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Research Article

Application of response surface methodology in the optimisation of polymer concrete mechanical properties

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ABSTRACT

Polymer concrete offers several advantages compared to conventional concrete, including increased strength, reduced water absorption, enhanced abrasion and chemical resistance, and lower labor costs. However, the production cost of polymer concrete is higher, and compliance with international standards is essential. Hence, determining the right component ratios becomes a crucial task. To address this issue, a study was conducted to investigate the influence of resin, calcite, and sand ratios on the mechanical properties of polymer concrete. The researchers employed the response surface method (RSM) and utilized the genetic algorithm (GA) to find the optimal mixing ratios. For the study, 15 different mixtures were prepared using the Box-Behnken (BB) design for the three components. Experimental tests were carried out to determine the densities, flexural and compressive strengths of these mixtures. The researchers then employed the least squares method to obtain linear and quadratic polynomial models. The accuracy of these models was assessed through ANOVA analyses. It was found that the quadratic model better aligned with the experimental results. Additionally, the study revealed that the mechanical properties were significantly influenced by the resin, with the combined effects of resin and calcite playing a significant role. Finally, the GA was applied to calculate the optimal mix proportions for achieving the best balance between price and performance, as well as for creating lightweight and durable products. According to the optimal mixture results, compressive strength improvement up to 13.8% and tensile strength improvement up to 13.4% were achieved. In conclusion, this study makes valuable contributions to enhancing cost-effectiveness and performance in the production of polymer concrete.

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INTRODUCTION

Polymer-based concretes are one of the preferred materials in many different sectors thanks to their high strength and physical performance [1-4]. In particular, polymer concrete drainage channels produced in accordance with EN 1433:2002 [5] have become one of the most preferred materials in the infrastructure sector thanks to their corrosion resistance, smooth surfaces and high compressive and tensile strength. In the production of polymer concrete, it is

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very important to mix the components in the most appropriate proportions and to reach the values in accordance with the standards in terms of mechanical performance. For this reason, many researchers have been conducting studies on the ratios in which components should be used in polymer concretes and the mechanical performance of polymer concretes [6-9].

Unlike conventional concrete, the binder in polymer concrete is resin material instead of Portland cement [8, 10-12]. Resins are binders that give excellent mechanical, chemical and physical properties to concrete and are generally found in the liquid phase [13]. Studies in the literature indicate that polymer concretes have higher damping capability than conventional concretes [14-16] and epoxy based polymer concrete shows better mechanical properties than polyester based concrete [17]. In addition, vinyl ester and unsaturated polyester resins are known to have high mechanical properties [7]. Some studies emphasize that polymer concrete is not actually perfect, and that they have made very little progress compared to conventional concrete [17, 18]. Researches in the literature show that polymer concretes have different mechanical properties. It is known that the main reason for the difference in the results is the mixture ratios of the materials that make up the polymer concrete and the type of resins that are binding materials [19]. Bulut and Şahin found that while increasing the resin increased the compressive strength significantly, it did not make a significant contribution to the splitting and tensile strengths [20]. In addition, the effect of curing conditions on the mechanical properties of polymer concrete is also known [6, 21, 22]. In fact, it has been reported that the chemical resistance of epoxy-based polymer concrete is considerably higher than that of conventional concrete [23]. When the effect of environmental temperatures on the mechanical properties of polymer concrete was examined, it was observed that the compressive strength and modulus of elasticity decreased significantly at high temperatures [6, 24].

The biggest factor in the production of polymer concrete at a reasonable, accessible and affordable price is the amount of resin. Therefore, in addition to the effect of resins on mechanical properties, their effect on production costs is crucial. In the literature, a resin ratio between 10% and 20% is a recommended value [21, 25, 26]. However, this range is quite wide for the manufacturer and it is not known what the desired optimal value is. In addition, the gradation of aggregates, the type of additives and the quality of production are parameters that affect the mechanical properties of polymer concretes [7, 27, 28].

In order to improve the mechanical properties of polymer concretes, many different components from resins to admixtures should be combined in optimal proportions. However, studies on the optimal component determination of polymer concrete are quite insufficient. In order to find optimal mixing ratios, manufacturers and researchers continue to work and produce by developing some assumptions and approaches. Ferdous et al. tried to find the optimal mix ratio for polymer concrete using different resin-filler ratios and matrix-aggregate ratios and developed empirical formulas to predict mechanical properties [6]. Tabatabaeian et al. 2019 in their study on permeable polymer concrete tried to optimize mechanical properties and price using statistical methods such as ANOVA analysis, signal-to-noise ratio and distance-based approach [29]. Vipulanandan and Dharmarajan reported that maximum tensile and compressive strength was obtained with a polyester resin content of 14%-16% [30]. Vipulanandan et al. reported that 14% resin ratio gave maximum mechanical strength in their experiments with epoxy resin [31]. Vipulanandan also gave different resin ratios for polymer concrete in other studies. In the study conducted to determine the optimal mix proportions of polymer concrete, it was recommended to use 11.25% resin ratio, 11.25% calcium carbonate, 29.1% andesite (5-20 mm), 9.6% fine sand, 38.8% coarse sand [32].Kim et al. determined 7.5% resin ratio and 42.5% sand ratio as the optimal mixture [33]. Muthukumar et al. used BB experimental design considering only grain size and tried to determine the optimal sand spacing ratio for minimum void ratio [34]. In another study, Muthukumar et al. used BB test design to determine the optimal blend that provides maximum compressive strength for different resin types [35]. In these experiments using furan resin, resin ratios ranging from 7.5% to 11% and aggregate ratios between 74% and 77.5% were given as the optimal ratio. Muthukumar and Mohan investigated the mechanical properties of polymer concretes containing silica particles of different sizes with statistically designed mixtures. Optimization was performed by comparing with experimental data to obtain the optimal values for each mix [36]. They calculated the optimal mix proportions for all mechanical properties. Li et al. reviewed the studies in the literature that determined the optimal conventional concrete component ratios with RSM [37].

As can be seen in the literature, there are extensive studies on the effects of components on the mechanical properties of polymer concretes and which components should be combined in which proportions [38-45]. Therefore, within the scope of this study, the effect of the proportions of the constituent components of polymer concrete on the mechanical properties was investigated and the change in mechanical properties was expressed by functions. RSM is frequently used to express experimental data mathematically and to reveal the correlation between inputs and outputs [46-49]. It was decided to use RSM as one of the experimental design methods for the three components. It was predicted that conducting experiments at each point would increase the number of samples and the number of experiments, so mixtures were prepared at 15 different points with the BB experimental design, which requires fewer experiments. The mechanical strengths of the specimens were obtained after three-point bending (flexural) and compressive tests. Density was also included in the results since it is one of the desired properties in the production of polymer concrete. Linear and quadratic polynomial model coefficients were obtained by least squares method and model consistency was tested by ANOVA analysis. After determining the function type and coefficients that best fit the experimental data, the optimization phase started. Optimal mix ratios for price/performance, lightest and most durable products were calculated with the optimization steps created with GA.

MATERIALS AND METHODS

In this section, after introducing the components used, information about the preparation of test specimens and mechanical tests will be given. Polymer concrete is a type of concrete consisting of aggregate, resin, hardener and accelerator. While preparing the specimens, the test points indicated by the response surface method will be used. The specimens prepared at the determined points were subjected to mechanical tests and their density, tensile and compressive strengths were determined.

Natural Aggregates

Aggregates are load-bearing elements in polymer concrete. Sand grains of sufficient size to meet the incoming load must be carefully selected. Sand grains should be washed in the stream bed, have rounded contours and be free of mud. In this study, 0.3-1 mm, 1-2 mm, 2-3 mm and 3-5 mm sized silica based sand from Istanbul and Kırklareli with an average density of 2.65 g/cc was used. Table 1 shows the chemical properties of the aggregates used.

Table 1. Chemical of aggregates

Chemicals	Aggregates			
	0.3-1 mm	1-2 mm	2-3 mm	3-5 mm
MgO (%)	0.1	0.06	0.06	0.06
Al_2O_3 (%)	0.245	1.86	1.86	1.86
SiO_2 (%)	98.86	94.15	94.15	94.15
CaO (%)	0.01	0.39	0.39	0.39
Fe_2O_3 (%)	0.148	0.46	0.46	0.46
SO_3 (%)	-	0.1	0.1	0.1
K_2O (%)	0.03	1.56	1.56	1.56
Na_2O (%)	0.02	1.12	1.12	1.12
Loss (%)	0.587	0.3	0.3	0.3

Resin

Resin is a component that provides binding in polymer concrete and since it is polymer based, it is called "polymer concrete" for this reason. Polymers are obtained by natural and synthetic means. If there are dense cross-links in the chain structure, it is called thermoset, if not and the molecular bonds are smooth, it is called thermoplastic. While thermosets change their chemical structure after heating, harden and remain solid, thermoplastics have a low melting temperature and can be recycled since their chemical structure is intact. Thermosetting (polyester, epoxy, polyurethane, phenol), tar-added, citrene and methyl methacrylate (MMA) resins are used in polymer concrete production [38]. Polyesters are divided into 4 groups as vinylester, aloud, saturated polyester and unsaturated polyester. In this study, unsaturated polyester resin was preferred because it has good thermal resistance, low shrinkage rate and high strength values.

Accelerator

Accelerator helps to reduce the duration of the curing reaction between the resin and hardener. Since heat is released during exothermic reactions, attention should be paid to occupational safety during and after production. Cobalt naphtenate, whose properties are given in Table 2, was selected as accelerator for this study.

Table 2. Properties of accelerator

Properties	Values
Density	0.92 g/cm^3 (20 °C)
Viscosity	300 mPa.s (20 °C)
Self-Accelerating decomposition temperature	≥ 150 °C
Flash point	62 °C
Cobalt content	% 1.50

Hardener

A hardener is needed for the reaction starting with the accelerator. Acetyl Acetone Peroxide (AAP), whose properties are given in Table 3, was used to start the curing reaction at room temperature.

Table 3. Properties of hardener

Properties	Values
Flash point	> 60 °C
Density	1055 kg/m^3
Viscosity	21 mPa.s
Self-Accelerating decomposition temperature	60 °C
Total active oxygen	%4-4.2
Peroxide content	%33
Diethyl glycol+water+diacetone alcohol	%67

Response Surface Method

RSM has emerged mainly to develop valid mathematical models for physical experiments. The purpose of using these methods is to take into account the factors that may affect the output and to determine the appropriate test points [8, 9, 13]. In RSM, firstly, the type of polynomial to be used is determined, then the experiments suitable for this polynomial are designed (inputs). After the experimental results (outputs) are obtained, the unknown coefficients of the polynomial are calculated using the least squares method. In RSM, the relationship between inputs and outputs is modelled by a polynomial (Eq. (1)). Usually second order polynomials are used, but higher order polynomials can also be used (Eq. (2)). The maximum and minimum levels of the input parameters are taken into account as well as intermediate value levels. Different trial points are determined according to these levels. When all trial points are used, this experimental design is called a full factorial design, thus increasing the number of experiments. Different methods are also used to reduce the number of experiments, such as BB or Central composite. In this study, the BB design was used and a total of 15 experimental points were determined. y represents the results of the experiment, i.e. the outputs, β_i represents the unknown coefficients, xi represents the independent variables of the experiment, i.e. the inputs, and ε represents the experimental error.

$$y = f(x_1, x_2, x_3, \dots, x_k) + \varepsilon \tag{1}$$

$$y = \beta_0 + \sum_{i=1}^{n} \beta_{1,i} x_i + \sum_{j=1}^{n} \beta_{2,j} x_j^2 + \sum_{i=1}^{n} \sum_{j>1}^{n} \beta_{3,ij} x_i x_j + \varepsilon \tag{2}$$

As can be seen in Figure 1, the number of experiments decreased from 27 to 15 compared to the full factorial experimental design since corner points were not used in the BB experimental design. The materials used for the BB experimental design and their levels are given in Table 4. Sand contains the grains to carry the load, calcite ($CaCO_3$) fills the void ratio and increases the strength and resin is the binder and holds the whole matrix together. -1,0 and 1 represent the lowest, medium and highest parameter levels respectively. Component quantities are trade secrets and their proportions will not be shared in this study.

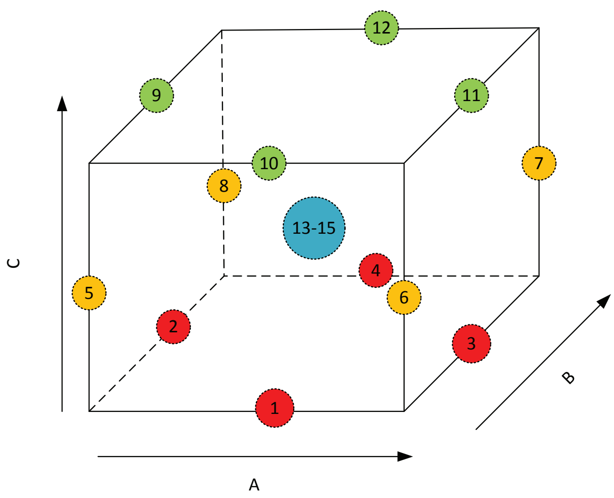

Figure 1. Experimental points according to Box-Behnken RSM.

If the inputs, unknown coefficients and experimental results are expressed as a matrix, it becomes an equation. To apply the least squares method and calculate the β coefficients, Eq. (5) is used.

$$\boldsymbol{Y} = \boldsymbol{X\beta} \tag{3}$$

$$\boldsymbol{Y} = \begin{Bmatrix} y_1 \\ \dots \\ y_{15} \end{Bmatrix}, \boldsymbol{X} = \begin{bmatrix} 1 & \dots & x_3 & x_1x_2 & \dots & x_{11}^2 \\ \dots & \dots & \dots & \dots & \dots & \dots \\ 1 & \dots & x_3 & x_1x_2 & \dots & x_{11}^2 \end{bmatrix}, \boldsymbol{\beta} = \begin{Bmatrix} \beta_0 \\ \dots \\ \beta_{15} \end{Bmatrix} \tag{4}$$

$$\boldsymbol{\beta} = (\boldsymbol{X}^T\boldsymbol{X})^{-1}(\boldsymbol{X}^T\boldsymbol{Y}) \tag{5}$$

Analysis of Variance (ANOVA)

The significance levels of the polynomial coefficients fitted according to the least squares method were determined by Analysis of Variance (ANOVA). R^2, adjusted R^2 and lack of fit parameter values were calculated for the suitability of the models.

Regression analysis is a statistical technique used to determine the strength and direction of the relationship between variables and to predict future values. An

Table 4. Experimental points and levels of compositions

Experimental Points	A: Aggregate	B: Calcite	C: Resin
1	0	-1	-1
2	-1	0	-1
3	1	0	-1
4	0	1	-1
5	-1	-1	0
6	1	-1	0
7	1	1	0
8	-1	1	0
9	-1	0	1
10	0	-1	1
11	1	0	1
12	0	1	1
13	0	0	0
14	0	0	0
15	0	0	0

inconsistent result means that the regression model does not fit the data or that some prerequisites are not met. When examining the model results, the first parameter to look at is the R^2 error value; it has been concluded that an R^2 of 0.80 and above is acceptable for the correlation between variables [39]. Other parameters should also be checked for the accuracy of the model. Non-fitting results should be evaluated by following the steps below.

I. To assess the fit of the regression model, statistics such as R^2, adjusted R^2, F-test and standard error values are examined. These statistics show how much the model explains the variance of the dependent variable and whether the model is significant. The higher the R^2, adjusted R^2 values, the lower the p-value and the smaller the standard error, the better the model fits.

II. Once the cause of a poorly fitting result has been found, some steps can be taken to improve the regression model. For example, inappropriate variables can be removed from the model, linearity can be ensured by adding transformation or polynomial terms, extreme values can be identified and eliminated, or a different regression method can be used. The terms used in the tables are explained below.

- Source: Indicates the different components of the regression model. Model refers to the effect of factors. Residual indicates the variance not explained by the model. Misfit indicates the deviation of the residuals from a normal distribution.
- df: Indicates the degree of freedom. For the model, df is equal to the number of factors. For the residual, df is the total number of observations minus the df of the model. The df for discordance is the residual df minus one.
- Sum of squares: Indicates the division of variance by different sources. The model sum of squares measures the magnitude of the effect of the factors on the dependent variable. Residual sum of squares measures the magnitude of variance not explained by the model. The discrepancy sum of squares measures the magnitude of the deviation of the residuals from a normal distribution.
- R^2: Also known as the coefficient of determination. It shows how well the model explains the dependent variable. It takes a value between 0 and 1 and the higher it is, the better the model fits.
- Adjusted-R^2: This is the adjusted version of R2. It is used to prevent R2 from becoming artificially high as the number of factors increases. It takes a lower value than R2 and the higher it is, the better the model fits.
- Coefficients: Indicates the parameters of the regression model. These coefficients give the ratio of one unit change in the dependent variable to the change in the independent variable.
- In the table, p-values with * sign indicate p-values less than 0.1, ** sign indicates p-values less than 0.05. In other words, these coefficients affect the result more than the other coefficients.

After calculating the polynomial coefficients, an algorithm was written in Matlab environment to ensure that the products are produced with the desired properties. Also, the unit prices of the materials used in the products were added to the algorithm. Thus, the product will be produced with the desired mechanical properties and the target price of the product will also be determined.

In this study, the objective function in Eq. 6 is formed by the density-dependent target price (F_4), tensile strength (F_2) and compressive strength (F_3) functions. The function constraints consisted of the lowest and highest levels used in the experiments.

$$\min_{A,B,C} f = |F_2(A,B,C) - 22| + |F_3(A,B,C) - 90| + |F_4(A,B,C) - 35| \\ \text{Constraints: } -1 \le A \le 1 \\ -1 \le B \le 1 \\ -1 \le C \le 1 \tag{6}$$

In the written algorithm, the "ga-Genetic Algorithm" command from Matlab library was used and the desired features will be provided under the specified constraints as the objective function approaches zero. The genetic algorithm was chosen because it does not get trapped in local extrema. This is because the genetic algorithm tries to preserve diversity to explore different regions in the search space. It can operate at different points in the search space thanks to its selection, crossover and mutation features. These operators increase the population's ability to both exploitation and exploration. Exploitation is about improving the best existing solutions, while exploration is about finding new and potentially better solutions. The disadvantage is that the convergence speed can be slow as it solves for more than one individual at a time. Depending on the size of the population, the convergence rate can be slow, but this is not always a disadvantage. An algorithm that converges too fast may miss the global optimum. After all the generated individuals have been tested in the objective function, some individuals are selected and survive by various natural selection methods. From the surviving parents, children are created through cross-over and mutations. The new individuals and children now form the next generation and are tested again with the objective function. Individuals that do well in this iterative cycle are kept in a pool and contribute to the creation of new generations.

The optimal component ratios that will ensure a tensile strength of 22 MPa, a compressive strength of 90 MPa and a target price of 35 TL were determined. In addition to resin, calcite and sand, hardener and accelerator prices were also included in the price function. The optimal component ratios for different objective functions were calculated using the same algorithm.

Preparation of Samples

After the samples were prepared, polymer concrete mixtures were made with the following steps:

- The desired aggregate proportions were determined.

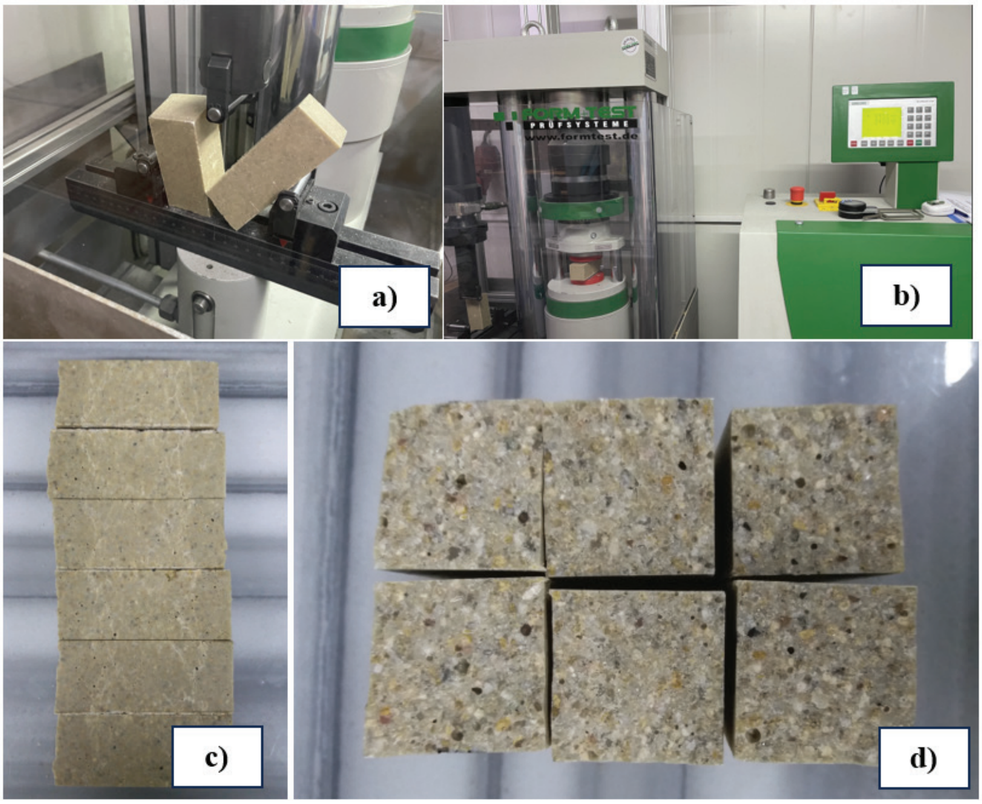

Figure 2. Experimental studies a) bending test b) compressive test c) samples after compressive test d) cracked surfaces

- The resin was slowly mixed with the aggregate and a powerful mixer was used for 15 minutes.
- Accelerator was added to the resin and aggregate mixture and a homogeneous consistency was obtained.
- Hardener was added to the mixture and mixed thoroughly with a powerful mixer.
- The fresh concrete was filled into steel prismatic molds and compacted with a shaking table.
- The specimens were kept in the molds until hardened and then kept in the laboratory at 20 ± 2 °C.

The specimens were prepared prismatically with dimensions of 40mmx40mmx160mm [40]. The specimens were kept for 7 days to ensure the desired strength and consistency of the test results. As stated in the study of Çakır, polymer concrete does not undergo a significant change 7 days after pouring [22]. For this reason, 7-day test results were used for all test results.

Experimental Studies

Flexural, compressive and density tests were performed on hardened specimens. Flexural tests were performed according to ASTM C78/C78M [41], compressive tests according to ASTM C109/C109M [42] and density tests according to ASTM C642 [43]. Additionally, the test regulations are mentioned in EN1433 [40]. The specimens were tested on a 600kN Form-Test machine until fracture. After the flexural test, one half of the specimen was used for compressive test. Figure 2 shows photographs of the experimental studies.

RESULTS AND DISCUSIION

Table 5 shows the 7-day compressive strength, tensile strength and density of the specimens as a result of 15 experiments depending on the selected parameters. For each experiment number, three samples were prepared (totally 45 specimens). Last 3 experiment mixtures are the same, hence thirteen different mixture recipes were prepared.

After the experimental results were obtained, two different models were proposed for the appropriate polynomial selection. In this section, linear and quadratic polynomial coefficients were obtained using the data in Table 5. ANOVA in Design Expert [44] software was used to determine which type of polynomial provided the best fit and which parameters dominated the results. F_1 represents density, F_2 represents tensile strength, F_3 represents compressive strength. As compared to literature, ratio of strengths is found higher. As shown in Table 5, tensile and compressive strength ratios were calculated. The comparison of this relationship obtained here with the studies in the literature is visualised in Figure 3 and it is seen that it is compatible with the previous data.

According to the above-mentioned investigations, when the result of Experiment 1 is included in the regression,

Table 5. Results of experiments

Experiment Number	Density [kg/m³]	Flexural Strength [MPa]	Compressive Strength [MPa]	Ratio of Strengths
	F_1	F_2	F_3	F_3/F_2
1	2162.70	8.40	45.10	5.37
2	2172.10	11.40	53.70	4.71
3	2199.00	13.50	61.20	4.53
4	2186.40	14.60	65.10	4.46
5	2161.90	14.80	65.60	4.43
6	2134.00	15.40	64.90	4.21
7	2105.70	21.20	91.90	4.33
8	2095.70	18.80	85.10	4.53
9	2000.00	20.80	86.50	4.16
10	1994.30	20.60	85.50	4.15
11	2017.40	20.80	85.40	4.11
12	2060.40	14.10	57.50	4.08
13	2111.30	12.20	57.30	4.70
14	2101.20	12.50	59.90	4.79
15	2191.00	12.60	61.60	5.37

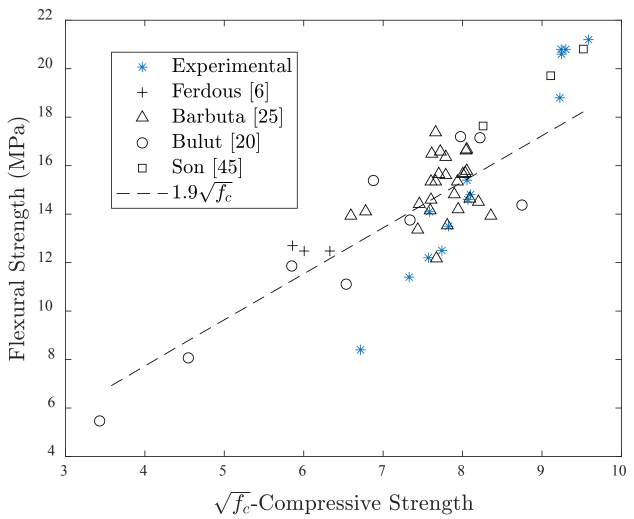

Figure 3. Flexural and compressive strength relationship with literature.

none of the polynomial types give sufficiently reliable results. However, after eliminating this result, the models became stronger. Therefore, linear and quadratic models were obtained by subtracting the 1st result.

Linear Model Results

Table 6 shows the regression results of the linear model and the results of the ANOVA analysis. The regression model used to explain the density fit reasonably well (R^2 = 0.8813, Adjusted-R^2 = 0.8417). The regression models used to explain the compressive and tensile strength of concrete showed lower fit (R^2 = 0.4174, 0.3029; Adjusted-R^2 = 0.2232, 0.0706). Thus, the influence of the factors on the compressive and tensile strength of concrete is non-linear. This means that the effect of the factors on the dependent variable is not constant. Here it appears that the resin is the effective component on the results because the p-value is less than 0.05.

If the obtained polynomial answers are illustrated, the results can also be evaluated visually. The red dots are the actual results from the experiment. In Figure 4-6, the z-axis shows a) density, b) flexural strength and c) compressive strength, respectively. In each figure, the graphs were plotted by keeping the mid-level of one component constant and changing the proportions of the other components. For

Table 6. Variance and regression coefficients of the linear model

Source	df	Sum of squares		
		F_1 [kg/m³]	F_2 [MPa]	F_3 [MPa]
Model	3	50299.03	68.05	691.4
Residual	9	6777.06	94.98	1590.85
Lack of fit	8	0.1884	0.0476	0.1006
R^2		0.8813	0.4174	0.3029
Adjusted-R^2		0.8417	0.2232	0.0706
Coefficients				
	β_0	2110.05	15.9145	69.725
	β_1	3.3	0.6375	1.5625
Linear	β_2	-5.4125	0.724671	3.38125*
	β_3	-85.8375**	3.08717**	9.79375*

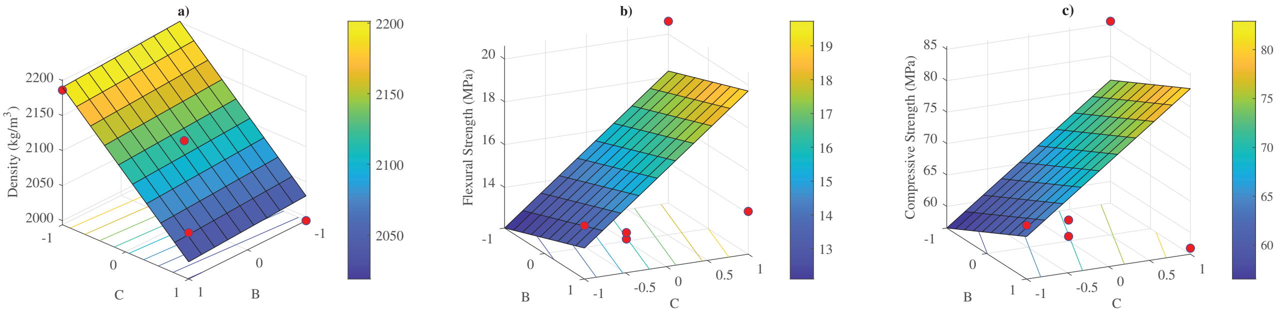

Figure 4. a) density b) flexural c) compressive strength regarding B and C while constant A component.

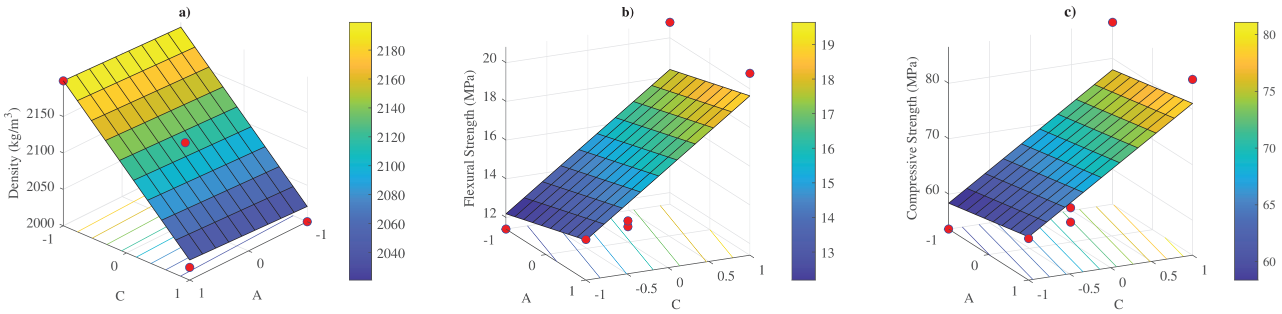

Figure 5. a) density b) flexural c) compressive strength regarding A and C while constant B component.

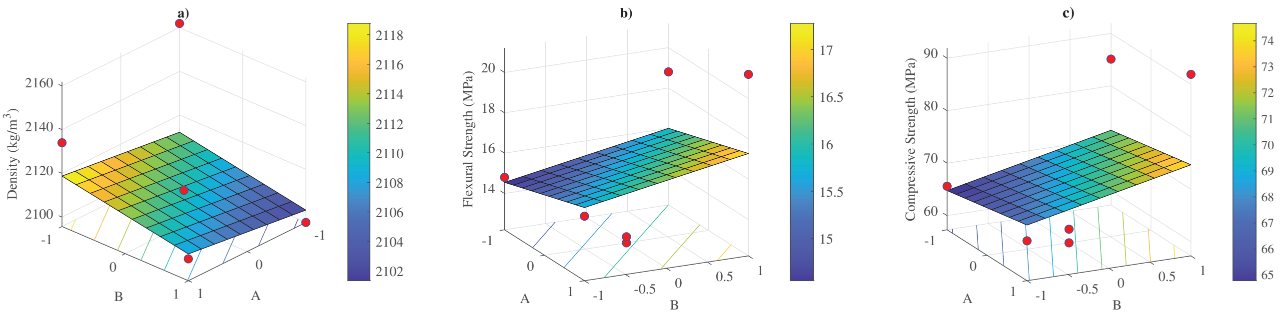

Figure 6. a) density b) flexural c) compressive strength regarding B and C while constant A component.

example, Figure 4 shows the change in mechanical properties as the ratios of calcite and resin change while the sand component is at 0. Although it seems that a linear model can be proposed for density, it is obvious that the test points do not match when the results in Figure 6 are examined. It is also clear from the graphs why the compressive and tensile strengths have low R^2 values.

Quadratic Model Results

Table 7 shows the regression results and ANOVA analysis results of the quadratic model. The regression models used to explain the density, compressive strength and tensile strength of polymer concrete fit reasonably well (R^2 = 0.9735, 0.9891, 0.9734; Adjusted-R^2 = 0.8941, 0.9565, 0.8935). The influence of the factors on the compressive and tensile strength of polymer concrete is non-linear. This means that the effect of the factors on the dependent variable is not constant. Resin again has a linear effect on all results. The effect of the calcite and resin components dominates the results both individually and together. However, the sand component is not linear but quadratic on the compressive and tensile strengths. When the quadratic model results were analysed, it was found that the quadratic model was superior to the linear model.

Quadratic result visualizations are given in Figures 7-9. The z-axis shows a) density, b) flexural strength and c) compressive strength, respectively. Again, in each figure, the graphs were plotted by keeping the mid-level of one component constant and changing the proportions of the other components. For example, Figure 7 shows the change

Table 7. Variance and regression coefficients of the quadratic model

Source	df	Sum of squares		
		F_1 [kg/m^3]	F_2 [MPa]	F_3 [MPa]
Model	9	55564.92	161.26	2221.48
Residual	3	1511.17	1.77	60.77
Lack of fit	2	1460.17	1.73	57.39
R^2		0.9735	0.9891	0.9734
Adjusted-R^2		0.8941	0.9565	0.8935
Coefficients				
	β_0	2106.25	12.35	58.6
	β_1	3.3	0.6375	1.5625
Linear	β_2	-15.8125	2.13125**	9.73125**
	β_3	-96.2375**	4.49375**	16.1438**
	β_{12}	9.475	0.45	1.875
Interaction	β_{13}	-2.375	-0.525	-2.15
	β_{23}	41.05*	-5.0625**	-21.8375**
	β_{11}	-8.1	4.64375**	18.2563**
Quadratic	β_{22}	26.175	0.55625	0.01875
	β_{33}	-1.025	-0.36875	-5.15625

in mechanical properties by changing the proportions of calcite and resin when the sand is at 0. The red dots show the experimental results and the response surfaces provide the experimental points. This shows that the quadratic model works better than the linear model. In contrast to the other results, Figure 9 a) shows inconsistency in some experimental points in the density function. Nevertheless, statistically the quadratic model is still strong.

Optimisation Results

Once it is determined that the quadratic model is the best model that provides the best experimental results, different mixtures can be prepared for different purposes. For this reason, with the help of the algorithm written and the "ga" command in Matlab, it will be easy to prepare the mixtures with the best price, the highest mechanical strength or the best mixtures in terms of both price and mechanical strength. Using Eq. (6), the optimal mix that meets the price and mechanical strength requirements is obtained. Other objective functions are not included in the algorithm when the maximum value of other mechanical properties is desired. Table 8 shows the optimal mix ratios obtained for the specified objective functions. Also, following graphics show GA results of three different objective functions (OF). The error values of the fitness functions are shown as best result data. The longest search can be seen in OF1, because of the three specific aims.

Density and unit prices can provide significant advantages for enterprises with large tonnage production. At the same time, the desired mechanical properties are the responsibility of the manufacturer. For this reason, various objective functions for price, mechanical strength and

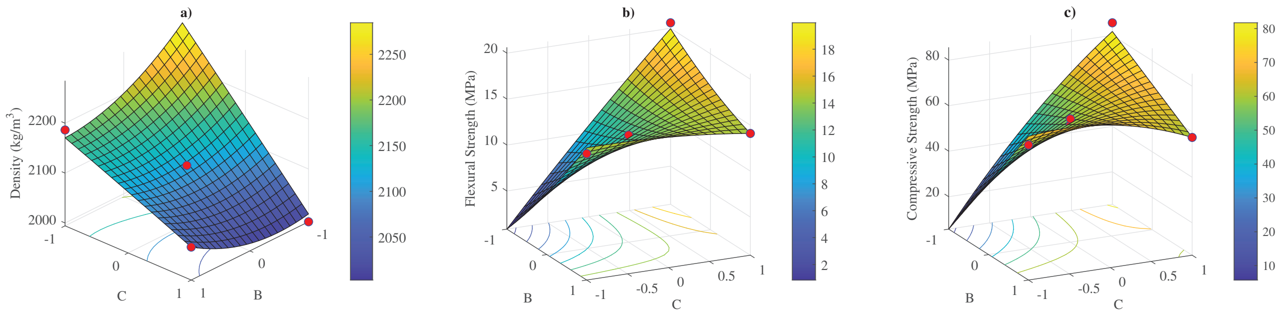

Figure 7. a) density b) flexural c) compressive strength regarding B and C while constant A component.

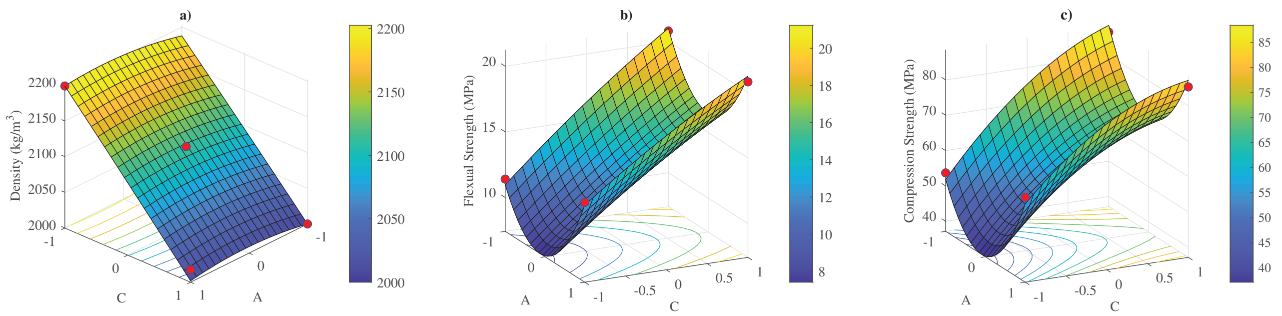

Figure 8. a) density b) flexural c) compressive strength regarding A and C while constant B component.

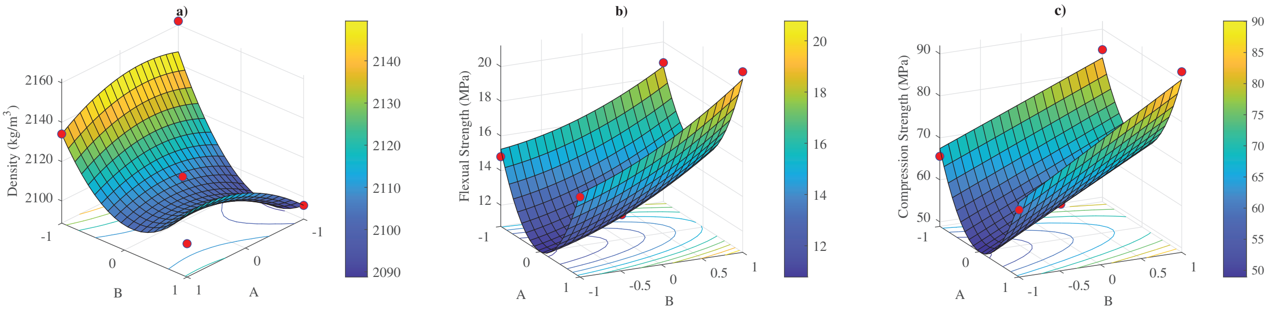

Figure 9. a) density b) flexural c) compressive strength regarding B and C while constant A component.

price/performance product designs have been prepared below. As seen in the table, having the lowest density does not always make the product price the cheapest. For the optimal product price and desired mechanical properties, i.e. the first objective function, it is noteworthy that the resin ratio is low. Because resin is an uneconomical product compared to other components.

It can be said that the first optimal mixture has a small price advantage due to the resin ratio. When the 3 optimal mixtures are compared, it is seen that although the price of all of them is close, their mechanical properties are different. When the third objective function was examined, it was seen that the resin ratio was kept at maximum and the calcite and sand ratio was kept at the lowest level in order to provide maximum mechanical properties. Although the third optimal mix is 13.8%-8.9% compression resistant and 13.4%-7.9% flexural resistant compared to the other mixes, it is 0.3% heavier than the first mix and 1% heavier than the second mix.

Polymer concrete is gaining more importance in the infrastructure and construction sector as it has superior mechanical and chemical properties compared to conventional concrete. Since resin is used as a binder, cost-effective production and meeting the requirements of international standards is a challenging process for manufacturers. For this reason, this study aims to predict the proportions of sand, resin and calcite used in polymer concrete provided that certain objectives are met. If the results are summarized:

- When the test results are analysed, any outliers should be removed. According to the results of the first

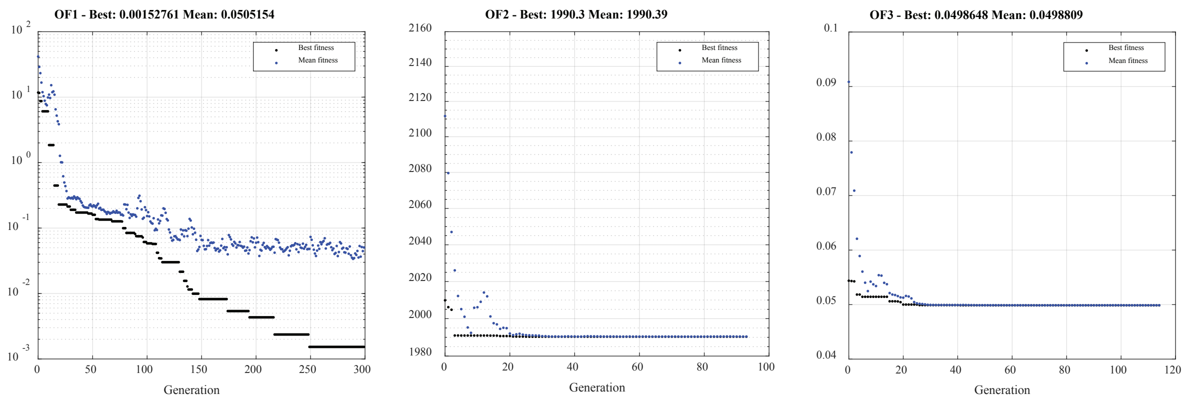

Figure 10. GA results over generations for three OF.

Table 8. Mixture ratios for different objective function

	Objective Function	Mixture ratios			Optimal Results			
		A	B	C	F_1 [kg/m^3]	F_2 [MPa]	F_3 [MPa]	F_4 [TL]
1	Eq. (6)	0.88	-0.8	0.915	2004.5	22.00	90.00	34.99
2	min(F_1)	1	-0.665	1	1990.3	23.12	94.05	35.11
3	max(F_2)&max(F_3)	-1	-1	1	2010.3	24.94	102.41	35.44

experiment, the mixture with the lowest calcite and resin has the lowest value in tensile and compressive tests and was not included in the analysis.

- The quadratic model, rather than the linear model, is more compatible with the experimental results and the lack of fit values are at the lowest level. The R2 error values for density, flexural and compressive strengths are 0.8813, 0.4174, 0.3029 in the linear model and 0.9735, 0.9891, 0.9734 in the quadratic model, respectively.
- In both models, resin dominates the mechanical properties. In fact, the importance of resin and calcite together is higher than the quadratic model. Moreover, the nonlinear behaviour of sand is revealed in the quadratic model.
- When the optimisation results were analysed, it was found that the price/performance product was slightly more suitable compared to the other optimal results.
- Although the second optimal design was lightweight, the high resin content escalated the prices. It was found that not every lightweight product is affordable.
- With the third optimal design, a maximum 13.8% more compression resistant and 13.4% more tensile resistant product was designed.
- In future studies, more components can be examined and a mathematical model of the fiber effect can be created.

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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