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Effects of Waste Powder, Fine and Coarse Marble Aggregates on Concrete Compressive Strength

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Abstract: The use of marble wastes in concrete mixtures, causing air and water pollution, has been promoted in the academic and practical spheres of the construction industry. Although the effects of various forms (powder, fine, coarse and mixed) of this waste on the concrete compressive strength has been subject to a decent number of studies in the literature, the difficulties in reaching specific conclusions on the effect of each test parameter constitute a major restraint for the proliferation of the use of marble wastes in the concrete industry. Most of these studies are far from underscoring all of the parameters affecting the concrete compressive strength. Due to the urgent need in the literature for comprehensive studies on concrete mixtures with marble wastes, the results of the axial compression tests on a total of 429 concrete mixtures with marble aggregates were compiled by paying special attention to reporting all test variables (form and content of marble wastes, water–cement ratio, cement content, proportion of coarse and fine aggregates in all aggregates) affecting the concrete strength. In this context, multivariate regression analyses were carried out on the existing test results. These regression analyses yielded to relationships between the change in concrete compressive strength and the test parameters for each and every form of marble waste (powder, fine and coarse aggregate). The study indicated that independent from the form of marble wastes (as powder, fine aggregate or coarse aggregate), aggregate replacements of up to 50% can yield to significant changes in the concrete compressive strength. In addition, the analytical estimates from the developed equations exhibited a high correlation (a least r value of 0.91) with the experimental results from the previous studies, yielding to rather low error values (RMSE value is 5.06 MPa at max). For this reason, the developed equations can consistently predict the changes in concrete compressive strength with varying amounts and forms of the marble aggregates as well as the other test variables.

Keywords: concrete with marble aggregate; marble dust; recycling of marble aggregate; reuse of marble powder; fine and coarse marble

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1. Introduction

Marble, which has been used in many areas such as ornaments, sculpture, decoration and the construction industry since ancient times, is a metamorphic rock formed by recrystallized calcite or dolomite, and a large part of its composition is composed of calcium carbonate ($CaCO_3$) [1,2]. The world's existing marble reserves are estimated to be approximately 15 billion cubic meters [3]. However, during the extraction of these marbles from the quarry and processing in the factories, between 30% and 75% marble waste is generated [4,5].

During the production of block marble in marble quarries, up to 50% of marble waste may form in the form of rubble and flat stone [6]. Rubbles in the quarry are generally amorphous wastes smaller in size than blocks resulting from faults during production and defects (cracks, faults, etc.). Flat stones are the lower, upper and side parts of the marble blocks, removed from the block during the cutting process to obtain blocks of certain dimensions. A very small portion of these wastes, which are in various sizes, are used as recycled material (in aggregate production) and filling material, and a large portion is generally piled up around the quarry [7]. These wastes accumulating around the quarry cause visual pollution by causing both the formation of masonry hills and additional connection roads (Figure 1). In addition, with the increase in accumulation areas and therefore the number of connection roads, vegetation is gradually being destroyed.

Figure 1. Hills formed by waste marble piles.

In contrast, marble wastes in factories generally appear as flat stone, palledien (small remnants from cutting plates into products of certain sizes and rupture of the plates) and marble powder. Of these wastes, palllediens are generally used in floor covering, and flat stones are used in the production of kitchen sinks, gifts and ornaments [8]. Marble powder is the type of remnant that usually appears during the wet cutting of plates and blocks and during wiping and polishing. The size of a great majority of this remnant is below 250 µm [9]. During the cutting of the plates, 15 to 50% of powder wastes may appear [6]. However, due to the water used during cutting, these powdered wastes are called marble sludge and are purified from water and compressed or stacked in sedimentation pools. Although this resulting waste marble powder and mud is used in many industries such as paper, ceramics, cement, paint, plastic and glass, their use has been quite limited in practice [10]. For this reason, the accumulation of this waste marble powder over time causes pollution of surface and groundwater resources, as well as the air and environment. In addition, the increase in the needed storage area for these wastes in parallel with the production increases the production costs of the companies [9].

In order to solve the environmental and stacking problems caused by marble wastes, researchers need to develop means to use these wastes in different products or applications and to recycle them. If available in proper grain size distribution, the marble wastes in the forms of particles and powder can be used as aggregates, fillers and mineral additives in concrete mixtures [11–14]. In this way, marble wastes can be processed much faster and in large quantities, and thus the stacking problems of the companies are reduced. In addition, the damages caused by marble wastes to the environment are also reduced. The marble waste has two different types of use in concrete mixtures. Firstly, by replacing the cement partially with marble powder, the cost of concrete and the carbon emissions from cement production can be reduced [14–18]. Secondly, these waste materials can be used in replacement for fine and/or coarse aggregates, to minimize the damage of wastes to the environment and also to prevent the consumption of limited natural resources [19–22]. In this context, researchers conducted general basic experiments such as compressive strength, splitting and flexural tensile strength, ultrasonic pulse velocity, water absorption and slump to determine the physical and mechanical properties of the concrete mixtures containing marble aggregates [19,23–25]. However, the effects of waste marble aggregates on the mechanical and physical properties of concrete have been very diverse in these experiments, since there were large variations in the ranges of the test parameters (cement type and amount, W/C ratio, fine and coarse aggregate type and amount, etc.) in these existing studies [12,13,23,26–28]. What is more, the findings and the comments of each of the studies in the literature could not be generalized since these findings relied on the limited number of parameters of the related study. A significant majority of the existing review studies discussed the changes in the mechanical properties of concrete by solely examining the proportion and form of the marble aggregates in the mixture [29–32]. The related findings, which do not take the parameters other than marble aggregates into account, can be misleading and only valid for the related studies.

To clarify, each and every one of the parameters that influence the compressive strength of concrete should be taken into consideration in the experiments and analyses as well as the proportion and form of marble aggregates. In addition, the relationships between the form and content of marble aggregates and the mutual effects of the test parameters should also be set forth. The experimental studies in the literature were designed by only considering some of the parameters affecting the concrete strength. Ignorance of certain parameters in these studies and the large variations in the ranges of parameters are responsible for different and even sometimes opposite conclusions on the effect of a certain parameter on concrete strength. In summary, the existing studies did not yield exact and specific conclusions on each parameter.

The effects of marble aggregates on concrete compressive strength cannot be isolated from the other test variables based on the studies in the literature. This situation leads to cautious approaches to the use of marble waste in the concrete mix and is one of the biggest obstacles in front of the use of waste marble as a recycling material in concrete. Additionally, the concrete compressive strength is a prominent factor affecting the durability of structural members and systems. The durability concern renders the influence of marble wastes on concrete compressive strength much more important. Within this scope, various experimental studies in the literature were compiled to form four different datasets containing a total of 429 tests. Multivariable regression analyses were conducted on these datasets. Three different concrete compressive strength equations were developed for three forms of marble aggregates, i.e., powder, fine and coarse aggregates, by also considering all of the test parameters. In addition, analytical equations were developed to link the variation in the concrete compressive strength to the amount and form of marble aggregates and other eminent test parameters.

2. Method

2.1. Compilation and Properties of Datasets

In the study, four different datasets were created according to the waste marble form, containing a total of 429 tests on concrete compressive strength, in order to develop relations between the compressive strength of concrete and the waste marble aggregate content.

In the first of these datasets, studies in which the fine aggregates were partially replaced with waste marble powder in the concrete mixture were compiled [15,18,19,22,24,27,33–40]. In the second, studies that adopted the waste fine marble aggregate in replacement for the conventional fine aggregate were compiled [21,23,28,41,42]. The third dataset consists of studies in which the conventional coarse aggregate was substituted with waste coarse marble aggregate [20,42–47]. Finally, the fourth dataset is composed of tests on mixtures with both waste fine and coarse (mixed) marble aggregates in substitution for the regular ones [42,48–50]. These datasets were created from 210, 82, 93 and 44 concrete compression tests, respectively. However, there are differences in the sizes and shapes of the test specimens among different studies in each dataset. Therefore, by minimizing these differences, concrete compressive strength conversion relations were used to determine the range values of concrete compressive strengths in the dataset presented in Table 1. In this context, since the majority of the tests in the datasets were conducted on 150 mm concrete cubes, the test results of the 150 × 300 mm cylindrical specimens (a diameter of 150 mm and a height of 300 mm) were converted into 150 mm cube strength values by using the related transformation equation (Equation (1)) [51]. In addition, numerous researchers in the literature [52,53] established that the compressive strength values of 100 × 200 mm cylindrical specimens are almost equal to the respective values of the 150 × 300 mm cylindrical specimens. Similarly, the strength values of 100 mm cube specimens are rather close to the related values of the 150 mm cube specimens [52]. Therefore, strength conversion was not conducted for these sizes.

$$f_{cu} = -0.00002 f_{cy}^3 + 0.00168 f_{cy}^2 + 1.18519 f_{cy} + 0.77452 \tag{1}$$

Here, f_{cu} is the compressive strength of a 150 mm cube concrete specimen (MPa), f_{cy} is the 28th day compressive strength of a 150 × 300 mm cylindrical concrete sample (MPa) and f_{cy} is in the range of $8 \leq f_{cy} \leq 100$ MPa.

Table 1. Dataset range values and limitations (from the data in Supplementary Materials).

	Waste Marble Powder				Fine Marble Aggregate				Coarse Marble Aggregate				Mixed Marble Aggregate			
Parameters	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**
Max. Aggregate Size (mm)	8.0	25.0	18.7	3.8	16.0	32.0	22.6	6.1	10.0	25.0	21.4	3.1	12.5	25.0	21.7	5.2
W/C	0.40	0.60	0.48	0.07	0.37	0.59	0.51	0.05	0.31	0.87	0.51	0.12	0.35	0.65	0.50	0.08
Water (kg/m^3)	135	255	181	30	157	242	206	26	120	209	178	22	158	228	188	21
Cement (kg/m^3)	300	500	376	61	350	441	406	30	240	450	360	56	350	480	381	37
Coarse Aggregate (kg/m^3)	556	1356	1010	217	962	1225	1153	83	0	1390	635	449	-	-	-	-
Sand (kg/m^3)	0	1089	635	225	0	872	401	237	647	1044	757	89	-	-	-	-
Marble (kg/m^3)	0	972	163	205	0	872	256	237	0	1421	475	464	-	-	-	-
Marble (%)	0	100	21	23	0	100	38	33	0	100	42	40	0	100	42	35
Curing Duration	3	90	32	28	7	90	30	27	7	90	36	29	7	90	31	23
Cube Compressive Strength (MPa)	13.3	63.5	37.8	12.0	18.9	56.9	36.5	9.1	5.1	66.6	40.9	14.8	16.7	64.0	39.8	11.2
Change in Compressive Strength of Reference Concrete (%)	−37.5	30.2	5.0	11.4	−22.5	65.2	8.23	14.5	−31.7	40.7	3.3	12.4	−22.1	60.0	6.6	18.1

In addition, in the study, some experimental data were excluded from the regression analyses because these outliers (data with a standardized residual value greater than absolute 2) affected the accuracy of the regression analyses adversely. In addition, the data whose estimated values are not given in Supplementary Materials were also not included in the regression analysis. The numbers of these eliminated tests are four, one and four for the waste marble powder, fine marble aggregate and coarse marble aggregate test datasets, respectively. The minimum, maximum, mean and standard deviation values of the parameters used in the assembly of the datasets of the present study are given in Table 1. The experimental studies used in these datasets are presented in Supplementary Materials.

In the present analyses, the density and workability of concrete were not included in the dataset, since the studies in the literature rely on many different test methods for determining the concrete workability. To be more specific, the workability and density of the fresh concrete mixes could not be compared due to significant variations in the test methods in the literature, which made it impossible to achieve a healthy and meaningful comparison.

2.2. Multivariate Regression Analysis

Regression analysis, which is a statistical technique widely used in many fields, is an analysis method that examines the relationships between variables [54]. This method can be univariate and multivariate depending on the number of variables used in the regression equation. Regression models with a single independent variable are called a simple linear regression model, and models with more than one independent variable are called a multivariate (multiple) linear regression model. The simple linear regression model is expressed with Equation (2) and the multiple linear regression model is expressed with Equation (3) [54,55]. However, regression models are not always expressed with a linear equation as in Equation (3) and these regression models are called nonlinear models. These models can be very diverse. Statistical methods can be used to establish nonlinear regression models as well as other methods such as genetic programming, multi-expression programming (MEP) and neural networks [56–59], which started being implemented recently. An example of a quadratic model that includes nonlinear, multivariate and interaction effects is given in Equation (4) [55].

$$y = \beta_0 + \beta_1 x + \varepsilon \tag{2}$$

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n + \varepsilon \tag{3}$$

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 + \varepsilon \tag{4}$$

Here, y is the response variable, β_0 is the point where the line intersects the y-axis, β is the coefficient of the independent variable, x is the value of the argument and ε is the random error component.

In this study, regression analyses were performed using Minitab 18 [60] software to predict the change in concrete compressive strength with marble aggregate content. In addition, the regression model was optimized to include the multivariate quadratic expressions containing interaction effects with the help of the "*optimize response*" module of Minitab 18 [60] due to its flexibility. In the optimization procedure, the software first applies a stepwise regression procedure and determines the terms with the highest correlation with the result. After deciding on the variables or interactive variables to add to the model according to their statistical importance, the results are optimized with the help of a numerical algorithm. However, while establishing the regression models in the study, the effects of the variables on the regression model were also determined manually by taking into account the changes in the regression coefficient by adding and removing the variables from the model. With the analyses made in this context, the compressive strength of concrete mixtures containing marble dust or marble aggregate could be estimated much more accurately as compared to the multiple linear regression analyses. In order to render the relationships between the results and variables statistically significant, reaching p values below 0.10 was assumed to be necessary in the present analyses.

2.3. Error Evaluation Criteria

A Pearson correlation analysis was performed in order to determine the level of relationship between the estimated variation values in concrete compressive strength from the regression analyses and the related values from the experimental studies (Equation (5)). Root mean square error (RMSE) (Equation (6)) and mean absolute error (MAE) (Equation (7)) statistical evaluation criteria were used to determine the mean sizes of the errors between the estimated and the experimental values. However, compared to MAE, RMSE gives higher weight to the error within the sample. In addition, the coefficient of determination (R^2) was used to reflect the ability of the independent variables to describe the dependent variable.

$$r = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2 \sum_{i=1}^{n}(y_i - \overline{y})^2}} \quad (5)$$

Here, r is the level of relationship between the variables (Pearson correlation coefficient) (+1 is perfect positive linear relationship, −1 is perfect negative linear relationship, 0 is no relationship), x_i is experimental value, $\overline{x}$ is the mean of the experimental data, y_i is the estimated value, $\overline{y}$ is the mean of the predicted values and n is the number of experiments.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(A_i - P_i)^2} \quad (6)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}(A_i - P_i) \quad (7)$$

Here, P_i is the estimated value, A_i is experimental value and n is number of experiments.

3. Effects of Waste Marble Aggregates on Concrete Compressive Strength

3.1. Use of Waste Marble Powder in Concrete Mix Instead of Fine Aggregate

In this part of the study, the effects of the replacement of regular fine aggregate with waste marble powder in various proportions on concrete compressive strength were investigated. In this context, a total of 210 tests were compiled from the literature [15,18,19,22,24,27,33–40]. The variation in the concrete compressive strength with the replacement ratio of fine aggregates with marble powder is illustrated in Figure 2.

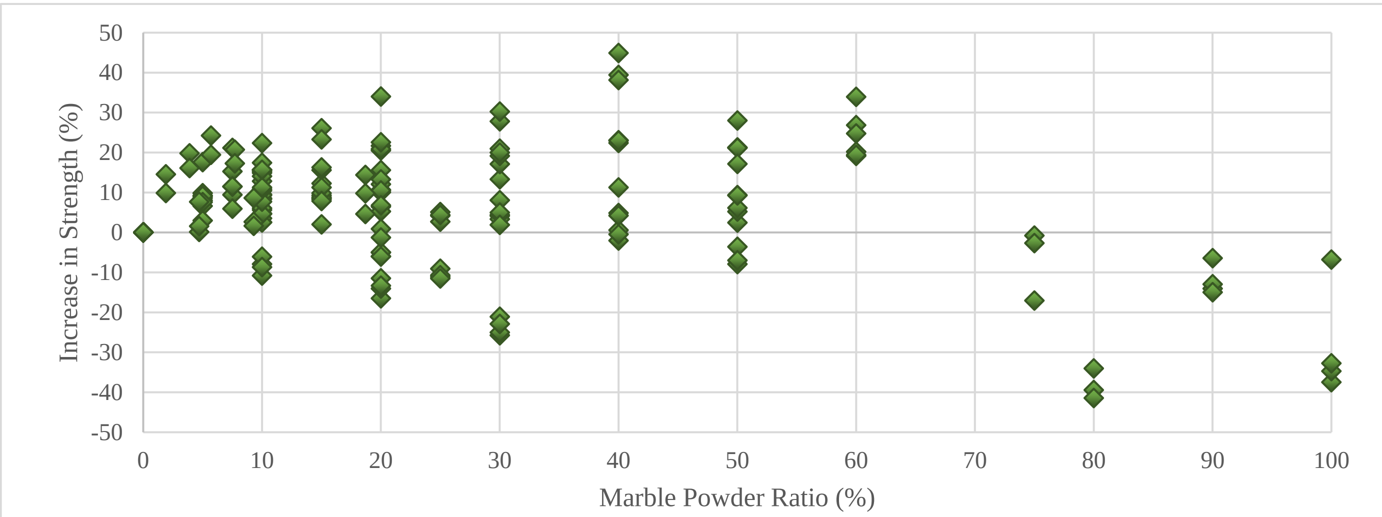

Figure 2. Increase in compressive strength of concrete with the amount of waste marble powder in replacement for fine aggregates.

Figure 2 indicates that marble powder replacements of up to 15% provide an increase between 2% and 26% in the concrete compressive strength. This effect is substantiated by the test results of all 67 samples, with the exception of only 4 samples. As 15% to 60% of the fine aggregates by mass is replaced with marble powder, however, a general increase tendency can be observed in the concrete compressive strength based on the test results of a total of 83 samples. However, 22 of these 83 specimens experienced reductions of up to 26% in the compressive strength. For specimens with more than 60% marble powder replacement, the concrete compressive strength was recorded to decrease significantly. In this situation, the workability of concrete decreases significantly with increasing marble powder content [19,61].

The previous studies appertaining to the concrete mixtures with marble powder associate the contribution of this powder to compressive strength with three main reasons [62]. The first reason is the ability of marble powder to fill the micro voids in the concrete owing to its lower fineness modulus compared to sand. The second reason is the pozzolanic reactions in concrete associated with the presence of marble wastes, which have particle sizes less than 100 microns. These reactions convert calcium hydroxide (CH) into calcium-silica-hydrate (C-S-H) gels, which improve the binding properties of cement. Nonetheless, several studies on the topic indicated that the marble dusts have a slight or no contribution to pozzolanic reactions [63–65]. Finally, the third reason is the positive contribution of this dust to the compressive strength due to higher degrees of mortar–aggregate cohesion associated with the greater calcium carbonate content of marble dust as compared to the conventional aggregates [42,44,62].

The excessive use of marble dust, however, can have negative effects on the concrete compressive strength. The fineness modulus of the fine aggregates decreases with increasing marble dust content, which in turn increases the surface area of the aggregates in the mixture. This increase results in the need for greater volumes of mixing water for workability. If adequate water cannot be provided, the workability of the mixture decreases. The workability problems can yield reductions in the concrete compressive strength since they might cause settlement problems and thereby a porous concrete mass.

To be able to make comprehensive evaluations and handle all these cases, the ratio of the mixing water to the total mass of cement and marble powder [W/(C + WMP)] should be considered (Figure 3). This figure portrays the positive effects of increasing the W/(C + WMP) ratio on the concrete compressive strength. As a matter of fact, only 6% of 152 samples with W/(C + WMP) ratios greater than 0.30 experienced reductions in compressive strength, whereas the compressive strength values of 52% of 58 samples with W/(C + WMP) ratios below 0.30 were reduced rather than being increased with the use of marble powder. These conclusions clearly depict that the marble powder ratio cannot be considered alone and this ratio can only yield to meaningful results if considered together with the W/(C + WMP) ratio. In this regard, if the W/(C + WMP) ratio remains above 0.36, marble dust replacement ratios of up to 20% become tolerable. Similarly, by allowing a maximum decrease of 11% in the concrete compressive strength, substitution ratios of up to 50% become tolerable as long as the W/(C + WMP) ratio is equal to at least 0.30.

The variation of concrete compressive strength with the water/cement (W/C) ratio, the mass ratio (R) of the coarse aggregates to all aggregates, the amount of marble powder per unit volume of concrete (WMP) and the cement dosage is illustrated in Figure 4. Accordingly, provided that the W/(C + WMP) ratio is equal to at least 0.30 and the cement dosage is equal to or greater than 380 kg/m^3, the marble powder was established to have a positive influence on the concrete strength with the exception of only a single sample. The fineness modulus of marble powder and the substitution ratio of fine aggregates cause the specific surface area of the marble powder in the concrete mixture to change. Consequently, the amount of binder needs to be increased to keep the concrete compressive strength fixed or to increase it. The range of change in the concrete compressive strength with varying mass ratio (R) of the coarse aggregates to all aggregates is rather wide, like other variables that make up the concrete mixture (W/C ratio, WMP and cement dosage). For this reason, regression analysis was performed in order to estimate the effects of all parameters on the compressive strength of the concrete.

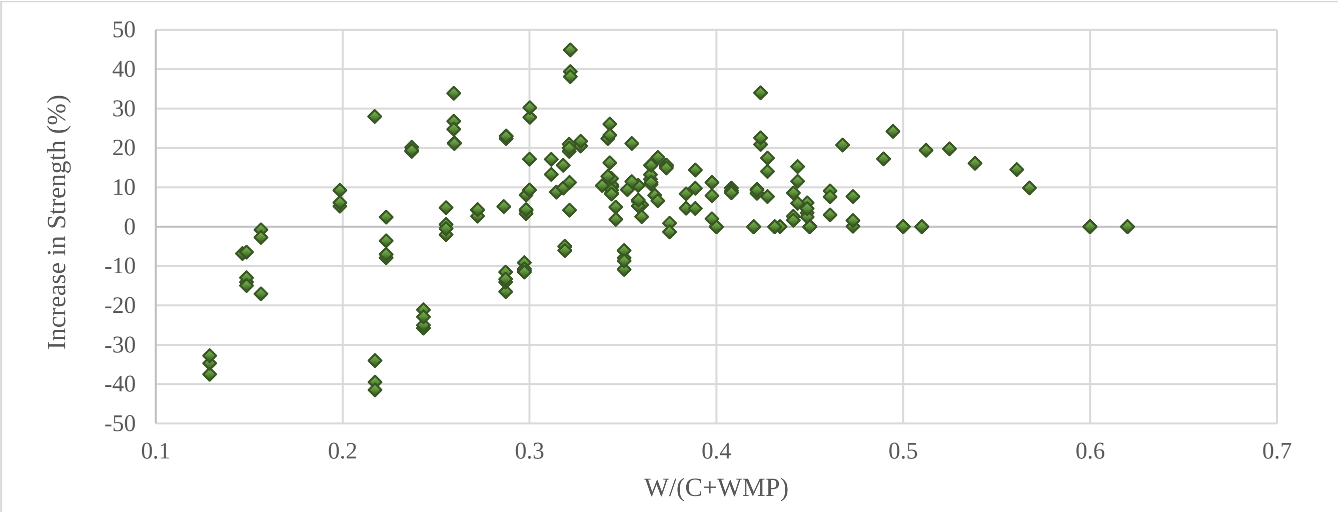

Figure 3. The effects of W/(C + WMP) ratio on the compressive strength of concrete mixtures.

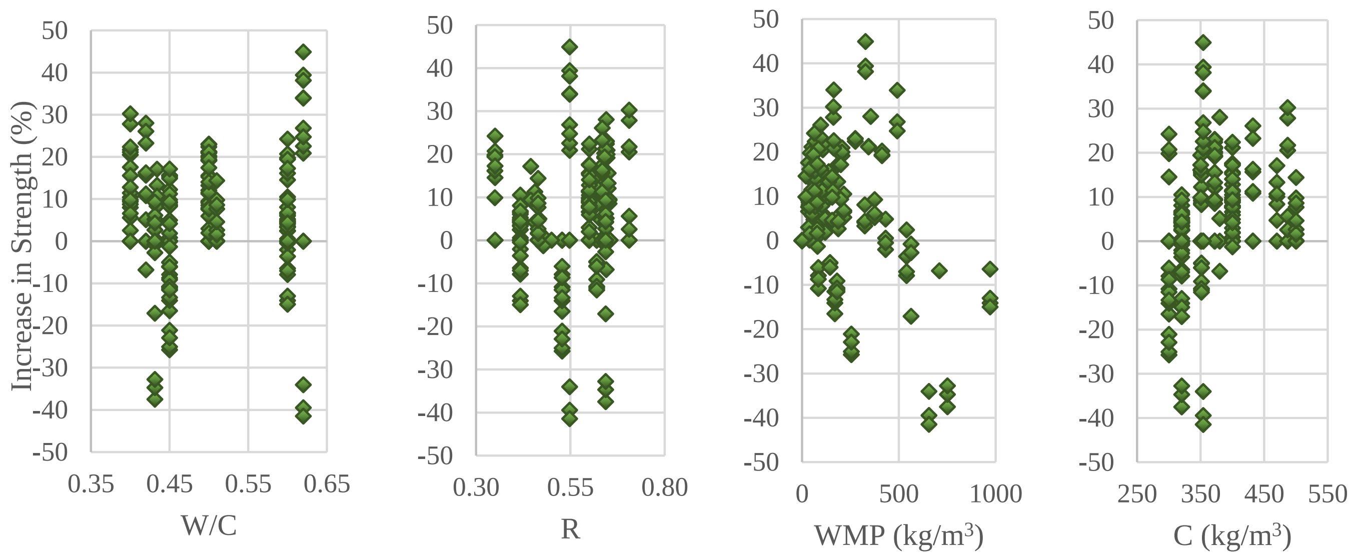

Figure 4. The effects of other parameters on the compressive strength of concrete mixtures with waste marble powder.

In the established regression model, the percentage of change caused by the marble powder replacement on the compressive strength of the concrete was used as the dependent variable. Experimental data such as the amount of water, cement, cement grade, max. aggregate size, fine and coarse aggregates and marble powder were used as independent variables. As a result of the regression analysis, Equation (11), which is a multivariate quadratic regression model including interaction effects, was obtained.

$$E_{1-MP} = -645.9 + 25.3D + 456R - 1.889M - 0.2644C + 63385\frac{W}{CG} \tag{8}$$

$$E_{2-MP} = -0.354D^2 - 316R^2 - 0.005932M^2 - 1348744\left(\frac{W}{CG}\right)^2 \tag{9}$$

$$E_{ie-MP} = -0.0808DR + 0.019DC - 1836D\frac{W}{CG} + 2.983RM - 0.2108RC + 0.003914MC + 73.7M\frac{W}{CG} \tag{10}$$

$$I_{MP} = E_{1-MP} + E_{2-MP} + E_{ie-MP} \tag{11}$$

Here, I_{MP} is the compressive strength increase of the concrete caused by the use of marble powder instead of fine aggregate (%), $E_{1\text{-}MP}$ is an equation containing first-degree expressions, $E_{2\text{-}MP}$ is an equation containing second-degree expressions, $E_{ie\text{-}MP}$ is the equation containing the interaction effects, W is the mass of the water in the concrete (kg/m^3), C is the mass of the cement in the concrete (kg/m^3), G is the cement grade (compressive strength of cement at the 28th day) (MPa), D is the maximum aggregate particle size (mm), R is the mass ratio of coarse aggregates to all aggregates (coarse, fine and marble powder) and M is the mass ratio of marble powder to the total fine aggregates (%).

In the proposed equations, the p value of only the W/CG variable is 0.124. The p values of all remaining parameters remained below 0.01, whereas the respective values of R2 and RC variables were 0.027 and 0.036, respectively. The W/CG variable with a statistical significance above 0.10 was used in the equations as it slightly increases the estimation ability of the equations, although it is a controversial variable. In this respect, all of the variables constituting the proposed equations can be said to have meaningful effects on the results.

The comparison of the results estimated by Equation (11) with the experimental results is presented in Figure 5. The prediction ability of the model can also be seen when the statistical values in Figure 5 are examined. There is a very high correlation between the results predicted by the recommended model and the experimental results (r = 0.94). In addition, the dependent variables in the proposed equation (Equation (11)) can describe the change in concrete compressive strength, which is the independent variable, with a high percentage (88%). According to these results, the effects of marble powder on concrete compressive strength should be considered together with other test parameters. When the RMSE and MAE values between the experimental and estimated results are examined, small error values of approximately 3.97 MPa and 3.14 MPa can be noticed, respectively. There is a minor difference of 0.83 between the RMSE and MAE values, although relatively more weights are given to large errors in RMSE as compared to the MAE. Considering that the average compressive strength of the test samples in the study is 37.8 MPa, the estimated results have an average deviation of 8.3% from the experimental ones.

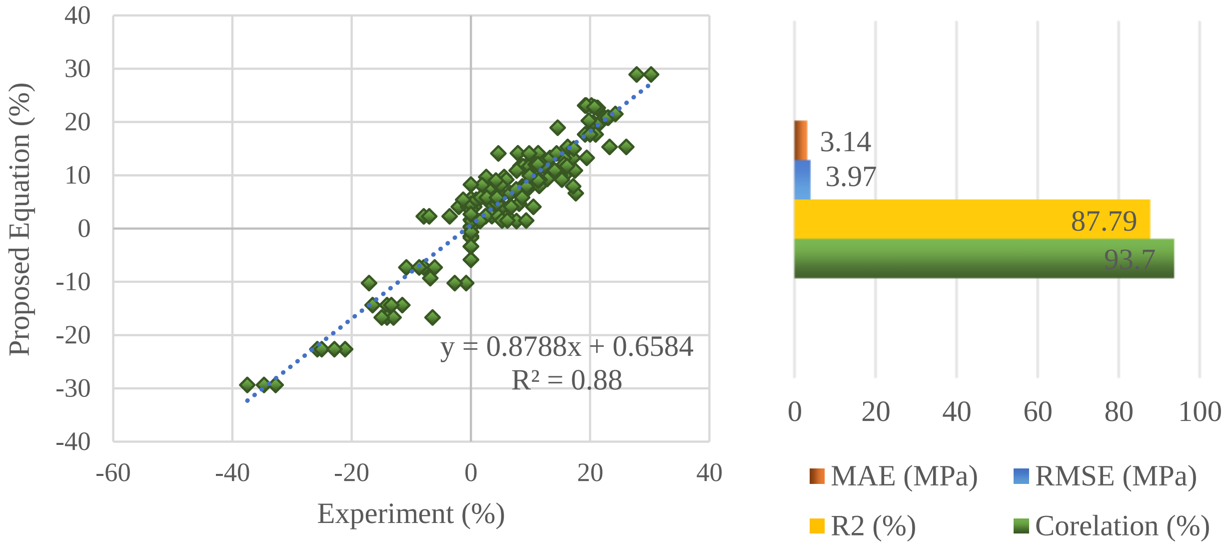

Figure 5. Statistics between the experimental and predicted concrete compressive strength changes of concrete mixtures using waste marble powder.

The comparison of the experimental results of concrete compressive strength changes with the results estimated by the proposed equation is presented in Figure 6, which illustrates a high correlation between the estimation results and the experimental results, just like the statistical results.

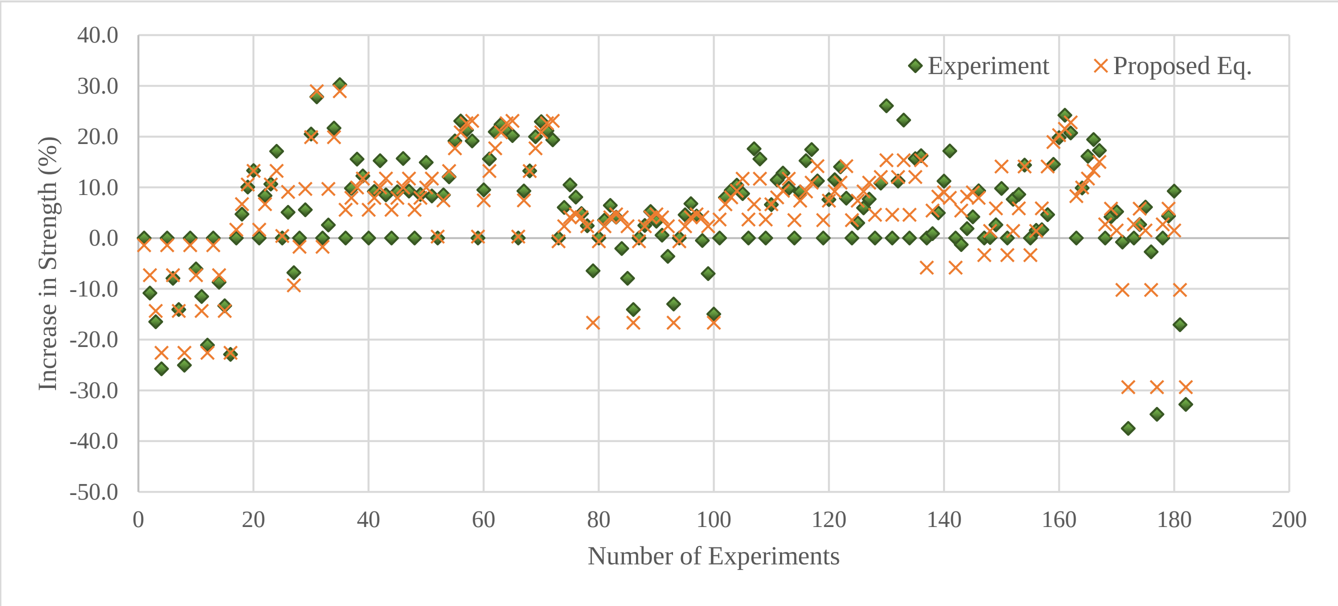

Figure 6. Comparison of experimental and predicted concrete compressive strength changes for concrete mixtures using waste marble powder.

3.2. Use of Fine Marble Aggregate in Concrete Mix in Replacement for Fine Aggregate

In this part of the study, the effects of replacing fine aggregates with fine marble aggregates in various proportions on concrete compressive strength were investigated. In this context, a total of 82 concrete compressive strength tests compiled from the literature were used [21,23,28,41,42]. It is seen in Figure 7 that replacing the fine aggregates with marble aggregates can affect the compressive strength of concrete positively (increase up to 65%) or negatively (decrease down to 23%). The most likely reason for these different effects is the strength differences between the aggregates used in the experiments. Although aggregates with different qualities and strength values were utilized in concrete mixtures of different studies, the negative effect of the replacement remained as low as 12% even for a replacement ratio of 50%. In this context, considering the reasonable decrease in concrete compressive strength with fine marble aggregate replacement, these aggregates can be allowed to be used in high percentages.

The effects of the W/C ratio, the mass ratio of coarse aggregates to all aggregates (including the fine and coarse aggregates and excluding the marble aggregate), fine marble aggregate amount and cement dosage on the compressive strength of concrete mixtures containing fine marble aggregates are presented in Figure 8. In concrete mixtures containing fine marble aggregates, the effects of the W/C ratio, fine marble aggregate amount and cement dosage on concrete strength vary in a wide range. Therefore, the positive or insignificant negative effects of the changes in these variables on the concrete compressive strength are ambiguous, since the experimental studies were not designed to examine the effect of a single test variable while keeping the other test variables fixed. In this regard, much more research is required to determine the effects of the variables on the compressive strength values of concrete mixtures with partial fine marble aggregate replacement. However, although the effects of the variables could not be clearly demonstrated in this study, a regression analysis was carried out to estimate the effects of all components on the compressive strength of the concrete at once.

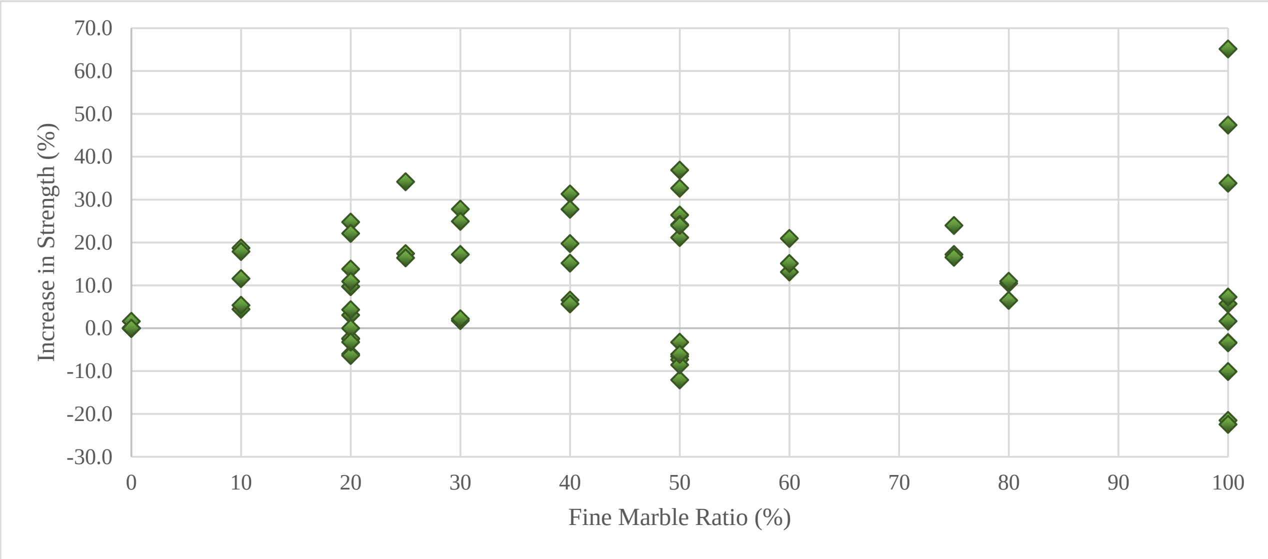

Figure 7. Increase in compressive strength of concrete depending on the rate of replacement of regular fine aggregates with fine marble aggregates.

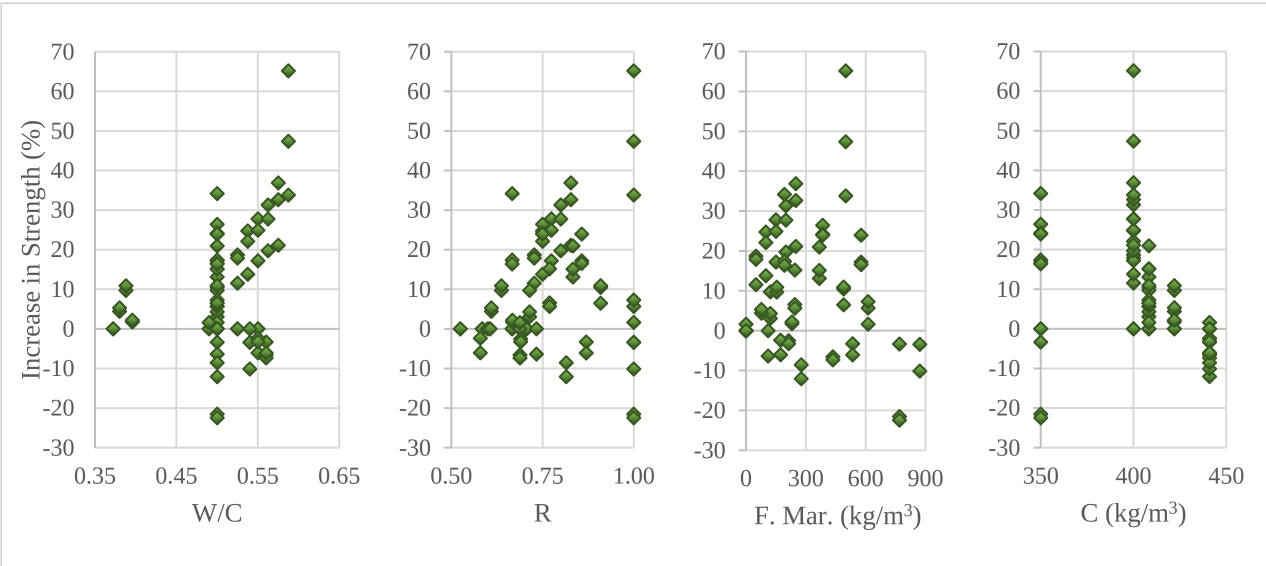

Figure 8. The effects of test variables on the compressive strength of concrete mixtures with fine marble aggregate.

In the established regression model, the percentage of change in concrete strength caused by the use of fine marble aggregate was used as the dependent variable. Experimental data such as the amounts of water, cement, fine and coarse aggregates and fine marble aggregate were used as independent variables. As a result of the regression analysis, Equation (15), which is a multivariate quadratic regression model including interaction effects, was obtained:

$$E_{1-MS} = -288 + 9.3C + 424\frac{W}{C} + 10.59M - 27.6D - 3425R \quad (12)$$

$$E_{2-MS} = -0.01854C^2 + 0.8D^2 \quad (13)$$

$$E_{ie-MS} = -0.02605CM + 7.798CR - 24.07\frac{W}{C}D + 0.04631MD \quad (14)$$

$$I_{MS} = E_{1-MS} + E_{2-MS} + E_{ie-MS} \tag{15}$$

Here, I_{MS} is the compressive strength increase of concrete originating from the use of fine marble aggregate instead of conventional fine aggregate (%), $E_{1\text{-}MS}$ is an equation containing first-degree expressions, $E_{2\text{-}MS}$ is an equation containing second-degree expressions, $E_{ie\text{-}MS}$ is the equation containing the interaction effects, W the amount of water in the mixture (kg/m^3), C the amount of cement in the mixture (kg/m^3), D is the maximum aggregate particle size (mm), R is the mass ratio of coarse aggregates to all aggregates (excluding marble aggregate) and M is the mass ratio of fine marble aggregates to the total fine aggregate (%).

In the proposed equation, the p values of variables D, W/C and WD/C were obtained as 0.203, 0.059 and 0.01, whereas the p values of all the remaining variables were below 0.01. Despite being controversial, the D variable was used in the equations, since its statistical significance was above 0.10 and had a positive influence on the estimating capability of the equation. In this respect, all parameters making up the equation were found to have meaningful effects on the equation.

The comparison of the results estimated by Equation (15) to the experimental results is presented in Figure 9. As can be seen from Figure 9, a very accurate prediction could be made with the established model. There is a very high correlation between the results predicted by the recommended model and the experimental results (r = 0.96).

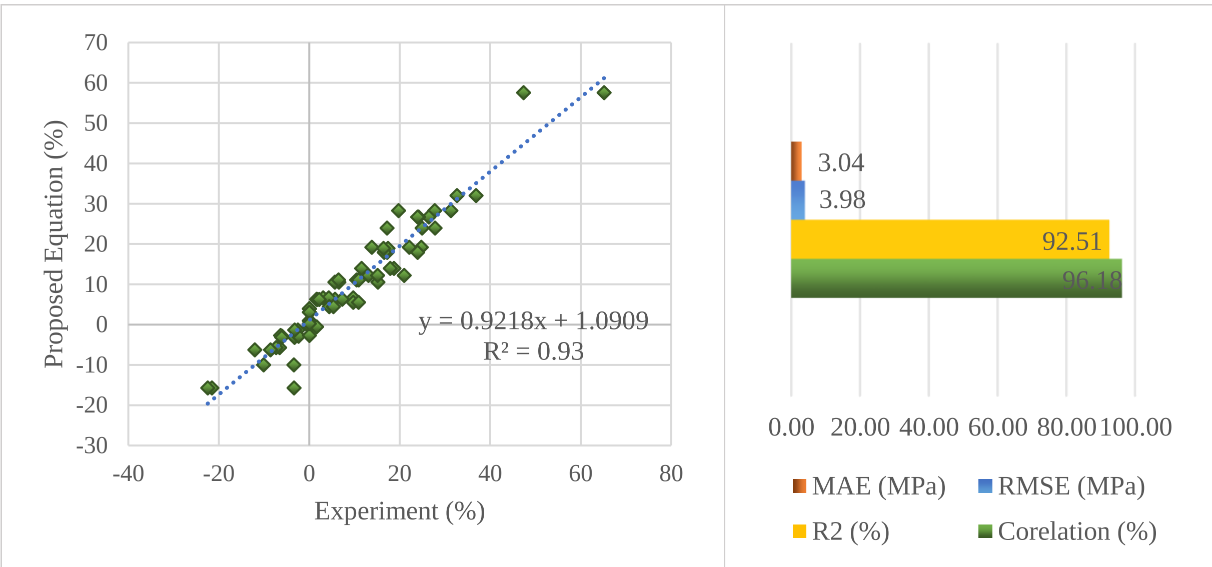

Figure 9. Statistics between experimental and predicted concrete compressive strength changes of concrete mixtures using fine marble aggregate.

In addition, it is seen that the independent variables in the proposed equation (Equation (15)) can define the dependent variable, the concrete compressive strength change, with a very high precision (93%). For this reason, the rate of contribution of the fine marble aggregate to the concrete also varies depending on the other test parameters. However, since the regression model contains interactive variables, the factors affecting the concrete compressive strength of concrete mixtures with partial fine marble aggregate replacement could not be interpreted clearly. In this context, it is necessary to carry out experiments where the fine marble aggregate ratio in the concrete mixture is kept constant and other test parameters are considered as variables.

When the RMSE and MAE values between the experimental and estimated results in Figure 9 are examined, small error values of 3.98 MPa and 3.04 MPa can be seen to be present. Considering that the average compressive strength of the test samples in the study is 36.5 MPa, the estimated results have an average deviation of 8.3% from the experimental ones.

There is a high correlation between the experimental results presented in Figure 10 and the predicted concrete compressive strength changes, just like the statistical results.

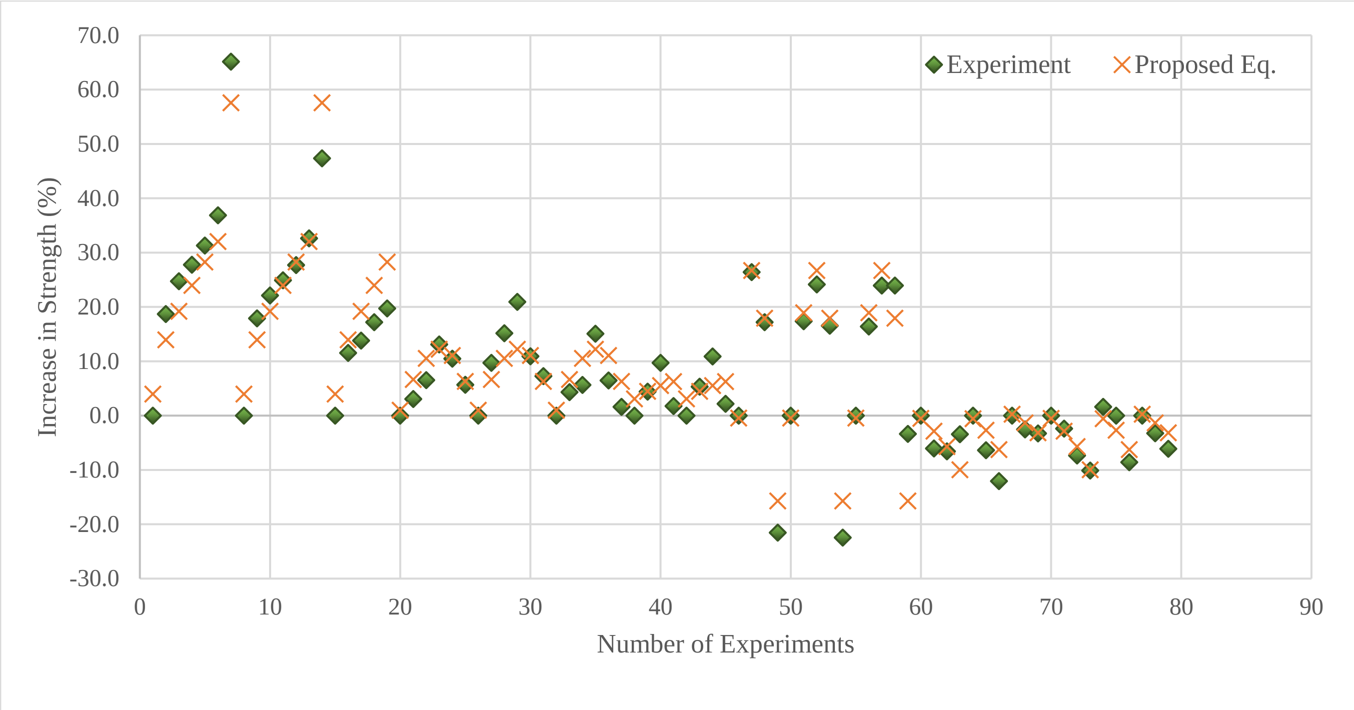

Figure 10. Comparison of experimental and predicted concrete compressive strength changes of concrete mixtures using fine marble aggregate.

3.3. Use of Coarse Marble Aggregate in Concrete Mix in Replacement for Regular Coarse Aggregate

In this part of the study, the effects of replacing regular coarse aggregate with coarse marble aggregate in various proportions on concrete compressive strength were investigated. In this context, a total of 93 concrete compressive strength tests compiled from the literature were used [20,42–47]. Figure 11 indicates that replacing the coarse aggregates with coarse marble aggregates can affect the compressive strength of concrete positively (increases up to 75%) or negatively (decreases up to 32%). The most likely reason for these different effects is the strength differences between the aggregates used in the experiments. However, even if the negative effects of marble aggregates are taken into account, replacements of regular coarse aggregates with marble aggregates of up to 20% and 50% are responsible for maximum decreases of only 6.3% and 12.6%, respectively, in the compressive strength. This shows that coarse marble aggregates can be consumed in high quantities in concrete.

The effects of W/C ratio, the mass ratio of coarse aggregates (marble and coarse aggregates) to all aggregates (marble, fine and coarse aggregates), coarse marble aggregate amount and cement dosage on the compressive strength of concrete mixtures containing coarse marble aggregate are presented in Figure 12. However, as in concretes containing fine marble aggregate, the positive or negative effects of the W/C ratio, the amount of coarse marble and the amount of cement on the concrete compressive strength are not clear because they are in a wide range. Therefore, depending on these components, a regression analysis was carried out using the aforementioned test data in order to determine the amount of replacement that can be tolerated with the least reduction in concrete compressive strength.

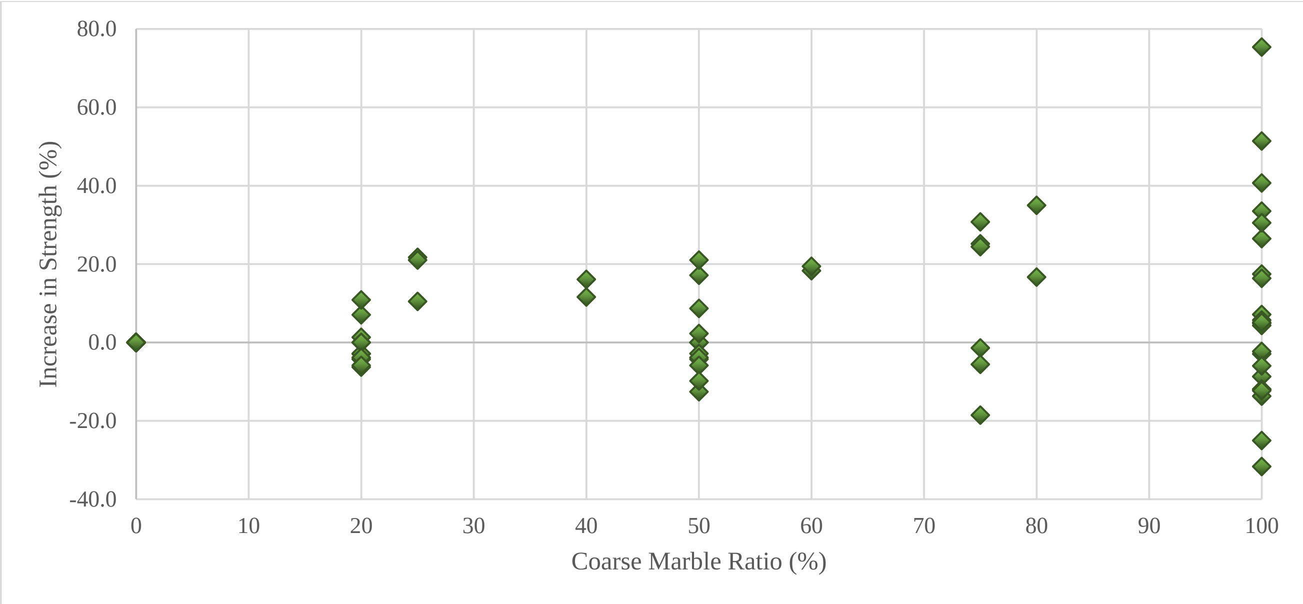

Figure 11. Increase in compressive strength of concrete depending on the rate of replacement of regular coarse aggregates with coarse marble aggregates.

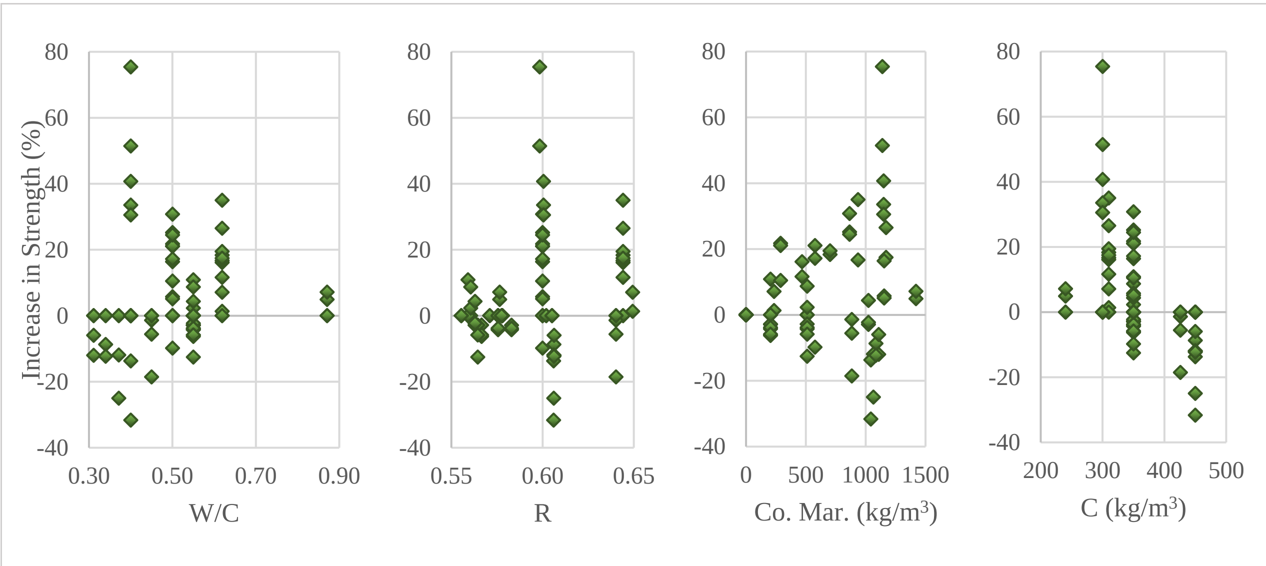

Figure 12. The effects of the other test variables on the compressive strength of concrete mixtures containing coarse marble aggregate.

In the established regression model, the percentage of change due to the use of coarse marble aggregate on the compressive strength of concrete was used as the dependent variable. Experimental data such as the amounts of water, cement, fine and coarse aggregates and coarse marble aggregates were used as independent variables. As a result of the regression analysis, Equation (19), which is a multivariate quadratic regression model including interaction effects, was obtained.

$$E_{1-MC} = 1023 + 7.81D + 162\frac{W}{C} - 0.0785C - 3864R + 1.116M \quad (16)$$

$$E_{2-MS} = 3282R^2 - 0.002077M^2 \quad (17)$$

$$E_{ie-MS} = -10.32D\frac{W}{C} - 0.99M\frac{W}{C} - 0.003981CM + 1.779RM \quad (18)$$

$$I_{MS} = E_{1-MS} + E_{2-MS} + E_{ie-MS} \quad (19)$$

Here, I_{MC} is the compressive strength increase of concrete produced by using coarse marble aggregates instead of coarse aggregates (%), $E_{1\text{-}MC}$ is an equation containing first-degree expressions, $E_{ie\text{-}MS}$ is the equation containing the interaction effects, W is the mass of the water in the mixture (kg/m^3), C is the mass of the cement in the mixture (kg/m^3), D is the maximum aggregate particle size (mm), R is the mass ratio of coarse aggregates (marble and coarse aggregates) to all aggregates (marble, fine and coarse aggregates) and M is the mass ratio of coarse marble aggregates to all coarse aggregates (%).

In the proposed equation, the p value of variable R was found to be 0.015, whereas the p values of all other parameters were smaller than 0.10. Since the p values of all parameters remained below 0.10, these variables were observed to have meaningful and significant effects on results.

The comparison of the results estimated by Equation (19) with the experimental results is presented in Figure 13. As can be seen from Figure 13, a very accurate prediction could be made with the established model. There is a very high correlation between the results predicted by the recommended model and the experimental results (r = 0.91).

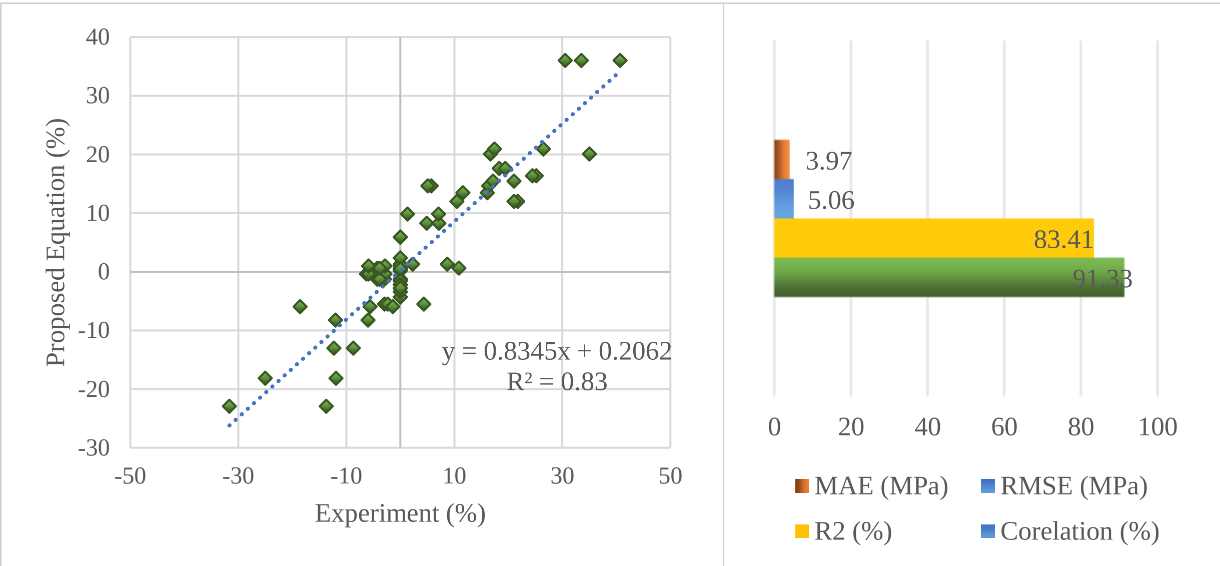

Figure 13. Statistics between the experimental and predicted concrete compressive strength changes of concrete mixtures containing coarse marble aggregates.

In addition, the independent variables in the proposed equation (Equation (19)) can define the dependent variable, the concrete compressive strength change, with a very high precision (83%). For this reason, the rate of the contribution of the coarse marble aggregate to the concrete mixture also varies depending on the other test variables. Just as in concrete with fine marble aggregates, in order to determine the effects of these variables in concretes with coarse marble aggregates, it is necessary to carry out experiments where the coarse marble aggregate ratio in the concrete mixture is kept constant and other test parameters are considered as variables.

The RMSE and MAE values between the experimental and estimated results (Figure 13) underscore reasonable error values of approximately 5.06 MPa and 3.97 MPa, respectively. Considering that the average compressive strength of the test samples in the study is 40.9 MPa, the estimation results have an average deviation of 9.7%.

The comparison of the experimental results with the results estimated by the proposed equation is presented in Figure 14. In Figure 14, there is a high correlation between the estimated and experimental results, just like the statistical results.

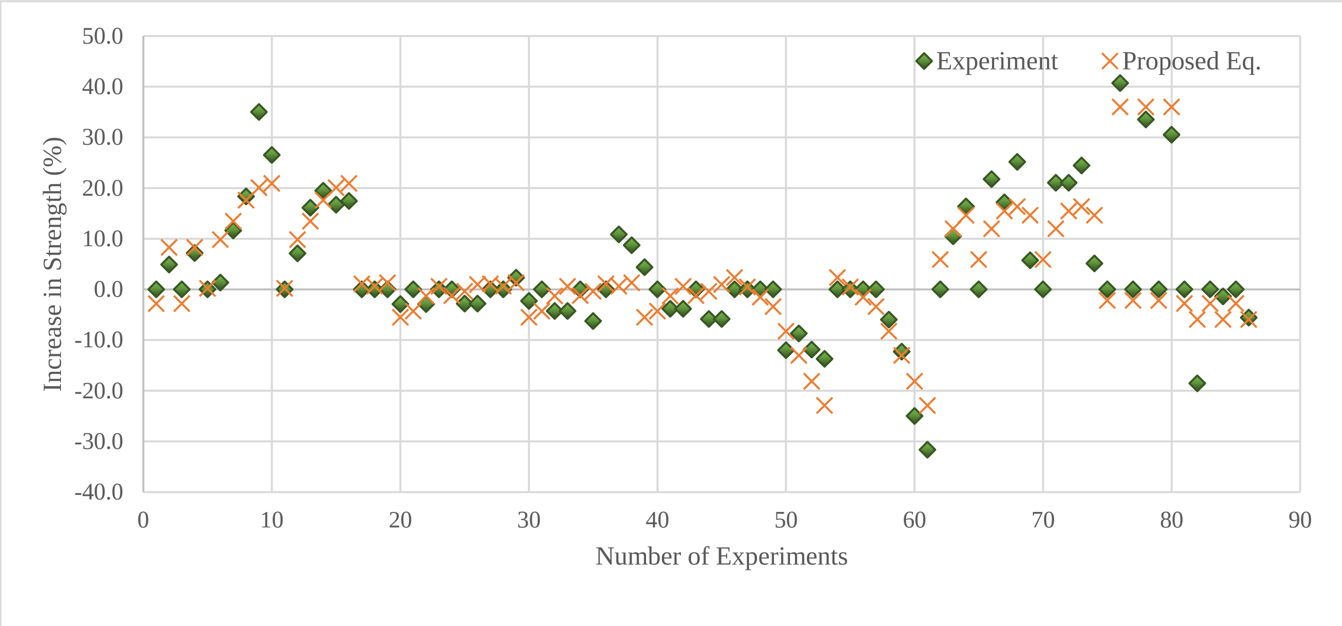

Figure 14. Comparison of experimental and predicted concrete compressive strength changes of concrete mixtures containing coarse marble aggregate.

3.4. Use of Fine and Coarse Marble Aggregates in Concrete Mixture Instead of Conventional Fine and Coarse Aggregates

In this part of the study, the effects of replacing fine and coarse aggregates with the related marble aggregates in various proportions on concrete compressive strength were investigated. In this context, 44 concrete compressive strength tests compiled from the literature were used [42,48–50]. Figure 15 depicts that the replacement of fine and coarse aggregates with fine and coarse marble aggregates can affect the compressive strength of concrete positively (up to 58%) or negatively (down to 22%). However, even if the negative effects of marble aggregates are taken into account, replacement percentages of up to 100% cause decreases of up to only 22% in the compressive strength of the concrete. This situation shows that coarse marble aggregates can be consumed in high quantities in concrete.

The effect rate of marble aggregates on the compressive strength of concrete varies depending on the other test parameters (Figure 16). However, regression analyses were performed to find these rates of change according to the components, but the relevant regression models could not be established due to the deficiencies in some experimental information while the dataset was being created. Therefore, since the effect of fine and coarse marble aggregate ratio on concrete compressive strength cannot be clearly expressed with independent variables, no equation can be proposed.

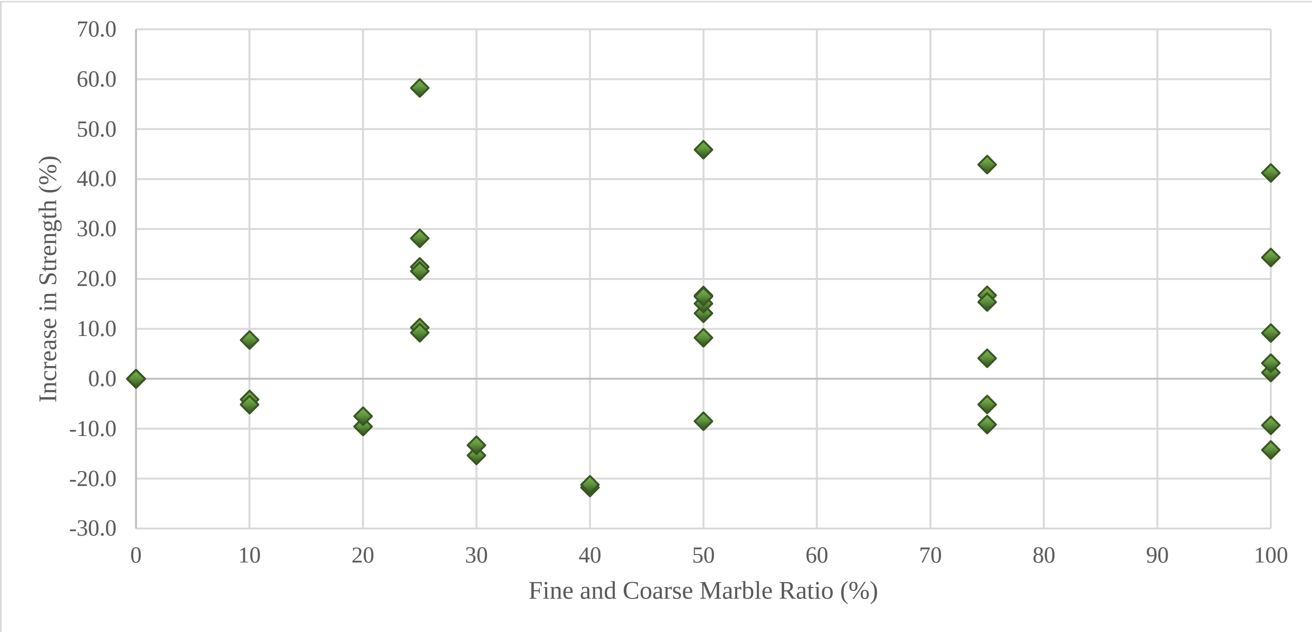

Figure 15. Increase in compressive strength of concrete depending on the rate of replacement of fine and coarse aggregates with the regular fine and coarse aggregates.

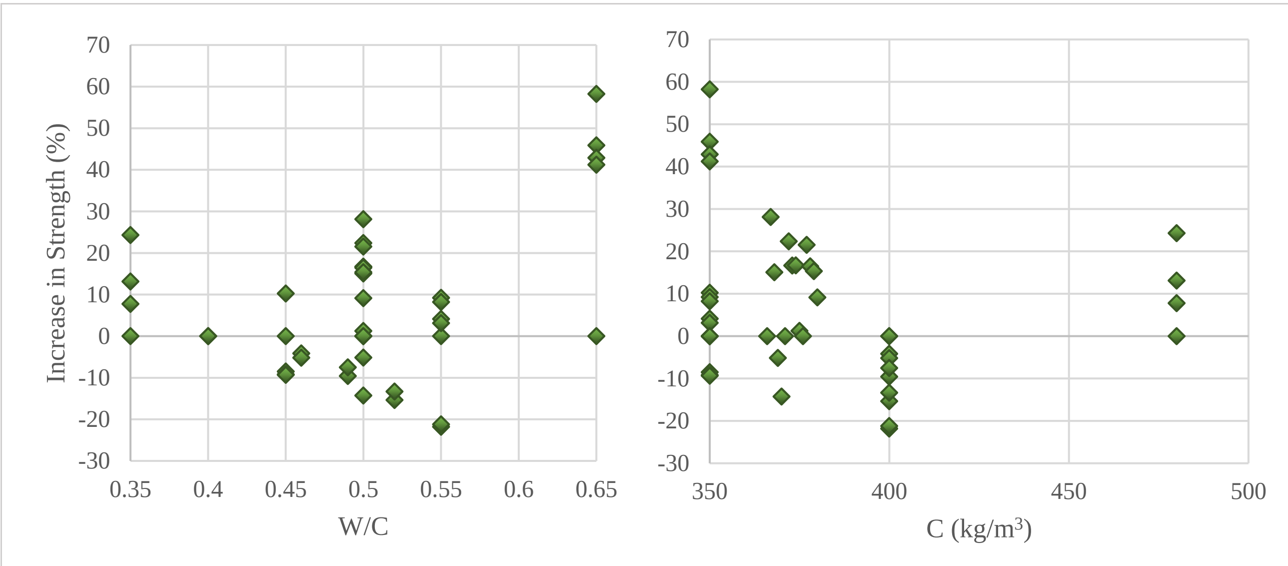

Figure 16. The effects of other components in the concrete mixture on the compressive strength of concrete mixtures containing fine and coarse marble aggregates.

4. Conclusions

In this study, the effects of using waste marble aggregates (waste powder, fine aggregate, coarse aggregate and both fine and coarse aggregate) in various proportions in replacement for natural aggregates on concrete compressive strength were investigated comparatively. In addition, multivariate regression analyses including interaction effects were conducted by using the test results of concrete mixtures with marble aggregates in the literature. The regression analyses yielded to analytical equations for estimating the change in the compressive strength of concrete with the form and content of marble aggregates (powder, fine and coarse aggregates) and other test parameters, including the fine and coarse aggregate ratio, maximum aggregate grain size, cement grade, cement dosage and the W/C ratio. The results obtained from the proposed relations were statistically compared with the experimental results. In this context, the following important results were obtained in the study:

1. Replacements of fine aggregates in concrete mixtures with marble powder of up to 15% had a positive effect on the concrete compressive strength owing to the reduction in the micro voids in the concrete mixture. This positive influence ranged between 2% and 26%.
2. Due to the greater specific surface area of the marble dust as compared to fine aggregates, the need for the amount of water for workability increases. Therefore, the ratio of the mixing water to the total mass of cement and marble powder rather than the water/cement ratio is more influential in concrete mixtures with marble powder. In this regard, fine aggregate replacements of up to 20% were observed to be tolerable as long as the mass ratio of water to cement and marble powder does not fall below 0.36. In a similar vein, replacement ratios of up to 50% were found to be feasible by tolerating an approximate decrease of 11% in the compressive strength as long as the ratio of water to cement and powder does not fall below 0.30. The marble powder was established to have the potential to increase the concrete compressive strength up to 45%. These results are rather beneficial for convincing researchers and the concrete industry partners to use marble powder in concrete mixtures, which will have considerable positive environmental effects.
3. The specific surface area of the marble powder changes with fineness modulus and replacement proportion of the marble powder in the mixture. In order to maintain or increase the concrete compressive strength with increasing specific surface area, the amount of binders in the mixture also needs to be increased. The marble powder replacement was observed to contribute to the concrete compressive strength in all samples with the exception of a single one, as long as the mass ratio of water to cement and marble powder was above 0.30 and the cement dosage exceeded 380 kg/m^3.
4. Replacements of conventional fine aggregates with fine marble aggregates of up to 50% were found to result in variations ranging from −12% to 37% in the concrete compressive strength. Only 24% of all specimens experienced reductions in compressive strength.
5. Replacements of conventional coarse aggregates with coarse marble aggregates of up to 50% were found to result in variations ranging from −12.6% to 21% in the concrete compressive strength. Only 40% of all specimens experienced reductions in compressive strength.
6. Replacing both fine and coarse natural aggregates with respective marble aggregates in quantities of up to 100% by mass might lead to adverse effects on concrete compressive strength. This replacement was found to increase the compressive strength of concrete up to 58% or decrease it down to 22%.
7. The form of marble aggregates was found to be rather crucial when using marble aggregates in concrete mixtures in replacement for conventional aggregates. The range of influence of this replacement was found to decrease with increasing grain size of marble aggregates. That is why the amounts of the other constituents of the mixture should be carefully adjusted if marble powder is added to the concrete mixture.
8. A wide range of variations in concrete compressive strength was encountered as a result of replacing natural aggregates with fine, coarse and both fine and coarse marble aggregates. The effects of water/cement ratio, cement dosage, cement grade, maximum aggregate grain size and the amounts of natural aggregates on the concrete strength were found to be ambiguous. Therefore, the effects of marble aggregates on the concrete compressive strength are complex and hard to quantify when taking the other test variables into account.
9. Three different concrete compressive strength variation equations were developed for three different forms of marble aggregates, i.e., powder, fine and coarse aggregates, by also taking all of the test parameters into account.

10. The estimates from the analytical equations, which were developed to quantify the effects of waste marble powder, fine marble aggregate and coarse marble aggregate on concrete strength together with other test variables, had high correlation coefficient (r) and low mean absolute error (MAE) values with regard to the experimental results. The correlation coefficient of the estimates from the equation proposed for the waste marble powder and the test results was determined as 0.94 and the MAE value as 3.14 MPa. Similarly, the correlation coefficient of the equation proposed for the fine marble aggregates was obtained as 0.93 and the MAE value as 3.04 MPa with the test results. Finally, the correlation coefficient of the equation proposed for the coarse marble aggregate was calculated as 0.91 with the test results and the MAE value as 3.97 MPa.

5. Limitations

The equations proposed in this study give accurate predictions within the variable ranges of the aggregate form (powder, fine and coarse aggregate) dataset. In order for the equations to make accurate predictions, first, the estimated value of the change in concrete compressive strength can be approximated to 0% in the absence of any waste marble aggregates in the concrete mixture. The closer the result is to zero, the more the concrete mixture approaches to the reference mixture (natural aggregate concrete). Then, the effect of the marble aggregate on the concrete compressive strength can be calculated by replacing the calculated content values of the reference mixture with the marble aggregate.

6. Future Studies

The equations proposed in this study, developed for predicting the effect of marble aggregate on concrete compressive strength, generated estimates in close agreement with the experimental results. However, the use of the equations is limited to the ranges of the variables in the dataset. The proposed equations are prone to producing irrational and rather inaccurate estimates for the experiments outside the ranges of the variables in the present dataset. The variable ranges of these datasets can be expanded with future research on the use of marble aggregates in concrete. In this way, equations can be assured to provide more reliable estimates for the usability of marble aggregates in concrete. In addition, since the number of studies on the use of marble aggregates instead of natural aggregates, especially in fine, coarse and mixed forms, is very low in the literature, more studies on this subject are required. In addition, the effects of marble waste and other test parameters should be considered together. In this context, it is necessary to carry out experiments where the marble aggregate ratio in the concrete mixture is kept constant and other test parameters are considered as variables.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su142114388/s1, The experimental studies used in the study and for which the datasets were created are presented in this section (Table S1). Table S1: Database of compressive strength tests on concrete samples containing waste marble powder. Table S2. Database of compressive strength tests of concretes containing fine marble aggregate. Table S3. Database of compressive strength tests of concretes containing coarse marble aggregate. Table S4. Database of compressive strength tests of concretes containing fine and coarse marble aggregates.

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