% to 75%, the f_c reduced from 32.5 to 30 MPa, respectively. Although the same behavior was observed in the tensile strength of recycled concrete, the changes were not considerable. For instance, for parent concrete with f_c of 33.5 MPa, when the substitution rate increased from 25% to 75%, the f_t enhanced from 3.1 to 3.2 MPa, respectively, which is negligible. The main reason could be attributed to the rough surface and angular shape of recycled aggregates, which provide better bond strength in the concrete matrix. The same phenomenon was seen in previous studies [10, 17]; i.e., the role of parent concrete on the mechanical properties of recycled concrete is significant.

When it comes to water absorption, concretes with higher strength values provided lower water absorption, normally because of the lower porosity of these concretes. To illustrate, at a 25% substitution rate, recycled concretes with f_c values of 33.5 MPa of parent concretes experienced water absorption of 5.2% while this value for parent concrete with f_c of 21.5 MPa was 6.8%. Moreover, in general, the more recycled aggregates were replaced, the higher was the water absorption rate. Previous studies observed similar results for water absorption of recycled concrete [10,18].

Since the effective parameters are both the compressive strength of parent concrete (X_1) and the substitution rate (X_2), it seems difficult to show the impact of each variable individually. Therefore, when the substitution rate is considered constant (50%), the impact of f_c of parent concrete on three responses is shown in Fig. 3. As it could be seen, as the f_c of parent concrete increases, the f_c of recycled concrete enhances accordingly. This observation is also true of tensile strength. However, the reverse phenomenon was seen for water absorption. In other words, the increase in f_c of parent concrete affected water absorption inversely. This observation could be attributed to the increased mechanical characteristics of recycled aggregates in higher strength parent concretes and lower possible porosity in these concretes.

3- 2- Statistical analysis of recycled concrete

In this set of information, each response is supposed to be a function of first-order (X_1, X_2), second-order (X_1^2, X_2^2), and interaction effects (X_1X_2). The responses included compressive strength (Y_1), tensile strength (Y_2), and water absorption (Y_3) of recycled concrete. In all mix ratios, free water and cement are considered constant (180 kg/m^3) and (360 kg/m^3), respectively.

The results were assessed using ANOVA in Design-Expert Software. For all responses, significant terms (P-value <0·05 for Y_1 to Y_3) were selected for inclusion in the reduced quadratic model. A new ANOVA was then performed for responses by removing specific terms and choosing the remaining set of variables. The regression models (Y_1 to Y_3) are represented by Eqs. (2) to (4), respectively, and the statistical factors obtained from ANOVA for the regression models are presented in Tables 7 and 8.

$$Y_1 = 26.08 + 2.27X_1 + 0.62X_2 + 1.03X_1X_2 + 3.59X_1^2 + 1.39X_2^2 \quad (2)$$

$$Y_2 = 2.74 + 0.21X_1 + 0.035X_2 + 0.05X_1X_2 + 0.14X_1^2 + 0.11X_2^2 \quad (3)$$

$$Y_3 = 7.10 - 0.84X_1 + 0.74X_2 - 0.025X_1X_2 - 0.31X_1^2 - 0.55X_2^2 \quad (4)$$

Table 7. Analysis of variance for the regression models.

Response	Source	*SS*	*DF*	*MS*	*F*	*P*	
Y_1	Model	144.30	5	28.86	6.62	0.014	Significant
	Residual	30.53	7	4.36			
	Lack of Fit	30.14	3	10.05	103.58	0.003	Significant
	Pure Error	0.39	4	0.097			
	Total	174.83	12				
Y_2	Model	0.56	5	0.11	5.29	0.025	Significant
	Residual	0.15	7	0.021			
	Lack of Fit	0.14	3	0.045	15.16	0.012	Significant
	Pure Error	0.012	4	0.003			
	Total	0.71	12				
Y_3	Model	12.43	5	2.49	12.33	0.002	Significant
	Residual	1.41	7	0.20			
	Lack of Fit	1.41	3	0.47			
	Pure Error	0.12	4	0.02			
	Total	13.84	12				

SS: sum of squares; *DF*: degrees of freedom; *MS*: mean square; *F*: *F*-value; *P*: probability error.

Table 8. Statistical parameters from the analysis of variance for the regression models.

Response	R^2	Adjusted R^2	*CV*	*S.D.*	*A.P.*	*PRESS*
Y_1	0.83	0.70	7.17	2.00	7.33	214.94
Y_2	0.80	0.64	5.04	0.15	5.98	0.99
Y_3	0.90	0.83	6.83	0.45	10.32	10.04

CV: coefficient of variance; *S.D.*: standard deviation; *A.P.*: adequate precision; *PRESS*: predicted residual error sum of squares.

Tables 7 and 8 show that the probability values (P-values) for all the models are less than 0.05 and all lack-of-fit F-values are larger than 0.05, which indicates that suggested models are statistically suitable. The regression coefficients (0.83, 0.80, and 0.90) were all acceptable which indicates reasonable compatibility between the models and observed data. The modified version of R^2 is adjusted R^2 that has been adjusted for the number of predictors in the model. The coefficient of variance (CV) is the percentage ratio between the standard error of the estimate and the mean value of the observed response, which indicates the reproducibility of the model. Since all coefficients of variance were low (less than 10%), the model seems to be reproducible. Adequate precision is described as a measure of the range in predicted response related to its associated error. As the adequate precision (A.P.) values were all higher than 4, models seem to be favorable. Moreover, the standard deviation (S.D.) for all experiments was under ∓ 2 which shows measurements are close to the true value. For a set of observations, the sum of squares (SS) is explained as the sum over all squared differences between the observations and their total mean. Generally, the degree of freedom (DF) is described as the number of observations when it is subtracted from the number of independent constraints imposed on the observations. Moreover, the average squared difference between the estimated values and the actual value is called the mean square value (MS).

3- 3- Perturbation plots

Perturbation plots were used as a sensitivity analysis to consider the behavior of responses due to deviation from the center point. A positive effect means that the response (Y) increases with the enhancement of the factor level (X) and a negative effect means that the response decreases due to an increase in factor level [21]. Fig. 4 shows the perturbation plots for all the responses: compressive strength (Y_1), tensile strength (Y_2), and water absorption (Y_3).

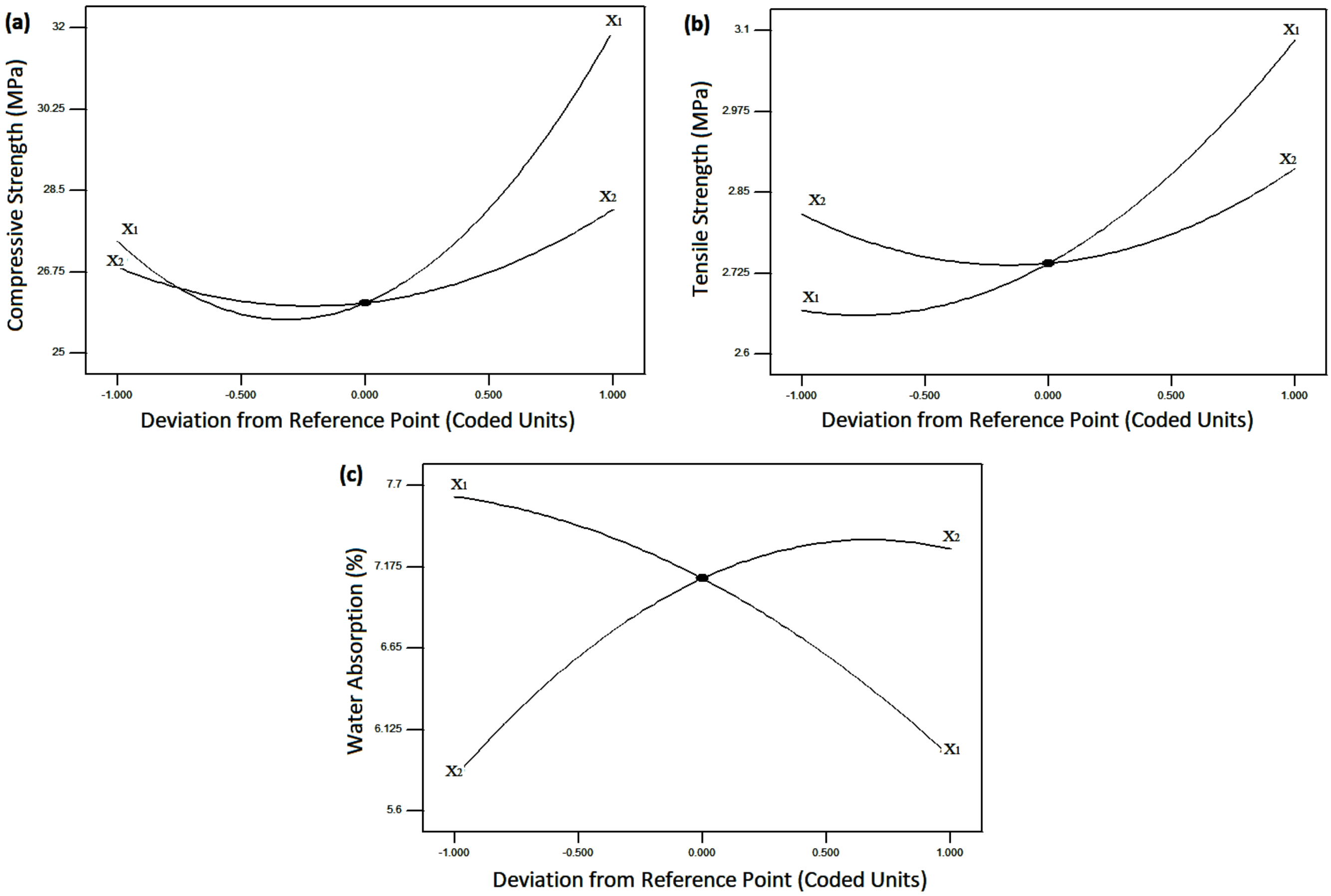

Fig. 4. Perturbation plots for Y1 to Y3.

As can be seen in Fig. 4(a), the influence of X_1 is mostly positive on Y_1. More precisely, for parent concretes with compressive strength values above 22 MPa, as the value of compressive strength of parent concrete increases, the value of compressive strength of recycled concrete enhances. However, for lower compressive strength this impact is not remarkable. Previous studies have also confirmed that the mechanical properties of recycled concrete are proportional to the compressive strength of parent concrete [17, 18]; however, no numerical equation has already been proposed. The impact of substitution rate (X_2) is also positive on the compressive strength of recycled concrete, specifically when parent concrete possesses high compressive strength. This observation is in contrast with previous reports [10]. This contradiction could be attributed to the mechanical properties of parent concrete; i.e., when parent concretes have relatively high compressive strength, recycled concrete with a high rate of substitution can gain higher mechanical properties. On the contrary, the substitution of low strength parent concrete could lead to recycled concrete with low compressive strength [17].

For tensile strength (Y_2), the perturbation plot (Fig. 4(b)) shows that the influence of X_1 is positive which seems rational because higher compressive strength of parent concrete results in higher tensile strength of recycled concrete due to better bond strength. In other words, rough surface and angular (polygon) shapes of recycled aggregates provide a better interfacial bond between matrix paste and aggregate structure [2]. The same pattern is also seen in Fig. 4(b), which recommends the use of high-strength parent concrete for higher tensile strength. The influence of X_2 indicates that for parent concretes with higher strength, a higher percentage of substitution results in higher tensile strength whereas this could not be seen in lower compressive strength (22 MPa) of parent concrete. The relative curvature in the response surface plot confirms this observation.

When it comes to water absorption (Fig. 4(c)), the perturbation plot demonstrates that the influence of X_1 is negative, which means that as the f_c of parent concrete increases, the water absorption of recycled concrete is made with such aggregates decreases. The reason is that aggregates which are derived from low strength parent concretes are probably more porous than aggregates derived from high strength parent concretes. This phenomenon was seen in previous studies as well and suggests the use of higher strength parent concrete if water absorption is needed to be limited [10, 17]. With the addition in substitution rate (X_2), water absorption of recycled concrete increases proportionally. The main reason for this phenomenon is the higher water absorption of recycled aggregates compared to natural aggregates [2, 9].

4- Conclusion

To propose an environmentally friendly method for concrete wastes, recycled concrete aggregate (RCA) was used as the substitution for natural coarse aggregates. The central composite design along with response surface methodology was practiced to model the procedure and run a sensitivity analysis. In this research, the impact of compressive strength of parent concrete (ranging from 19 to 36 MPa), and the influence of substitution rate (ranging from 15% to 85%) were considered as influential factors while compressive strength, tensile strength, and water absorption were observed as response targets. In the following, some of the most significant achievements of this study are presented.

(a) Compressive strength (f_c) of parent concrete can have an effective role in the determination of mechanical properties of recycled concrete. When 50% of RCA is added to the mixture, increasing the f_c of parent concrete from 19 to 36 MPa could enhance the f_c and f_t of recycled concrete up to 40% and 36%, respectively. To gain recycled concretes with high compressive strength values, high strength parent concretes are recommended to be used. Meanwhile, the high substitution rate of such parent concretes seems reasonable.

(b) When parent concretes possess compressive strength values lower than 22 MPa, compressive strength and tensile strength of recycled concrete would be affected negatively. For such parent concretes, addition to the substitution percentage would lead to concretes with unfavorable mechanical properties.

(c) In the design procedure, statistical analysis of the investigated models revealed R^2 values ranging from 0.80 to 0.90, which seems desirable. F-value, adequate precision, and adjusted R^2 as important factors confirmed the reproducibility of the models.

(d) Provided equations for response targets enable researchers and contractors to have a logical prediction of the behavior of parent concrete in recycled concrete.

References

[1] G. Winkler, Recycling Construction & Demolition Waste: A LEED-Based Toolkit (Green Source), McGraw-Hill, 2010.

[2] M. Batayneh, I. Marie, I. Asi, Use of selected waste materials in concrete mixes, Waste management, 27(12) (2007) 1870-1876.

[3] K. Pandurangan, A. Dayanithy, S.O. Prakash, Influence of treatment methods on the bond strength of recycled aggregate concrete, Construction and Building Materials, 120 (2016) 212-221.

[4] J. Shi, Y. Xu, Estimation and forecasting of concrete debris amount in China, Resources, Conservation and Recycling, 49(2) (2006) 147-158.

[5] L. Senas, C. Priano, S. Marfil, Influence of recycled aggregates on properties of self-consolidating concretes, Construction and Building Materials, 113 (2016) 498-505.

[6] S. Laserna, J. Montero, Influence of natural aggregates typology on recycled concrete strength properties, Construction and Building Materials, 115 (2016) 78-86.

[7] S.B. Huda, M.S. Alam, Mechanical behavior of three generations of 100% repeated recycled coarse aggregate concrete, Construction and building materials, 65 (2014) 574-582.

[8] D. Mostofinejad, S.M. Hosseini, F. Nosouhian, T. Ozbakkaloglu, B.N. Tehrania, Durability of concrete containing recycled concrete coarse and fine aggregates and milled waste glass in magnesium sulfate environment, Journal of Building Engineering, (2020) 101182.

[9] M. Nili, N. Biglarijoo, S.M. Hosseinian, S. Ahmadi, Disposing waste demolition in concrete as aggregate replacement, International Journal of Materials, 1 (2014) 105-110.

[10] N. Biglarijoo, M. Nili, S.M. Hosseinian, M. Razmara, S. Ahmadi, P. Razmara, Modelling and optimization of concrete containing recycled concrete aggregate and waste glass, Magazine of Concrete Research, 69(6) (2017) 306-316.

[11] C.J. Zega, A.A. Di Maio, Use of recycled fine aggregate in concretes with durable requirements, Waste management, 31(11) (2011) 2336-2340.

[12] S.C. Bostanci, Use of waste marble dust and recycled glass for sustainable concrete production, Journal of Cleaner Production, 251 (2020) 119785.

[13] R. Zaharieva, F. Buyle-Bodin, E. Wirquin, Frost resistance of recycled aggregate concrete, Cement and Concrete Research, 34(10) (2004) 1927-1932.

[14] S.C. Kou, C.S. Poon, M. Etxeberria, Influence of recycled aggregates on long term mechanical properties and pore size distribution of concrete, Cement and Concrete Composites, 33(2) (2011) 286-291.

[15] S. Mesgari, A. Akbarnezhad, J. Xiao, Recycled geopolymer aggregates as coarse aggregates for Portland cement concrete and geopolymer concrete: Effects on mechanical properties, Construction and Building Materials, 236 (2020) 117571.

[16] G. Bai, C. Zhu, C. Liu, B. Liu, An evaluation of the recycled aggregate characteristics and the recycled aggregate concrete mechanical properties, Construction and building materials, 240 (2020) 117978.

[17] A. Ajdukiewicz, A. Kliszczewicz, Influence of recycled aggregates on mechanical properties of HS/HPC, Cement and concrete composites, 24(2) (2002) 269-279.

[18] Padmini, K. Ramamurthy, M. Mathews, Influence of parent concrete on the properties of recycled aggregate concrete, Construction and Building Materials, 23(2) (2009) 829-836.

[19] N.M. Biglarijoo, S.A.; Ehteshami, M.; Moavenzadeh, S., Optimization of Fenton process using response surface methodology and analytic hierarchy process for landfill leachate treatment, Process Saf. Environ. 104 (2016) 150-160.

[20] N. Asadi, H. Zilouei, Optimization of organosolv pretreatment of rice straw for enhanced biohydrogen production using Enterobacter aerogenes, Bioresource technology, 227 (2017) 335-344.

[21] A. Amiri, M.R. Sabour, Multi-response optimization of

Fenton process for applicability assessment in landfill leachate treatment, Waste management, 34(12) (2014) 2528-2536.

[22] R. Oliveira, M.F. Almeida, L. Santos, L.M. Madeira, Experimental design of 2, 4-dichlorophenol oxidation by Fenton's reaction, Industrial & engineering chemistry research, 45(4) (2006) 1266-1276.

HOW TO CITE THIS ARTICLE

H. Salehi, N. Biglarijoo , H. Barkhordari, Response Surface Methodology Modelling to Study the Influence of Recycled Aggregates on Some Mechanical Properties of Recycled Concrete , AUT J. Civil Eng., 5(2) (2021) 301-310.

DOI: 10.22060/ajce.2021.18634.5689