

Technical Report

Statistical analysis for freeze–thaw resistance of cement mortars containing marble dust and glass fiber

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ARTICLE INFO

Article history:

Received 10 February 2014

Accepted 3 April 2014

Available online 18 April 2014

ABSTRACT

This paper investigated the usability of marble dust and glass fiber against the harmful effects of freeze–thaw (FT) cycles on cement mortars as experimentally and statistically. To this end, the cement mortar specimens containing marble dust (0%, 20%, 40% and 50% by volume) and glass fiber (0 kg/m³, 0.25 kg/m³, 0.50 kg/m³, 0.75 kg/m³) were prepared. The compressive and flexural strengths of the specimens were determined after being exposed to FT cycles. In order to reduce the numbers of experiments, an L₁₆ (4² × 2¹) Taguchi orthogonal array was adopted to the study. Amounts of glass fiber, percentages of marble dust and cycles of freeze–thaw, were changed to explore their effects on the compressive and flexural strengths of the mortar specimens. Statistically effects of the factors were also determined by using analysis of variance (ANOVA) method. Finally, experimental findings were compared with statistical results and a good agreement between them was achieved.

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1. Introduction

In cold environments, freeze–thaw (FT) cycles can be harmful for a porous brittle material such as concrete when it is subjected to lower temperatures. Concrete structure subjected to repetitive FT cycles may deteriorate rapidly by losing strength and/or crumbling. When the water begins to freeze in a capillary pore, the increase in volume accompanying the freezing of the water requires an expansion of the void equal to 9% of the volume of frozen water, or forcing of the amount of excess water out through the boundaries of the specimen, or combination of both effects. The greatness of this hydraulic pressure depends on the permeability of the cement paste, the degree of saturation, the distance of the nearest unfilled void and the rate of freezing. If the pressure exceeds the tensile strength of the cement paste at any point it will be cause local cracking. In repeated cycles of freezing and thawing in a wet environment, water will enter the cracks during the thawing part of the cycle to freeze again later and there will be progressive deterioration with each FT cycle [1,2]. Thus, the strength of cement based material decreases after FT cycles [3]. Besides, the surfaces of specimens will scale off and crumble due to the expansion occurred when water freezes to ice [1].

Addition of the fiber into concrete or cement mortar considerably improves the structural characteristics such as tensile

strength, ductility and toughness [4–6]. Hence, the harmful effect of the FT cycles may reduce with addition of fiber into the cement based materials. Glass, steel, carbon and polymer based fibers are commonly used in many fiber reinforced composite applications [1,7–11]. Glass fiber is the most commonly used materials in the concrete industry [12]. Many researchers have investigated the various properties of glass fiber reinforced concrete or cement mortars [1,13–15].

Marble has been commonly used as a building material since ancient times. The industry's disposal of the marble powder material, consisting of very fine powders, is one of the environmental problems worldwide today [16]. Therefore, utilization of the marble dust in various sectors that especially the construction, agriculture, glass and paper industries will help to protect the environment [17]. Recently, many studies have been carried out on the possibility of re-use of waste marble dust in useful industries especially with regard to the building and construction materials such as cement, concrete and brick blocks [18]. The technical importance of using waste marble dust in concrete production is expressed by performance improvement of concrete. The economic benefit generally attributes to the reduction of the amount of expensive and or scarce ingredients with cheap materials. Environmentally, when waste marble dusts are recycled, less material is dumped as landfill and more natural resources are saved [2]. The effect of marble dust on the various properties of cement based materials was investigated; many researches indicated positive results and benefits [16,19–21]. Generally, in literature waste

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marble dust has been replaced with either fine aggregate (0–4 mm) or passing 1 mm sieve. But, no previous study was encountered on performance of cement mortar prepared by replacing very fine sand (passing through 0.25 mm sieve) with waste marble dust in the open literature. Studies concerning the utilization of marble dust in cement mortar are necessary to fully evaluate the potential using of this waste material.

The main objective of this study was to investigate the effects of the marble dust and glass fiber on the compressive and flexural strengths of the cement mortars exposed to FT cycles. The effect of experimental parameters on compressive and flexural strengths was evaluated as statistically and the level of significance of these parameters was determined by using analysis of variance (ANOVA) method.

2. Experimental study

2.1. Materials

Commercial grade ASTM Type I Portland cement, which is produced in Turkey as CEM I Portland cement, was used in the preparation of all cement mortar specimens used in the study.

The marble sludge containing both Elazig Cherry and Hazar Beige marble dusts was obtained in wet form as an industrial by-product directly from the deposits of marble factories, which forms during the sawing, shaping and polishing processes of the marbles in the Elazig province of Turkey. The marble sludge was dried before the preparation of the cement mortar specimens. The dried material was passed through 0.25 mm sieve and finally the marble dust was obtained to be used in the cement mortar specimens as very fine sand. The chemical properties of the marble dusts and cement used in the experiments are presented in Table 1.

High quality river sand was used as aggregate which is widely employed in cement mortars. Maximum grain size of aggregate was 4 mm. The density of the river sand was 2690 kg/m³. Various proportions (0%, 20%, 40% and 50% by volume) of the fine sand (passing through 0.25 mm sieve) were replaced with waste marble dust. The grain size distributions of very fine sand and waste marble dust are shown in Fig. 1.

The glass fibers were circular straight fibers obtained from Camelsan. The properties of the glass fiber used in this study are presented in Table 2.

In the study, modified polycarboxylate based superplasticizer obtained from Sika, was used as 1% of cement weight. Regular tap water was used as the mixing water during the preparation of the cement mortar specimens.

2.2. Casting and testing

Sixteen different cement mortar mixes were prepared to be used in the tests for the purpose of evaluating the compressive and flexural strengths of the specimens containing various amounts of glass fiber and marble dust. The mixture designs of

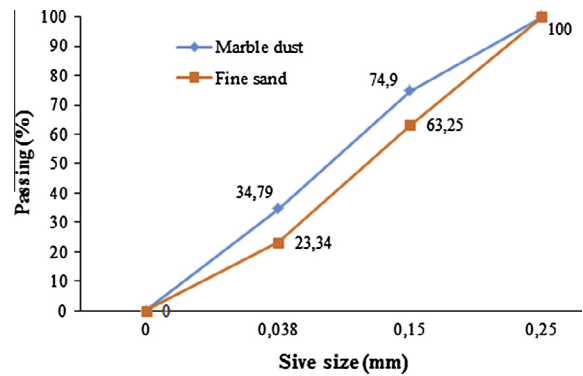


Fig. 1. Grain size distribution of the very fine sand and marble dust.

the all cement mortar groups are given in Table 3. A superplasticizer (SP) was used to improve the workability of the mixes.

All test batches were mixed using an electrically driven mechanical mixer conforming to the requirements of ASTM: C305-13. This practice covers the mechanical mixing of hydraulic cement pastes and mortars of plastic consistency. The mixtures were cast from the same batch into prismatic (40 × 40 × 160 mm) and cubic (50 × 50 × 50 mm) steel molds for flexural and compressive strength tests, respectively. The specimens were kept in the molds for 24 h at room temperature of about 20 ± 2 °C. After demolding, these specimens were cured in lime saturated water for 28 days. Thus, the mortar specimens were matured sufficiently prior to the freeze–thaw cycles.

In accordance with the objective of this study, FT cycles were applied to the mortar specimens. The FT tests were realized according to the ASTM: C666 Procedure B. This test method covers the determination of the resistance of concrete specimens to rapid freezing in air and thawing in water. All mortar specimens were exposed to 30 cycles freezing in “deep-freeze” at −20 ± 2 °C for 16 h and thawing in water at 4 ± 1 °C for 8 h. Many studies performed on concretes subjected to FT cycles have not provided sufficient information on the mechanical properties of concrete under compressive and tensile stress states. Because concrete cracks in maximum numbers of FT cycles are chosen very high as 300–400. Therefore, it is not possible to obtain compressive and flexural strength values of the specimens. In this study, because the maximum number of FT cycles was chosen as 30, visible deteriorations could not occur in the cement mortar specimens; thus, it was possible to apply flexural and compressive strength tests to the specimens.

After the FT processes had been completed, tests were conducted on the prismatic and cubic specimens to determine the flexural and compressive strengths of the mortars, respectively. For flexural strength of the mortars specimens, the specimens were loaded from their mid span and the clear distance between simple supports was 120 mm. The flexural and compressive strength test results were compared with the test results of control specimens. The averages of the five specimens were used for each experimental result.

The microscopic analyses of the specimens were performed at the Electron Microscopy Laboratory of Firat University using a Jeol JSM7001F scanning electron microscope.

2.3. Design of experiments

Taguchi's method of experimental design provides a simple, efficient, and systematic approach for the optimization of experimental designs for performance quality and cost [22]. To evaluate the each independent factor or their interaction effects on the

Table 1
Chemical analyses of the cement and marble dusts.

Oxide compounds (mass%)	CEM I 42.5 N	Marble dust (Elazig Cherry)	Marble dust (Hazar Beige)
SiO ₂	21.12	28.35	0.18
Al ₂ O ₃	5.62	0.42	0.03
Fe ₂ O ₃	3.24	9.70	0.12
CaO	62.94	40.45	53.24
MgO	2.73	16.25	0.10
Density (g/cm ³)	3.10	2.80	2.72

Table 2

Properties of the glass fiber used in the experiments.

Color	Fiber length (mm)	Fiber diameter (μm)	Density (g/cm ³)	Young's modulus (MPa)	Tensile strength (MPa)
White	6	13	2.68	72,000	1700

Table 3Details of the cement mortar mixes (kg/m³).

Exp. no.	Designation of mixture	Fiber glass	Marble dust	Aggregate (0–0.25)	Aggregate (0.25–4)	Water	Cement	SP
1	FG0-MD0	–	–	407	1253.8	221.4	450	4.45
2	FG0-MD20	–	77.25	325.4	1253.8	221.4	450	4.45
3	FG0-MD40	–	154.5	243.6	1253.8	222.8	450	4.45
4	FG0-MD50	–	193.12	203.6	1253.8	222.8	450	4.45
5	FG0.25-MD0	0.25	–	407	1253.8	221.4	450	4.45
6	FG0.25-MD20	0.25	77.25	325.4	1253.8	221.4	450	4.45
7	FG0.25-MD40	0.25	154.5	243.6	1253.8	222.8	450	4.45
8	FG0.25-MD50	0.25	193.12	203.6	1253.8	222.8	450	4.45
9	FG0.50-MD0	0.50	–	407	1253.8	221.4	450	4.45
10	FG0.50-MD20	0.50	77.25	325.4	1253.8	221.4	450	4.45
11	FG0.50-MD40	0.50	154.5	243.6	1253.8	222.8	450	4.45
12	FG0.50-MD50	0.50	193.12	203.6	1253.8	222.8	450	4.45
13	FG0.75-MD0	0.75	–	407	1253.8	221.4	450	4.45
14	FG0.75-MD20	0.75	77.25	325.4	1253.8	221.4	450	4.45
15	FG0.75-MD40	0.75	154.5	243.6	1253.8	222.8	450	4.45
16	FG0.75-MD50	0.75	193.12	203.6	1253.8	222.8	450	4.45

process characteristics, Taguchi uses standard orthogonal arrays. A loss function is then defined to calculate the deviations between the experimental value and the desired value. This loss function is further transferred into a signal-to-noise (S/N) ratio, η [23]. Usually, there are three S/N ratios available, depending on the type of characteristic; the lower-the better (LB), the higher-the better (HB), and the nominal-the better (NB). The S/N ratios for each type of characteristic can be calculated as follows:

1. Lower is better: choose when goal is to minimize the response. The S/N can be calculated as given in Eq. (1) for smaller the better.

$$S/N = -10 * \log_{10} \left(\frac{1}{n} \sum_{i=1}^n Y_i^2 \right) \quad (1)$$

2. Higher is better: choose when goal is to maximize the response. The S/N is calculated as given in Eq. (2) for larger the better.

$$S/N = -10 * \log_{10} \left(\frac{1}{n} \sum_{i=1}^n \frac{1}{Y_i^2} \right) \quad (2)$$

3. Nominal is better: choose when goal is to target the response and it is required to base the S/N on standard deviations only. The S/N is calculated as given in Eq. (3) for smaller the better.

$$S/N = -10 * \log_{10} \left(\frac{1}{n} \sum_{i=1}^n (Y_i - Y_0)^2 \right) \quad (3)$$

In quality characteristic determination; HB was chosen for compressive and flexural strengths of the cement mortar specimens used in the study.

In this study, three control factors, i.e., (1) amount of glass fiber, (2) percentage of marble dust and (3) cycle of freezing-thawing, which were labeled by A, B and C, respectively, and four control levels for each control factor, except factor C which has two levels, were considered as shown in Table 4.

When the design type is full factorial, it is necessary to conduct 32 ($4 \times 4 \times 2$) experiments because all the possible combinations should be introduced in the design. To reduce the number of tests, an L_{16} ($4^2 \times 2^1$) orthogonal array that only needs 16 experimental runs was adopted. The orthogonal array and experimental results are given in Table 5.

Table 4

Control factors and their levels.

Designation	Control factor	Level 1	Level 2	Level 3	Level 4
A	Amounts of glass fiber (kg/m ³)	0	0.25	0.50	0.75
B	Percentages of marble dust (%)	0	20	40	50
C	Cycles of freeze–thaw	0	30	–	–

Table 5 L_{16} orthogonal array and experimental results.

No.	A Glass fiber (kg/m ³)	B Marble dust (%)	C FT cycles	Experimental results (MPa)	
				Compressive strength	Flexural strength
1	1	1	1	84.70	11.51
2	1	2	1	91.91	12.38
3	1	3	2	88.98	11.71
4	1	4	2	89.63	12.10
5	2	1	1	82.73	11.84
6	2	2	1	85.41	12.69
7	2	3	2	85.32	12.27
8	2	4	2	87.10	12.46
9	3	1	2	76.64	11.43
10	3	2	2	80.09	11.96
11	3	3	1	88.18	13.56
12	3	4	1	90.15	13.76
13	4	1	2	74.96	11.98
14	4	2	2	78.84	12.52
15	4	3	1	87.43	13.73
16	4	4	1	88.65	13.98

3. Experimental findings, data analysis and discussion

3.1. Experimental findings

The effects of control factors on responses are plotted in Figs. 2 and 3. It can be seen from these figures, compressive and flexural strengths of the cement mortar specimens increased with increasing the percentage of marble dust. On the other hand, in contrast to marble dust effect, the use of glass fiber in the cement mortars with and without marble dust increased the flexural strength but decreased the compressive strength of the specimens.

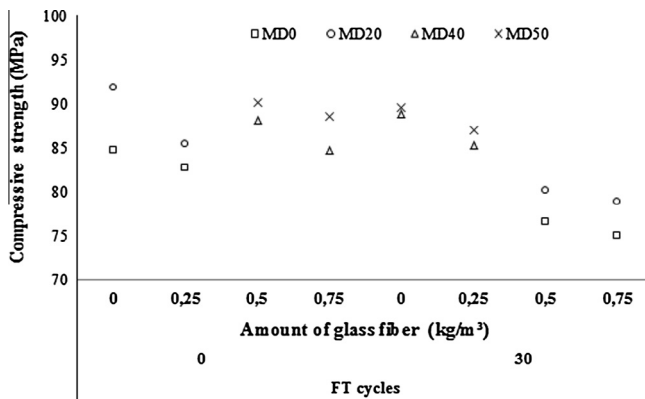


Fig. 2. Change in the compressive strength values of the mortar specimens.

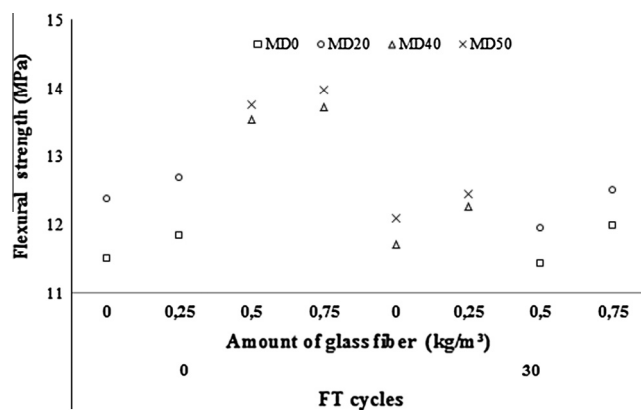


Fig. 3. Change in the flexural strength values of the mortar specimens.

As seen from Fig. 2, compressive strength of the mortar specimens decreased depending on the increase in the amount of glass fiber. Since the fibers have more ductile structure compared to the cement matrix and aggregate when the fibers are added to mortars, they cause discontinuity in the cement matrix. This is therefore expected to decrease the compressive strength of mortars [1,24]. Additionally, the reduction in compressive strength of the glass fiber reinforced cement mortars used in the study can be attributed to the poor adhesion between the glass fiber and mortar. The poor adhesion causes voids occurrence in the mortar as can be seen in Fig. 4, therefore compressive strength of the cement

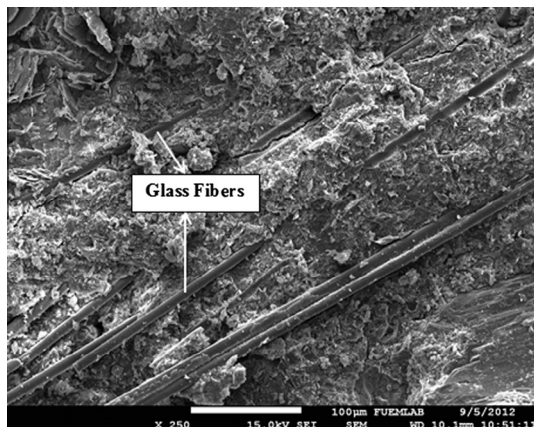


Fig. 4. SEM image of the glass fibers in the cement mortar.

mortars containing glass fiber decreased. Due to poor adhesion between the glass fibers and mortar, smooth and clean surfaces without continuous mortar particles were observed.

As can be clearly concluded from Fig. 3, in contrast to compressive strength, compared with the control specimens, in generally, glass fiber addition increased the flexural strength of the cement mortar specimens.

The addition of marble dust as very fine sand into the cement mortars with glass fiber resulted an increase in the compressive and flexural strengths. This result may have one underlying reason; the reason is that the marble dust has a much smaller grain size compared to very fine sand, enabling it to fill in the voids. The fineness of an admixture is highly critical for the modification of aggregate/cement paste interface zone, which is the weakest link of a concrete's structure [25].

As seen in Fig. 1, average particle size of the very fine sand is very large compared to marble dust, thus its filler effect may not be sufficient as marble dust. It can be concluded that compressive and flexural strengths of the mortars without marble dust relatively low, because filler effect of fine sand is not as good as those of marble dust. The marble dust particles, however, may act as ideal microfiller in the interfaces between fine sand and cement paste or pores in the bulk paste. Therefore, high levels of the compressive and flexural strengths are achieved in the mortars containing both glass fiber and marble dust compared to that of the only glass fiber. These observations agreed fairly well with those obtained by other researchers for similar test conditions [21,26,27].

The test results have shown that the FT cycles had important effects on the mechanical properties of the all cement mortars used in this study. As seen from Fig. 2, the compressive strengths of the mortar specimens decreased after exposed to the FT cycles. Although the mortar specimens with glass fiber generally had less compressive strength than the control specimens, the strength loss percentages in glass fiber reinforced mortars were less than the control specimens after FT cycles.

When the effect of FT cycles on the flexural strength of the mortars with glass fiber was investigated, it was seen that, the flexural strength of the mortars decreased after FT cycles. However, the glass fiber reinforced mortars showed better comparative performance than non-fibrous ones depending on the increase in the amount of glass fiber (Fig. 3). After 30 FT cycles, flexural strength of the non-additive control specimen decreased by 8.34%. This decrease for all glass fiber reinforced mortar specimens was average 5.60%.

As can be clearly seen in Figs. 2 and 3, although addition of the glass fiber into the cement mortars increased the freeze–thaw resistance, the addition of marble dust decreased this resistance significantly.

Micro-cracks mainly exist at cement paste–aggregate interfaces in concrete even prior to any loading and environmental effects. When the number of FT cycles increases, the degree of saturation in pore structures increases by sucking in water near the concrete surface during the thawing process at temperatures above 0 °C. Some of the pore structures are filled fully with water. Below the freezing point of those pores, the volume increase of ice causes tension in the surrounding concrete. If the tensile stress exceeds the tensile strength of concrete, micro-cracks occur. By continuing FT cycles, more water can penetrate the existing cracks during thawing, causing higher expansion and more cracks during freezing. The load carrying area will decrease with the initiation and growth of every new crack. Necessarily the compressive strength will decrease with FT cycles [28–30].

Fig. 5 shows SEM micrographs illustrating the microstructure characteristics of the cement mortar specimens prior to FT cycles and after 30 cycles of FT.

It can be seen from Fig. 5a that there is no micro-cracks in microstructure of the mortar specimens prior to FT cycles. Fig. 5b

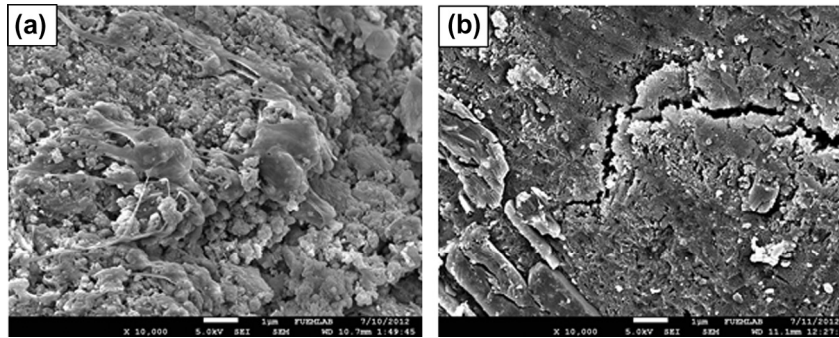


Fig. 5. SEM micrographs of the mortar specimens (a) prior to FT cycles, (b) after 30 cycles of FT.

shows the micro-cracks in the mortar specimen occurred after 30 FT cycles. The reduction in flexural and compressive strengths of the mortar specimens subjected to FT cycles can be attributed to the formation of micro-cracks that lead to weakening interfacial transition zone and bonding between the fine aggregate and cement paste. Although the general trends of the influence of FT cycles on mechanical properties of the cement mortars were similar, compressive and flexural strengths were affected differently after 30 FT cycles. It can be seen from Figs. 2 and 3 that the deteriorating effect of FT cycles on flexural strength of the mortar specimens was more severe than compressive strength. This may be due to the fact that, the destructive effect of micro-cracks that form under FT cycles was more apparent in the case of tensile stress created in flexural test.

The use of fiber technology promotes air entrainment into concrete. Air entrainment was identified by the lower densities of fiber reinforced concretes when compared to control concretes without fibers [31]. The lower densities are due to retained water, or low bleed characteristics, which produce high volumes of cement paste. When the cement paste dries out, small water voids are created due to the original water retention and this provides an air entrained system. A large majority of these voids are at the upper limit (1 mm) of large air entrained voids that provide freeze/thaw protection (mesopores) [31,32]. The fibers are extremely fine and represent about 30 million discontinuities in the cement paste per m^3 . From visual observations the fibers dispersed evenly and this is how an air void protection was afforded at a microscale [31].

The marble dust particles, however, may act as microfiller for these air voids in the mortar specimens. Therefore, addition of the marble dust into the cement mortars with glass fiber decreased the freeze–thaw resistance compared to that of the only glass fiber.

In addition to the air void system created by the addition of fibers into concrete, the fibers have a low modulus of elasticity and low density when compared to the surrounding concrete. When exposed to the FT cycle the fiber will yield under hydrostatic pressure before the concrete, thus providing further pressure relief and subsequent freeze–thaw protection [31].

3.2. Data analysis of the S/N ratios

Table 6 shows the corresponding S/N ratios for flexural and compressive strength values of the cement mortars obtained by using Eq. (2). The mean S/N ratio for each level of the other factors was calculated in a similar manner and the results are shown in Tables 7 and 8. Additionally, the total mean S/N ratio is computed by averaging the total S/N ratios. It can be seen from Tables 7 and 8 that the optimum parameter of compressive strength was different from flexural strength. Based on the data presented in Table 7, the optimal performance for compressive strength of the cement mortars was obtained at 0 kg/m^3 glass fiber (Level 1), 50% marble dust

Table 6

L_{16} orthogonal array and corresponding S/N ratios for compressive and flexural strengths.

No.	A Glass fiber (kg/m^3)	B Marble dust (%)	C FT cycles	S/N ratio for compressive strength	S/N ratio for flexural strength
1	1	1	1	38.66	21.26
2	1	2	1	39.11	21.76
3	1	3	2	38.98	21.45
4	1	4	2	39.12	21.63
5	2	1	1	38.29	21.54
6	2	2	1	38.74	22.05
7	2	3	2	38.61	21.73
8	2	4	2	38.75	21.91
9	3	1	2	37.64	21.18
10	3	2	2	38.09	21.68
11	3	3	1	38.95	22.55
12	3	4	1	39.09	22.73
13	4	1	2	37.50	21.44
14	4	2	2	37.96	21.94
15	4	3	1	38.81	22.81
16	4	4	1	38.95	22.99

(Level 4) and 0 cycle (Level 1) settings. According to Table 8, the optimal performance for flexural strength of the mortar specimens was obtained at 0.75 kg/m^3 glass fiber (Level 4), 50% marble dust (Level 4) and 0 cycle (Level 1) settings. Figs. 6 and 7 present plots of the S/N ratio for the three control parameters A, B, and C studied at four levels except factor C which has two levels for the compressive and flexural strengths. The S/N ratio corresponds to the smaller variance of the output characteristics around the desired value.

3.3. Analysis of variance (ANOVA)

The analysis of variance (ANOVA) is the statistical treatment most commonly applied to the results of the experiment to determine the percent contribution of each factor and factor interactions. ANOVA employs sums of squares which are mathematical abstracts that are used to separate the overall variance in the response into variances due to the processing parameters and measurement errors [33]. In this study, ANOVA analysis and *F*-tests were carried out to determine statistically significant process parameters and percent contribution of these parameters on the compressive and flexural strengths of cement mortar containing glass fiber and marble dust. MINITAB software was used for calculation. ANOVA results are tabulated in Tables 9 and 10 for compressive and flexural strengths, respectively. The last column of these tables indicates the statistically effect of each factor on responses. The *F*-test was performed according to confidence level 95% ($\alpha = 0.05$ in this study). At this level, all control factors are suitable since calculated *F*-ratios are greater than the tabulated *F*-ratio (4.06) value. As shown from the ANOVA tables, when the ANOVA

Table 7

Response table mean signal-to-noise (S/N) ratio for compressive strength factor and significant interaction.

Mean S/N ratio					
Symbol	Control factor	Level 1	Level 2	Level 3	Level 4
A	Amounts of glass fiber (kg/m ³)	38.96 ^a	38.60	38.44	38.30
B	Percentages of marble dust (%)	38.02	38.48	38.84	38.98 ^a
C	Cycles of freeze–thaw	38.83 ^a	38.33	–	–

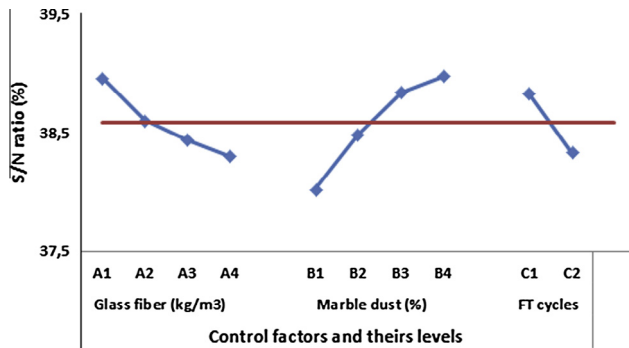
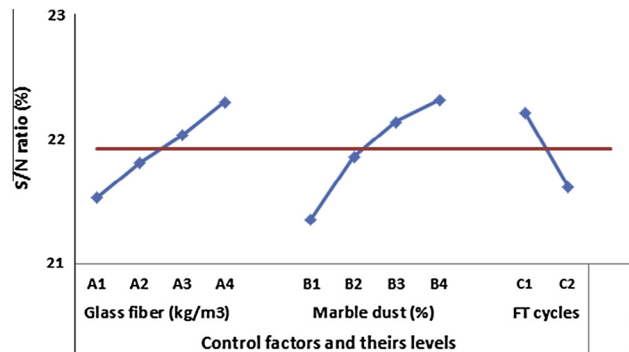
Total mean S/N ratio: 38.58.

^a Optimum level.**Table 8**

Response table mean signal-to-noise (S/N) ratio for flexural strength factor and significant interaction.

Mean S/N ratio					
Symbol	Control factor	Level 1	Level 2	Level 3	Level 4
A	Amounts of glass fiber (kg/m ³)	21.53	21.81	22.03	22.30 ^a
B	Percentages of marble dust (%)	21.35	21.86	22.14	22.31 ^a
C	Cycles of freeze–thaw	22.21 ^a	21.62	–	–

Total mean S/N ratio: 21.92.

^a Optimum level.**Fig. 6.** S/N ratios of the compressive strengths.**Fig. 7.** S/N ratios of the flexural strengths.

results are scrutinized, the most effective factor is marble dust percentage on the both compressive and flexural strengths. Additionally, the statistically effect of the FT cycles on the both compressive and flexural strengths was found more than the effect of glass fiber used in the test specimens. The percent contributions of the factors on responses are given in Figs. 8 and 9. It can be seen from these figures that the marble dust percentage is the most effective factor on the compressive strength (51.26%) and flexural strength (42.43%) compared to the FT cycles and glass fiber. The experimental errors are very low levels for compressive strength (2.88%) and flexural strength (3.03%), respectively.

Table 9

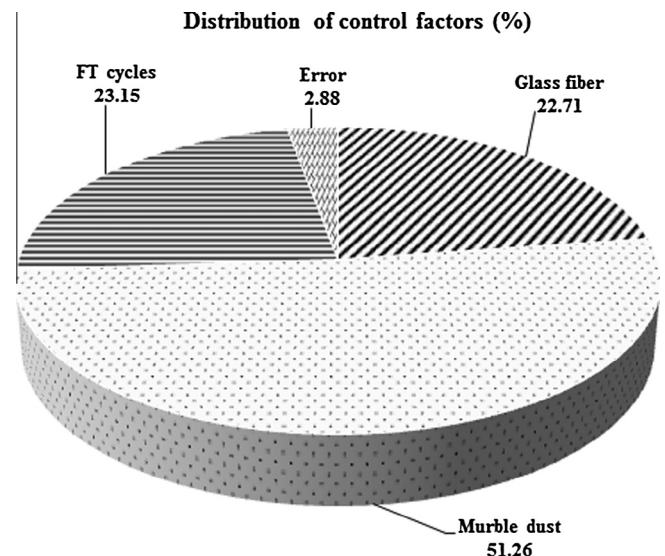
Analyses of variance (ANOVA) for compressive strength.

Control factors	Degrees of freedom	Sum of square	Variance	F	Contribution of factors (%)
Glass fiber	3	0.97	0.33	40.43	22.71
Marble dust	3	2.17	0.72	90.01	51.26
FT cycles	1	0.98	0.98	121.61	23.15
Error	8	0.06	–	–	2.88
Total			–	–	100

Table 10

Analyses of variance (ANOVA) for flexural strength.

Control factors	Degrees of freedom	Sum of square	Variance	F	Contribution of factors (%)
Glass fiber	3	1.29	0.43	43.65	25.89
Marble dust	3	2.10	0.70	70.88	42.43
FT cycles	1	1.41	1.41	142.58	28.65
Error	8	0.08	–	–	3.03
Total			–	–	100

**Fig. 8.** Effect of control factors on the compressive strength.

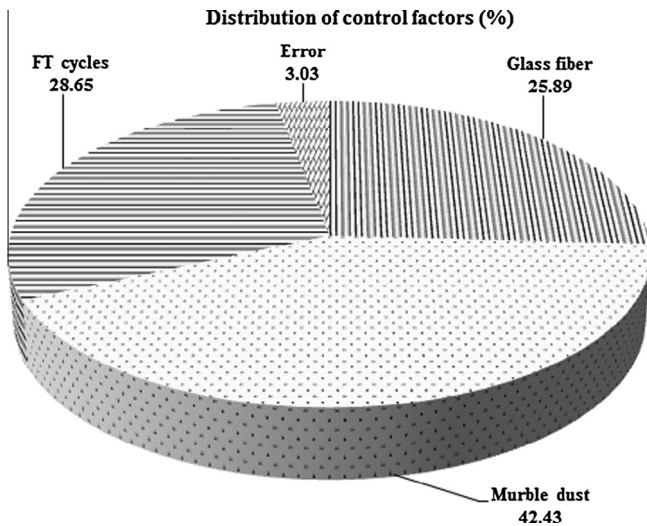


Fig. 9. Effect of control factors on the flexural strength.

4. Conclusions

On the basis of experimental and statistical works that have been carried out and presented in this paper, the following conclusions can be drawn;

- The experimental test results indicated that the compressive and flexural strengths of the mortar specimens increased as a result of the fact that increase in ratio of marble dust was added to mortar instead of very fine sand. This finding is due to the marble dust particles may act as ideal microfiller in the interfaces between fine aggregate and cement paste or pores in the bulk paste.
- In contrast to marble dust effect, the use of glass fiber in the cement mortars increased the flexural strength but decreased the compressive strength of the specimens. The reduction in the compressive strength of the mortars can be attributed to the poor adhesion between the glass fiber and mortar. Additionally, fibers cause discontinuity in the cement matrix due to they have more ductile structure compared to the cement matrix and aggregate.
- The mechanical strengths of the all cement mortars decreased after repetitive FT cycles. However, glass fiber reinforced mortar specimens presented better performance than non-fibrous ones.
- Although the glass fibers decreased the compressive strength of mortars, the decreases were less than the control specimens after 30 FT cycles. For flexural strength, there were similar out comes to that of compressive strength.
- As a result of the experiments conducted for the purpose of determining the effects of marble dust and glass fiber on the mechanical properties of cement mortars exposed to FT cycles, it has been observed that the deteriorating effect of FT cycles on flexural strength of the mortar specimens was more severe than the compressive strength. This may be due to the fact that, the destructive effect of micro-cracks that form under FT cycles was more apparent in the case of tensile stress created in flexural test.
- The experimental findings indicated that the addition of the glass fibers into the cement mortars can increase the air voids system when compared to control mortar, thus providing an alternative to air entrainment as a method of freeze–thaw protection.
- Addition of the marble dust into the cement mortars with glass fiber decreased the freeze–thaw resistance compared to that of

the only glass fiber. This finding can be attributed to the marble dust particles may act as microfiller for air voids created by the addition of glass fibers into the mortar specimens.

- According to the S/N ratio results, optimum parameter of compressive strength was different from flexural strength. The optimum compressive strength was achieved at A1–B4–C1 parameter settings. Optimal performance for flexural strength of the mortar specimens was obtained at A4–B4–C1 settings.
- Based on the ANOVA results, the most efficient parameter was found the marble dust percentage on the both compressive strength (51.26%) and flexural strength (42.43%) of the cement mortar specimens. The FT cycles was found the second ranking factors on the both compressive strength (23.15%) and flexural strength (28.65%). These factors do not seem to have much of an influence on the responses.

Acknowledgment

The authors gratefully acknowledge the financial support from the Scientific Research Projects Management Council of the Firat University for this study performed under project with Grant No. TEF1111.

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