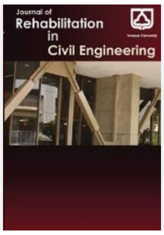

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Modeling and Optimizing Recycled Concrete Properties Using Central Composite Design: The Impact of Parent Concrete

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ABSTRACT

Recycled aggregates have gained popularity in the recent decade. In this paper, central composite design and response surface methodology as an analytical approach were implemented to determine experimental design and prepare models of concrete properties made by recycled aggregates in the lab. Three important factors were chosen: the compressive strength (f_c) of parent concretes, the rate of substitution of parent concretes, and the amount of cement. In contrast, compressive strength (f_c), tensile strength (f_t), and water absorption of recycled concrete were considered target responses. Statistical analyses reveal that models were acceptable with R^2 values. Both statistical and experimental studies represent that f_c, f_t, and water absorption of concrete mainly relied on f_c of parent concretes. The increase in the f_c of parent concretes from 19 MPa to 36 MPa led to the rise in the f_c of new concretes from 27 MPa to 38 MPa. In addition, when the substitution rate changed from 8% to 92%, f_c of concretes changed from 26 MPa to 30 MPa. Recycled concretes with higher strength could be generated if the f_c of parent concrete is high enough, mainly because of the better bond between paste and aggregates. The optimization of multiple responses reveals that a high percentage of parent concretes with high f_c could be used in concrete mixtures without a considerable fall in mechanical properties.

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1. Introduction

Waste management has always been a great concern for people. Recently, managing waste from its production to its ultimate disposal has been the center of attention throughout the world. In general, waste materials are classified into three significant items: solid waste, air emission, and wastewater. Urban solid waste creates an underlying section of solid unneeded (waste) materials among which the ratio of construction and demolition (C&D) is significant [1]. Research has demonstrated that 25 to 40 percent of all discarded solid waste in the US is related to C&D waste [2]. In addition, a large amount of solid waste materials produced in Jordan is categorized as building construction waste [3–5]. One practical approach for many construction and demolition waste materials (masonry scrap and rubble, glass, concrete, glass, ceramic, ceiling tiles, asphalt, and glass) is supposed to be disposed of in concrete material structures [6–9]. Far from the construction industry, some natural and human-induced disasters: namely flood, war, earthquake, and hurricane could result in the generation of urban solid waste. Concrete seems to be the potential material in terms of recycling since it engages a remarkable proportion of destruction materials. Previous studies provided a report that one hundred million tons of destructed concrete is produced per year in Chinese cities, which includes a large part (around 33%) of global C&D waste. Unluckily, a noticeable volume of this debris is conventionally disposed in landfill sites whereas they possess this possibility to be recycled [5,10–13]. Construction industry exploits a large number of natural aggregates resources to produce concrete structures, which is considered as a possible environmental risk [4]. One feasible remedy to the aforementioned international threat is utilizing unwanted items as recycled elements in cementitious mixtures [14]. Studying carefully the properties of recycled concretes, we can have better predictions of their performance. The performance of this eco-friendly concrete hinges upon the adhered mortar of the parent aggregates that leads to higher porosity, lower abrasion resistance, and higher water absorption in comparison with natural aggregates [15,16]. Recycled concretes are more porous normally resulting in lighter hardened mixtures in addition to less durable concretes [17]. A large number of recent researches have confirmed that the introduction of RCA lessened compressive, tensile and flexural strengths of recycled concrete [2,7,8]. In contrast, other experts have demonstrated that the performance of this eco-friendly concrete relies mainly on physical properties of original (parent) concrete and in some cases might lead to the enhancement in physical strength of new (recycled) concrete [8]. This effect mainly depends on the mechanical as well as physical properties of parent concretes which would be crushed and sieved for the generation of recycled aggregates.

Via modeling the characteristics of concrete, experts do not run unnecessary lab tests while within a short time, they can have logical predictions of concrete performances. Once different variables and their interactions are concerned, a reliable tool that could be introduced is response surface methodology (RSM), in which the experimental details could be designed and the minimum number of tests are applied [18]. RSM is a statistical as well as mathematical method that models and analyzes the process where the responses (targets) are influenced different variables [19]. Indeed, another purpose in this method is optimizing the responses [20]. A factorial-based design of experiments may be utilized to estimate a first-degree polynomial model. Nonetheless, for a second-degree polynomial model, a more comprehensive design of experiments, namely a central composite design (CCD) can be applied.

Aggregates, which are recycled from C&D waste, have different physical or mechanical properties. This would make contractors feel confused when they wish to use recycled aggregates as natural aggregates replacement. This is true that there are numerous contributions in this area, few specific models and simulations were introduced for the impact of parent (original) concrete on physical characteristics of new concrete. In other words, experimental investigations have been performed on the behavior of recycled concretes, but few models were presented to assess the impact of f_c of parent concrete, substitution percentage, and w/c ratio. Moreover, maintaining the appropriate behavior of recycled concretes as well as disposing a large amount of wastes in recycled concrete could be considered as both a cost-effective and an environmental-friendly approach.

The main objective of this research article is to cover a section of this gap in literature as a rehabilitation approach by i) conducting laboratory tests focusing on the influence of RCA on the mechanical characteristics of recycled (new) concretes; ii) introducing a model for the impact of parent concretes on f_c, f_t, and water absorption of new concrete and optimize the affecting factors. It is notable that this paper only address f_c, f_t and water absorption of recycled concretes, and durability properties are not seen.

2. Experimental studies

2.1. Aggregates

In this research, two types of aggregates were used. The first type refers to natural aggregates, which include both fine aggregates (sand) and coarse aggregates (gravel). The second type refers to recycled concrete aggregates (RCA) that include only coarse aggregates (gravel). It is notable that the main reason fine RCA was not examined is that previous studies have reported the unpleasant impact of fine RCA on concrete characteristics [10].

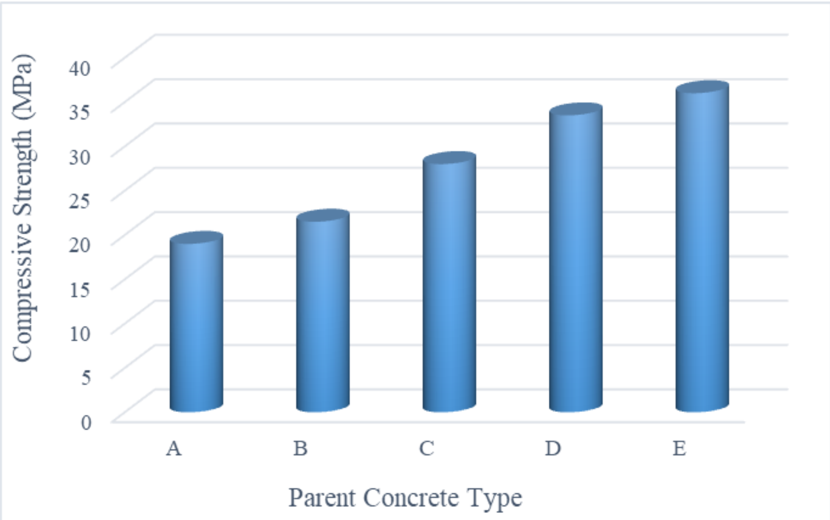

Fig. 1. Compressive strengths of parent concretes.

In order to have a broad range of mechanical/physical characteristics for recycled aggregates, five particular parent concretes were selected from laboratory specimens, debris and sidewalk curbs. Then, these five parent concretes were mechanically broken into small sizes and sieved at objective sized in the lab to generate recycled aggregates. The wide range (from 19 MPa to 36 MPa) of strength which is common in real-case projects gives us the opportunity to evaluate the impact of parent concrete as the substitution of natural coarse aggregates. In Figure 1, f_c of five distinctive parent concretes, namely: A to E are reported.

These recycled concrete aggregate (RCA) had different properties from natural aggregates. The physical characteristics of the natural aggregates (coarse as well as fine) and recycled aggregates (coarse) are illustrated in Table 1. As it could be seen in table 1, recycled aggregates (all five types) were lighter than natural aggregates but absorbed more water. The main reason for the lighter weight and more absorption of water is the higher and larger porosity of RCA aggregates in comparison with natural ones. Moreover, these aggregates possess some adhered mortar on their surface, which affect their physical/mechanical characteristics remarkably. The curves (for analyzing the size) of natural sand, natural gravel and recycled gravel are demonstrated in figures 2, 3, and 4, respectively. The largest size particle of gravel was restricted to 19 mm in all mix designs. As could be seen in figure 3, the grading curve for five recycled aggregates was approximately close to each other.

Table 1. Physical/mechanical characteristics of gravel and sand.

Aggregate	Specific gravity (SSD)	Water absorption (%)
Natural sand	2.51	0.87
Natural gravel	2.63	0.43
RCA-Type A	2.44	4.45
RCA-Type B	2.42	4.35
RCA-Type C	2.48	3.65
RCA-Type D	2.53	3.30
RCA-Type E	2.62	3.30

2.2. Cement

Cement type I was utilized in this research. The chemical and physical characteristics of cement is represented in table 2. No other cementitious materials were used.

2.3. Water

Water from tap was used to prepare concrete mixtures and specimens. For all test designs, slump test was conducted to examine workability of the fresh mixture to hold suitable workability. In order to keep the objective workability of the concrete mixes at slump number of 10cm, a high range water reducer (HRWR) was applied. Meanwhile, the value of water for all mixtures was fixated at 180 kg/m^3 and the value of cement changed.

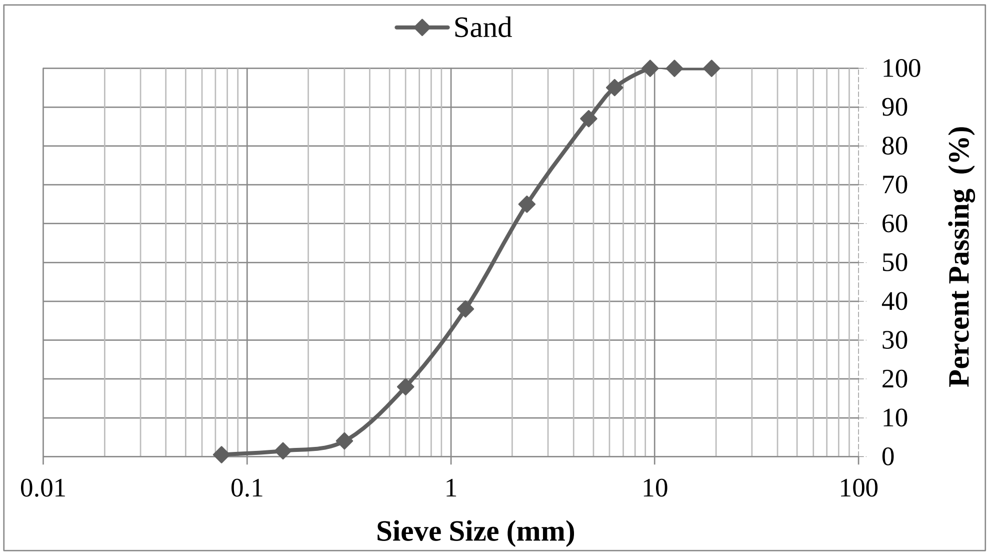

Fig. 2. The grading curve of natural sand.

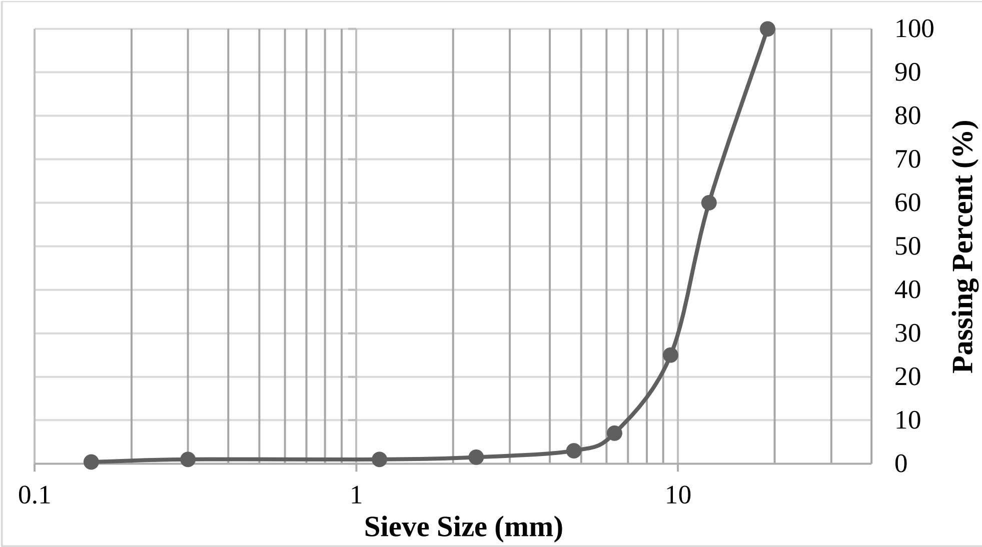

Fig. 3. The grading curves of natural coarse aggregate.

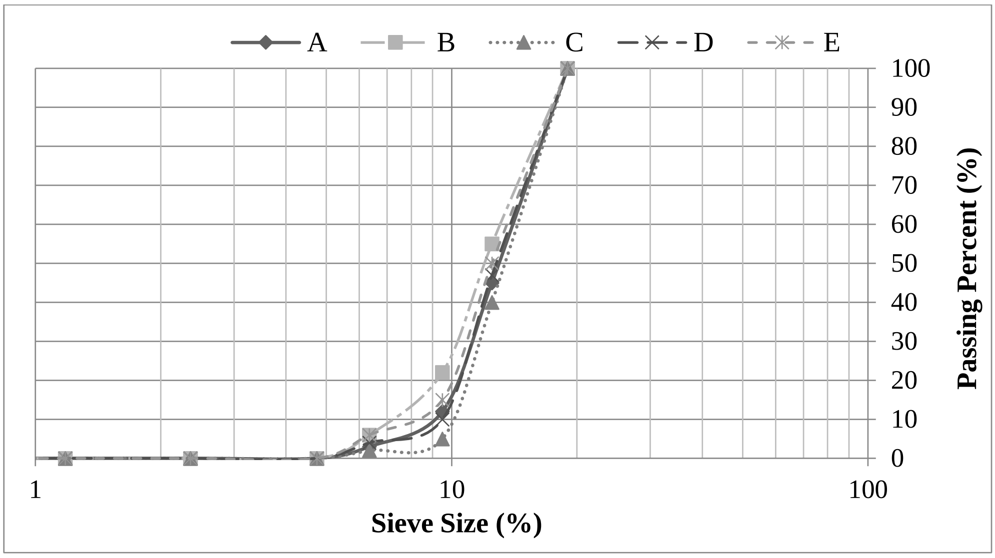

Fig. 4. The grading curve of recycled coarse aggregate.

Table 2. Chemical/physical characteristics of cement.

Property	Percentage
SiO_2	21.41%
Al_2O_3	4.88%
Fe_2O_3	3.82%
CaO	63.69%
MgO	1.56%
SO_3	2.36%
K_2O	0.65%
Na_2O	0.47%
C_3A	6.47%

2.4. Test design

Since designing experimental tests with conventional methods due to a large number of tests does not seem cost-effective and is time-saving, in the current study, central composite design (CCD) joined with response surface methodology (RSM) [21] were implemented to design experiments and evaluate the impact of three significant factors (X_i) on three significant responses (Y_i). Therefore, the Design Expert Software (11.0.0) was applied for the design of tests and data assessment. With the aid of CCD, test numbers can be minimized whereas this method helps with statistical assessment in terms of sensitivity analysis, and modeling relations [18]. Since five levels of tests were considered for each variable, 125 tests had to be done in the traditional test design; however, with the help of CCD test design, this large number reduced to 20 tests only.

Three variables were considered as major factors consisted of f_c of parent concrete (X_1), substitution percentage of recycled aggregates (X_2) and cement amount (X_3). Five values of X_1 were used as replacement for natural gravel (19, 22.5, 28, 33, and 36 MPa). These recycled aggregates were replaced partially at 8, 25, 50, 75 and 92 percent with natural gravel. The high percentage of replacement was suggested in other papers to evaluate the real influence of RCA in the concrete matrix [10,15]. Cement was also used as 310, 330, 360, 390 and 410 kg/m^3 in this experiment design. Major factors including X_1, X_2 and X_3 and their variations are shown in table 3. As could be seen, in CCD method, each variable is coded between -1.68 and +1.68.

Table 3. Details of factor for the test.

Test variable (unit)	Symbol	Coded quantities				
		-1.68	-1	0	+1	+1.68
Parent f_c (MPa)	X_1	19	22.5	28	33	36
Substitution rate (%)	X_2	8	25	50	75	92
Cement value (kg/m^3)	X_3	310	330	360	390	410

In order to assess the effect of major factors on the characteristics of concrete, 20 mix designs were introduced. Table 4 shows the proposed mix designs generated by the software. In this table, since all variables are shown by coded values, some meaningful names are attributed to each mix design to make it more understandable. For instance, f36S25C390 shows the mix design with the following properties: i) compressive strength of parent concrete (f = 36 MPa); ii) recycled aggregate substitution rate (S = 25%); iii) cement value (C = 390 kg/m^3).

In this test design, the experiment design consists of (a) six tests of the two stage factorial design, (b) eight tests at the star nodes and (c) one central area and its five repetitions to discern the experiment error and any probable influences of a curving shape in the response surfaces. Every target response could be designated by the quadratic model demonstrated as follows [20]:

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

where Y is the target, Xi is the coded number relevant to factor i (changing from 1 to 3), β_0 is a fixated number that is related to the target when X_j is zero for every input element (intercept), β_i is the coefficient value of the linear impacts of elements on the target, β_{ij} is the coefficient of the interactions between variable factors and β_{ii} can be explained as the curve 'shape' components identifying quadratic impacts of the elements [20].

Thereafter, three specific properties consisting of compressive strength (Y_1), splitting tensile strength (Y_2), and water absorption (Y_3) tests were introduced as responses in the Design Expert Software. After 28 days, the aforementioned tests were done on hardened concrete and were inserted in Design Expert Software to produce the model and analyses.

Table 4. Proposed mix design by Design Expert Software.

Run	Experiment	X_1	X_2	X_3	Cement	Water	w/c	Natural Gravel	Recycled Gravel	Natural Sand
		(MPa)	(%)	(kg/m^3)	(kg/m^3)	(kg/m^3)	-	(kg/m^3)	(kg/m^3)	(kg/m^3)
1	C390S25F33	1.00	-1.00	1.00	390.00	180.00	0.46	617.00	206.00	908.00
2	C390S75F33	1.00	1.00	1.00	390.00	180.00	0.46	206.00	617.00	908.00
3	C360S50F28	0.00	0.00	0.00	360.00	180.00	0.50	416.50	416.50	928.00
4	C360S50F28	0.00	0.00	0.00	360.00	180.00	0.50	416.50	416.50	928.00
5	C360S50F36	1.68	0.00	0.00	360.00	180.00	0.50	416.50	416.50	928.00
6	C390S25F22	-1.00	-1.00	1.00	390.00	180.00	0.46	617.00	206.00	908.00
7	C390S75F22	-1.00	1.00	1.00	390.00	180.00	0.46	206.00	617.00	908.00
8	C330S25F33	1.00	-1.00	-1.00	330.00	180.00	0.55	632.00	211.00	948.00
9	C360S92F28	0.00	1.68	0.00	360.00	180.00	0.50	0.00	833.00	928.00
10	C330S75F22	-1.00	1.00	-1.00	330.00	180.00	0.55	211.00	632.00	948.00
11	C360S50F28	0.00	0.00	0.00	360.00	180.00	0.50	416.50	416.50	928.00
12	C330S25F22	-1.00	-1.00	-1.00	330.00	180.00	0.55	632.00	211.00	948.00
13	C330S75F33	1.00	1.00	-1.00	330.00	180.00	0.55	211.00	632.00	948.00
14	C360S50F28	0.00	0.00	0.00	360.00	180.00	0.50	416.50	416.50	928.00
15	C360S50F28	0.00	0.00	0.00	360.00	180.00	0.50	416.50	416.50	928.00
16	C360S8F28	0.00	-1.68	0.00	360.00	180.00	0.50	833.00	0.00	928.00
17	C360S50F28	0.00	0.00	0.00	360.00	180.00	0.50	416.50	416.50	928.00
18	C310S50F28	0.00	0.00	-1.68	310.00	180.00	0.60	424.00	424.00	963.00
19	C360S50F19	-1.68	0.00	0.00	360.00	180.00	0.50	416.50	416.50	928.00
20	C410S50F28	0.00	0.00	1.68	410.00	180.00	0.43	409.00	409.00	893.00

3. Results and discussion

3.1. Experimental results

Figure 5 (5a, 5b, and 5c) illustrates the response surface plots for response targets (Y_1 to Y_3 respectively). As can be observed in figures 5 to 7, when the amount of cement is fixed at 360(kg/m^3) and substitution rate is constant at 50%, by increasing the compressive strength (f_c) of parent concrete from 19 MPa to 36 MPa, the compressive strength of recycled concrete improved from 27 MPa to 38 MPa, which is over 40% increase in compressive strength. The similar phenomenon was scrutinized for tensile strength of recycled concretes. The tensile strength increased from 2.7 MPa to 3.4 MPa. This increase in strength was around 25%. Additionally, water absorption reduced from 7.6% to 5.2% for this comparative observation. Previous researches have reported the same observation [22,23]. The main reason for this favorable behavior is better bond between recycled aggregates and concrete matrix. Moreover, higher strength recycled aggregates (from parent concretes) possessed less adhered mortar, which dictates a better mechanical performance. The main reason is that the adhered mortar to recycled aggregates mostly possess higher mechanical strength in high strength parent concretes; therefore, the derived concretes perform better in terms of compressive and tensile strength. This aligns with previous research [24].

According to ACI 318 code, for residential applications, f_c of 2500 psi (17 MPa) is required. For non-residential structures, the minimum required strength is higher and around 3000 psi (21 MPa) or more. Concretes made with recycled aggregates in this paper were all above 21 MPa which indicates the applicability of such concrete for structural uses. More importantly, in case higher cement content and adequate substitution rate are considered, compressive strengths higher than 30 MPa were achieved.

Another interesting observation was for constant value of cement (360 kg/m^3) and constant value of compressive strength of parent concrete (28 MPa). In this condition, when substitution rate changed from 8% to 92%, compressive strength (f_c) of concrete changed from 26 MPa to 30 MPa. In addition, tensile strength (f_t) of concrete improved from 2.8 MPa to 3.1 MPa. All these behaviors are favorable since there is a relative improvement in mechanical properties of recycled concrete.

However, this observation was not seen for other specimens. In other words, for mixtures that compressive strength of parent concrete was 22.5 MPa and cement value was 330 kg/m^3, when substitution rate enhanced from 25% to 75%, compressive strength of recycled concretes decreased from around 28 MPa to around 26.5 MPa. As a result, the quantity of compressive strength (f_c) of parent concrete plays an important role in substitution rate. Based on our observations, when compressive strength (f_c) of recycled aggregates is above 28 MPa, higher substitution rate can be desirable while for lower values, this substitution should be restricted. Not surprisingly, as the substitution rate enhanced, the water absorption of concretes increased. The main reason could be the higher value of attached mortar to recycled aggregates than natural aggregates [18].

In case the f_c of parent concrete and substitution rate were fixed at 28 MPa and 50%, by enhancing the value of cement from 310 kg/m^3 to 410 kg/m^3, the f_c of recycled concretes grew from 26 MPa to 29 MPa. The main reason could be relevant to the better bond between aggregates and paste. In general, the cement content in concrete mixtures contributes to higher compressive strength because cement is the binding agent that binds the ingredients together (aggregates and water). Therefore, more amounts of cement is interpreted as more binder that causes a denser and stronger concrete matrix. Nevertheless, this trend falls at a specific point that adding too much cement can, in fact, weaken the concrete and result in concerns such as cracking [25]. In contrast, no specific change was seen for tensile strength. When it comes to recycled aggregates, high cement content could be interpreted as a remedy for micro-gaps to create better bonding between matrix elements. Moreover, high cement content would increase f_c and f_t of recycled concrete in the range of this test design.

One important point that must be mentioned is the complicated quality control in real-world applications of recycled aggregates. They are variable in properties that makes maintaining workability, bonding, durability and mechanical properties a big concern for engineers. Moreover, as long-term influences of such aggregates are not seen, engineer try to be cautious using high percentage of substitution for some possible long-term effects. In order to help with quality control in real-world practices, this suggestion is presented. In general, recycled coarse aggregates possess lower adhered mortar, so their properties are closer to natural aggregates. Sieving recycled aggregates help remove fine aggregates (most likely with unfavorable properties) and keep coarse aggregates.

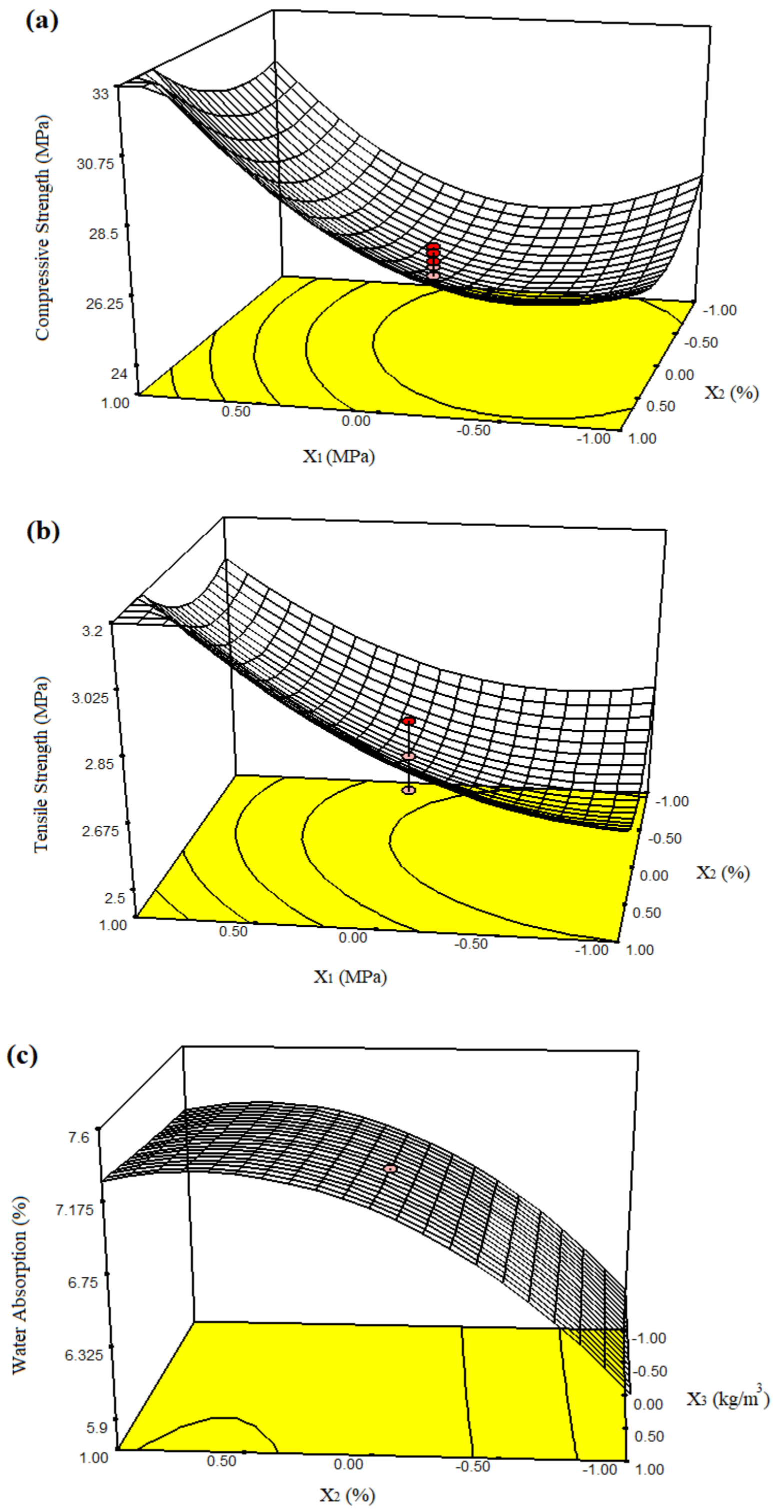

Fig. 5. Response surface figure for responses Y_1 to Y_3.

3.2. Statistical analysis of recycled concrete

To our knowledge, few research papers have concentrated on modelling the impact of parent concrete on recycled concretes. Table 5 shows the variable factors (X_1 to X_3) and observed targets (Y_1 to Y_3) in this research. Every response is supposed to be a math function of first order (X_1, X_2, X_3), second order (X_1^2, X_2^2, X_3^2) and interaction influences (X_1X_2, X_1X_3, X_2X_3). The responses consisted of f_c (Y_1), f_t (Y_2), and water absorption (Y_3) of recycled concrete.

Table 5. Designed items and laboratory quantities of the CCD.

RUN	Experiment	X_1	X_2	X_3	Y1	Y2	Y3
		(MPa)	(%)	(kg/m^3)	(MPa)	(MPa)	(%)
1	C390S25F33	1.00	-1.00	1.00	31.8	3.1	5.2
2	C390S75F33	1.00	1.00	1.00	35.4	3.4	5.8
3	C360S50F28	0.00	0.00	0.00	26.5	2.8	7.1
4	C360S50F28	0.00	0.00	0.00	26.0	2.7	7.1
5	C360S50F36	1.68	0.00	0.00	37.8	3.4	5.2
6	C390S25F22	-1.00	-1.00	1.00	32.4	3.0	6.8
7	C390S75F22	-1.00	1.00	1.00	32.5	3.1	7.5
8	C330S25F33	1.00	-1.00	-1.00	34.0	3.3	5.1
9	C360S92F28	0.00	1.68	0.00	30.0	3.1	7.55
10	C330S75F22	-1.00	1.00	-1.00	26.5	2.6	7.4
11	C360S50F28	0.00	0.00	0.00	26.3	2.7	7.1
12	C330S25F22	-1.00	-1.00	-1.00	28.2	2.8	6.7
13	C330S75F33	1.00	1.00	-1.00	36.0	3.5	5.7
14	C360S50F28	0.00	0.00	0.00	25.5	2.6	7.1
15	C360S50F28	0.00	0.00	0.00	25.8	2.8	7.1
16	C360S8F28	0.00	-1.68	0.00	26.0	2.8	4.3
17	C360S50F28	0.00	0.00	0.00	25.8	2.7	7.1
18	C310S50F28	0.00	0.00	-1.68	22.5	2.4	7.1
19	C360S50F19	-1.68	0.00	0.00	27.0	2.5	7.6
20	C410S50F28	0.00	0.00	1.68	28.7	2.8	7.4

All achieved results were thoroughly examined the utilization of ANOVA in Design Expert Software. The coefficient of correlation (R^2) and the adjusted R^2 were used in ANOVA to evaluate the variance examination and the fitting ability of the suggested formula. Additionally, for the assessment of linear and quadratic terms, F-test was run. According to the p-values obtained from ANOVA with a 95% certainty, the ultimate subset of variables was chosen. For the whole targets, meaningful terms were opted for entering the reduced quadratic model. A new ANOVA was then run for targets by omitting particular terms and selecting the remaining set of variables. The regression relations (Y_1 to Y_3) are shown by Equations 2–4 and the statistical factors achieved by the ANOVA for the regression equations are displayed in Tables 6 and 7. Using these equations, by substituting objective values as X_i, Y_i could be obtained. It is remarkable to note that in order to use models, values for X_i should be replaced as coded values ranging from (-1.68) to (+1.68).

$$Y_1=25.88+2.62X_1+0.79X_2+1.31X_3+0.90X_1X_2-1.62X_1X_3+0.43X_2X_3+2.96X_1^2+1.40X_2^2+0.55X_3^2 \quad (2)$$

$$Y_2=2.71+0.24X_1+0.066X_2+0.079X_3+0.075X_1X_2-0.12X_1X_3+0.50X_2X_3+0.14X_1^2+0.14X_2^2+0.014X_3^2 \quad (3)$$

$$Y_3=7.11-0.78X_1+0.59X_2+0.066X_3-0.025X_1X_2-0.29X_1^2-0.46X_2^2+0.007X_3^2 \quad (4)$$

Table 6. Variance evaluation for the predicting formulas.

Response	Source	SS	DF	MS	F	P	
Y_1	Model	298.88	9	33.21	7.80	0.0018	Significant
	Residual	42.59	10	4.26			
	Lack of Fit	41.92	5	8.38	62.73	0.0002	Significant
	Pure Error	0.67	5	0.13			
	Total	341.45	19				
Y_2	Model	1.63	9	0.18	6.59	0.0034	Significant
	Residual	0.28	10	0.028			
	Lack of Fit	0.25	5	0.049	8.72	0.0165	Significant
	Pure Error	0.028	5	0.005			
	Total	1.91	19				
Y_3	Model	17.15	9	1.91	12.24	0.0003	Significant
	Residual	1.56	10	0.16			
	Lack of Fit	1.56	5	0.31			
	Pure Error	0.00	5	0.00			
	Total	18.70	19				

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

Tables 6 and 7 show that P-values (probability) for the presented formulas are less than 5% and all F-values (lack-of-fit) are larger than 5%, which proves that proposed formulas are logical in terms of statistical studies. The regression values (0.88, 0.86, and 0.92) were all within the acceptable range which shows reasonable adjustability between the formulas and experimental data. Generally, the altered version of R^2 is adjusted R^2 that is modified for some predictors in the model. It is notable that the adjusted R^2 can be negative and is always lower than the R^2 and based on the obtained results, this value seems reasonable. The coefficient of variance or CV is a ratio in percentage between the standard error of the estimated value and the mean value of the evaluated target that indicates the reproducibility of the model. All CV values were under 10%, which indicates that the models are reproducible. Adequate precision (A.P.) is defined as an evaluation criterion of the range in foreseen target relevant to its connected error. As A.P. numbers were all more than 4, proposed formulas sound to be acceptable. Usually, a significant level (denoted often as α with the value of 0.05) is a set of threshold. If the p-value is less that this index, it is considered significant. It means there is strong evidence that the factor influences the dependent variable.

The main source of variance could be the input data; i.e. in experimental work the existence of error is inevitable. This would affect the results as noise. Meanwhile, for small datasets, it is possible that regression line that must fit the data cannot interpret it well.

Table 7. Statistical elements from the variance evaluation for the predicting formulas.

Response	R^2	Adjusted R^2	CV	S.D.	A.P.	PRESS
Y_1	0.88	0.76	7.06	2.06	9.56	317.73
Y_2	0.86	0.73	5.71	0.17	8.64	1.91
Y_3	0.92	0.84	5.98	0.39	10.79	11.82

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

Figure 6 demonstrates the figures of predicted quantities versus actual quantities for all targets. These figures indicate logical agreement between the experimental information and these fitted formulas. This figure confirms that proposed models are reasonable predictors of recycled concrete behaviors.

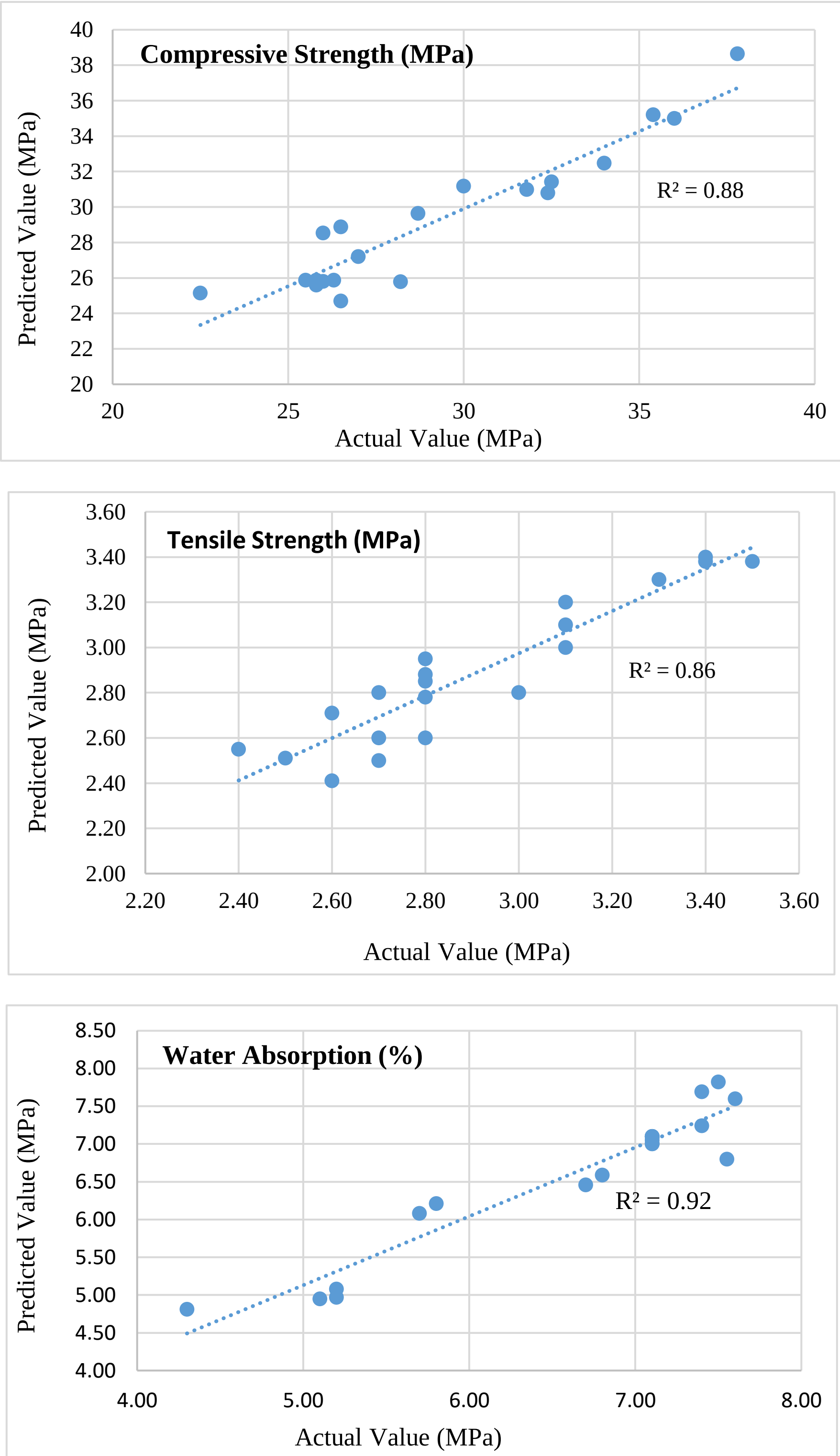

Fig. 6. Actual versus predicted quantities for targets. (a) Compressive strength; (b) Tensile strength; (c) Water absorption.

3.3. Perturbation figures

Perturbation figures were utilized as sensitivity analysis so as to evaluate the behavior of targets in terms of deviation from the central point. A positive impact has the meaning that the target (Y) enhances by rise of the factorial level (X) and a negative impact is interpreted as the target decreases due to a rise in factorial level [3]. Figures 7 (7a, 7b, and 7c) illustrates the perturbation figures for three targets: f_c (Y_1), f_t (Y_2), and water absorption (Y_3) respectively.

According to figure 7a, the influence of X_1 parameter is mainly positive on Y_1. More accurately speaking, for parent (original) concretes with f_c quantities above 28 MPa, as the value of f_c of parent concrete enhances relatively, the f_c of new concrete rises. This could be related to the fact that parent concretes with higher compressive strength possess lower water to cement ratio, better bond between aggregates and paste, and lower porosity in the matrix. When parent concretes are crushed and sieved, the adhered mortar to aggregates (in recycled aggregates) could play the important part in the final strength of every single recycled aggregate. Thus, the higher the f_c of parent concrete (in this research this threshold is determined based on the statistical analysis), the higher f_c of recycled concrete. The threshold for this strength increase (28 MPa) is derived from statistical analysis and sensitivity analysis of the experimental results, but the explanation for this phenomenon is due to the fact that parent concretes with fc lower than 28 are usually classified as middle range or low range compressive strength that have high porosity and weak bond between aggregates and paste. However, for lower values of f_c this influence is not noticeable and articles in the literature have acknowledged that mechanical/physical characteristics of new concrete depends remarkably on the physical characteristics of parent concrete [10] whereas no formula has been suggested yet. The influence of replacement rate (X_2) is positive as well on f_c of recycled concrete, particularly when compressive strength of the parent concrete is high. This mentioned phenomenon is not compatible with recent research papers [18] and could be interpreted as the physical mechanical features of parent concrete differ; i.e. when compressive strength in parent concretes is relatively high, recycled (new) concretes can have better mechanical properties in high substitution rates. In contrast, the lower f_c values of parent concretes, the lower the f_c of new concretes [10]. The influence of cement (X_3) is thoroughly positive which seems very logical since for a constant amount of water, the w/c ratio decreases relatively [26]. This lower w/c ratio enhances f_c of recycled concrete.

The perturbation figure (figure 7b) of tensile strength (Y_2) indicates that the impact of X_1 is positive. It looks logical since the high f_c values of parent concrete leads to high tensile strength (f_t) of recycled (new) concrete. This is mainly because of better bond between aggregates and paste in parent concrete. It means recycled aggregates have rough surface and angular or polygon shapes that could make better interfacial bond between aggregate structure and matrix paste [22]. Therefore, high tensile strength in new concretes require high compressive strength of parent concrete. The impact of X_2 implies that when f_c of parent concrete is higher than 28 MPa, higher substitution percentages can be used with high tensile strength. On the contrary, this phenomenon could not be seen for f_c lower than 28 MPa of parent concrete. The partial curvature in the surface figure verifies this information. According to figure 6, the highest tensile strength is seen at the highest fc of parent concrete. At this high fc of parent concrete, high rate of substitution could be applied. However, the partial curvature around the center indicates that low tensile values could be for parent concrete lower than 28 MPa which is exactly at the center point. The influence of X_3 is not that noticeable although it partly helps to reach high tensile strength (f_t) of concrete with the rise in cement value.

Figure 7c depicts water absorption of recycled concrete. The perturbation figure indicates that X_1 has a negative influence; i.e. with the rise of f_c of parent concrete, water absorption decreases. This negative correlation in figure 11 suggests the utilization of high f_c of parent concrete for low values of water absorption of recycled concrete [18]. With addition in substitution rate (X_2), water absorption of recycled (new) concrete enhances. This is because recycled aggregates possess high water absorption in comparison with natural gravel [6]. The amount of cement did not play a critical role in Y_3 compared to other factors (X_1 and X_2). This impact was positive and linear which shows that with the increase in X_3, the value of Y_3 enhances relatively. It is notable that submersion of concretes with higher water absorption could lead to some unfavorable consequences such as lower strength, chemical attack, and corrosion. Concretes with lower w/c may be more resistant and are more desirable.

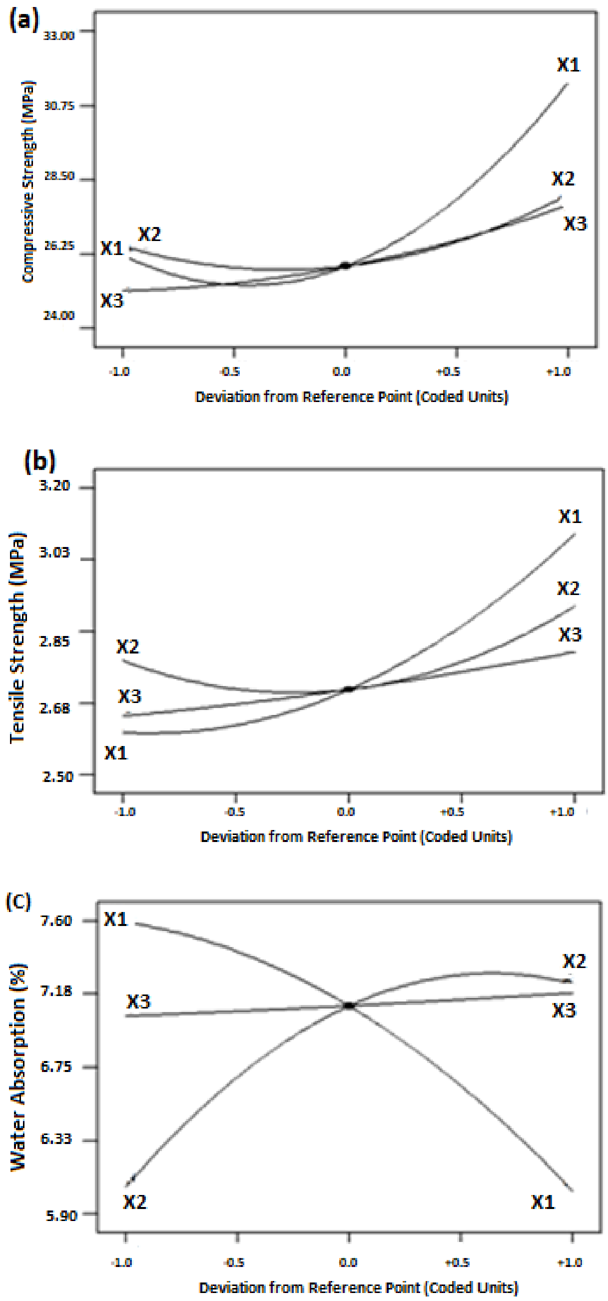

Fig. 7. The perturbation plot for responses Y_1 to Y_3. (a) Compressive strength; (b) Tensile strength; (c) Water absorption.

3.4. Optimization of the process

One major benefit of multiple responses is to introduce conditions in which the whole targets can favorably perform. In the current paper, the numerical optimization process from Design Expert Software was utilized to have the most desirable condition for all three target responses. In this procedure, f_c and f_t were determined to be maximized while water absorption was supposed to be minimized. Nevertheless, in practice, there may be situations where other purposes of optimization might be objective, namely: high water absorption for permeable concretes or light weight insulating concrete. It is notable that the importance of each factor was assumed to be the same. Therefore, after criteria had been defined in the optimization section of the software, the best solution was proposed. The suggestion for input values are as follows: parent concrete strength: 36 MPa, substitution rate: 92%, and cement value: 310 kg/m^3. The main reason is that we are looking for a point in which all three response targets can perform efficiently. Although the cement content could slightly increase compressive strength, the impact on tensile strength is negligible and the effect on water absorption is not favorable. Therefore, the lowest cement content decreases the water absorption (favorable impact), does not affect tensile strength, and negligible effect on compressive strength.

According to these results, not only is the highest amount of substitution necessary, but also the lowest value of cement is added for the most favorable concrete mixture. Figure 8 depicts the achieved results. As it can be seen, the optimized value for three responses is as follows: compressive strength: 34.99 MPa, water absorption: 6.08%, and tensile strength: 3.38 MPa.

It is remarkable to point that in this paper the optimization is done based on the desire to produce concrete with high compressive and tensile strength with low water absorption. However, in cases where strength is of second important and water absorption could be pleasant, other optimization goals might be considered. First, permeable concrete for storm water management in which permeable pavement helps storm water infiltrate and filter through concrete to recharge groundwater or reduce runoff; second, lightweight and insulating concrete to provide high porosity for better insulation.

3.5. Economic and environmental considerations

From an environmental aspect, recycling aggregates helps minimize the disposal needs. First, this action reduces the volume of waste materials delivered to landfills. Also, recycling debris and demolitions extend the life cycle of natural aggregate sources and support a more sustainable circular economy because materials are reused instead of disposed. Second, protecting natural resources is important as mining natural gravel and sand is reduced by recycling and natural habitat is protected against mining and quarrying that put ecosystem and habitat in danger. Third, in terms of energy consumption and CO_2 emission, recycled concretes can be helpful as they reduce energy in production processes (namely: crushing, processing, and transportation) that contribute to less CO_2 emission. Fourth, in the production processes, a lot of water is used for washing that not only wastes the water sources but also generate wastewater that both are environmental concerns. Last, using recycled aggregates would help build more green constructions and earn points in certifications such as LEED.

From an economic aspect, recycling can help in the following ways. First, producing aggregates is cost-benefit because the costs of extraction, crushing, and transportation decrease in comparison with recycled aggregates. Second, the cost of disposing wastes in landfills and related transportation costs decrease. Third, this could create new job opportunities for new-coming businesses to produce and sell such aggregates. A photo from recycled aggregate versus natural aggregates is shown in figure 9. The amount of adhered mortar is clear in the recycled aggregate.

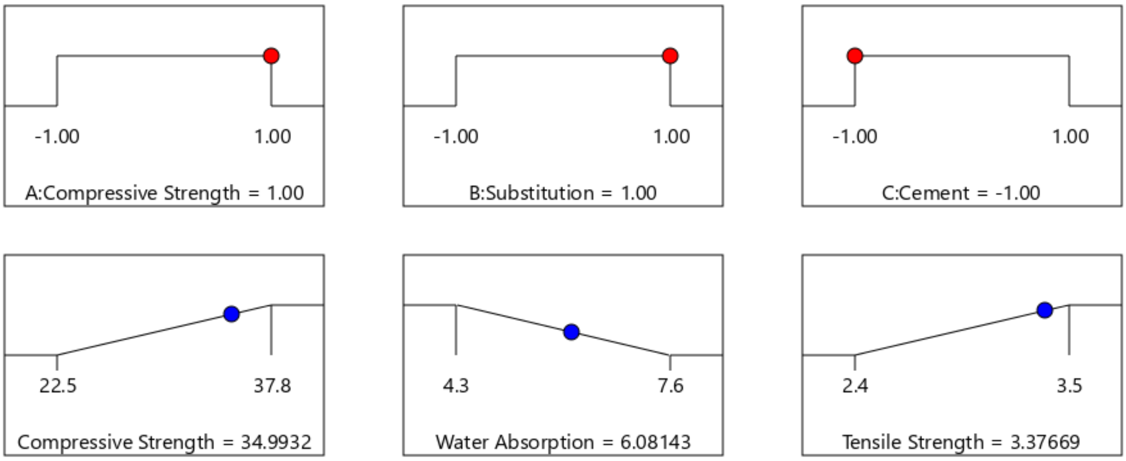

Fig. 8. Achieved results from the Design Expert Software for optimization.

Fig. 9. A real picture of recycled aggregates versus natural aggregate.

4. Conclusions

To safely dispose of solid wastes in concrete, recycled concrete aggregate (RCA) was replaced with natural coarse aggregates. For modeling the procedure and performing the sensitivity analysis, the CCD, along with RSM, was practiced. In the current article, the effect of f_c of parent concretes (changing from 19 MPa to 36 MPa), the impact of replacement rate (changing from 8% to 92%), and the value of cement (altering from 310 kg/m^3 to 410 kg/m^3) were introduced as effective elements whereas f_c, f_t, and water absorption were studied as targets. Some of the most remarkable accomplishments of this environmentally friendly practice are introduced hereunder for the rehabilitation of environmental resources.

(a) Mechanical and physical characteristics of parent concrete determine the physical properties of recycled (new) concrete. Indeed, the higher the f_c of parent concrete, the higher the f_c and f_t of recycled concrete.

(b) Statistical evaluation indicates that all models possess R^2 values between 0.86 and 0.92 that are acceptable. The quantities of F-value, A.P., and adjusted R^2 all confirm reproducibility of the predicting models.

(c) Optimization of all three responses at the same indicates that a high substitution rate of parent concretes with high compressive strength could be used while the minimum amount of cement is required.

(d) In terms of real-world applications, the f_c of parent concrete could play an important role in f_c, f_t, and water absorption of generated recycled concretes. The finding shows parent concretes possessing f_c equal to 28 MPa and higher could produce new structural concretes with acceptable f_c values. In this case, a high percentage of recycled aggregates would not harm the physical characteristics of the final concrete and could diminish the use of natural coarse aggregates.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution statement

Nader Biglarijoo: Conceptualization; Methodology; Software; Writing – original draft.

Amin Shams: Investigation; Resources; Writing – review & editing.

Hasan Salehi: Conceptualization; Supervision; Writing – review & editing.

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