

DESIGN AND OPTIMIZATION OF BASALT FIBER ADDED LIGHTWEIGHT PUMICE CONCRETE USING TAGUCHI METHOD

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In this study, physical, mechanical and durability properties of basalt fiber reinforced lightweight pumice concrete including water absorption, bulk density, strength and sulfate attack resistance were investigated. Taguchi method was proposed to optimize compressive strength, flexural strength and sulfate resistance properties. Ground Calcium Carbonate (GCC), Basalt Fiber (BF), and Pumice Aggregate (PA) ratio were used as three factors in the L16 Taguchi array. GCC was partially replaced with cement at the rates of 0 %, 5%, 10% and 15 % by weight. BFs (6mm) were added in four contents of 0.25 %, 0.50 %, 0.75 % and 1 % by volume of the mixtures. PA to aggregate content ratio were considered as 25 %, 30 %, 34 % and 38 %. 16 series of laboratory tests were performed on the prepared samples. The contribution of each factor was also evaluated with analysis of variance (ANOVA) method to determine the optimum levels. Experimental tests were also conducted in order to validate Taguchi optimization and ANOVA results.

Keywords: Lightweight concrete, basalt fiber, pumice concrete, optimization, Taguchi method, GCC

1. Introduction

Concrete is known as one of the fundamental materials in construction with its high amount of use. Due to its high consumption, the normal weight aggregates (NWAs), such as granite and gravel, in construction concrete, natural stone deposits have decreased dramatically. Such amount of usage caused no recoverable damages to the natural environment. Consequently, the need for sustainable materials has become obvious in recent years[1].

Lightweight concrete (LWC) can be helpful material in reducing the environmental effect of concrete by decreasing the self-weight and dimensions of the structure[2]. In order to reduce self-weight of concrete artificial aggregates are used, and it also contributes to developing a sustainable material [3]. LWC is defined as a versatile material and the construction industry paid great attention to it in recent years. Oven dry density of LWC is at the range of 300-2000 kg/m³ and compressive strength of a cube is from 1 to 60 MPA [4]

The strength of LWC is a vital criterion for utilization of LWC in various construction projects and needs to be higher than certain values. In order to improve lightweight concrete properties, fibers are commonly used. The influence of fibers on the mechanical properties of LWC has been investigated by the researchers [5-7]. These fibers can be mainly divided into 3 main types; metallic, synthetic and natural. Carbon, glass, steel, rubber,

waste cable steel and glass are commonly used fibers for their various advantages. Among others, steel fibers (SF) are mostly used to increase the compressive strength of both normal and lightweight concrete.

Compressive strength of LWC is one of the vital criteria as it is also important for normal-weight concrete. In this study 21 different (various) researches on LWC have been investigated along with the compressive strength. The main objective of this study to understand the influence of various fibers and especially steel and glass fibers on LWC. Due to the lack of enough data about utilization of SF and GF in LWC, this study aims to explore the impact of SF and GF on LWC and provide numeric data.

2. Literature review

Many researchers have focused on the impact of fibers on LWC mechanical behaviors[8]. Recent studies report that compressive strength can be increased by adding SF. Furthermore, SF addition results in an increase of flexural strength and splitting tensile [7,9]. LWC is known for its low shear capacity in comparison to normal weight concrete. However, this shortcoming attribute can be developed by adding fibers to the concrete specimen. The impact of SF on LWC shear behavior has been reviewed and results show that , SF contributes to the development of shear behavior [10] . 0.5 % of SF addition increased shear resistance from 50.7 kN to 76.6 kN which is

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51% higher than no fiber added to concrete. Similarly, when SF addition is 1.0%, the shear resistance enhancement determined to be 68%.

There is a limited number of researches on the utilization of glass fiber in LWC. However recent study(4) reports that LWC that contains 0.06% glass fiber, shows 7-11% higher compressive strength than 0% glass fiber added LWC[11,12]. The compressive strength difference increases by a higher level of GF addition. Similarly, a recent study [13] verifies that with the use of GF 0.00 to 0.06%, the compressive strength goes up remarkably from 57.85 MPa to 66.01 MPa. Also, it is mentioned that when the amount of GF is higher than 0.06%, the increase of compressive strength is insignificant. Splitting tensile on the other hand, has increased trend with the increase of GF from 0.00% to 1.2%. The increase in splitting tensile is higher than compressive strength.

In the recent study effect of carpet wastes in LWC was investigated[14]. Unlike SF added concrete, Compressive strength reduces 5,39%, 8,49% and 14,76% with the use of carpet waste with 1%,2% and 3%. Flexural strength shows a similar trend with the compressive strength [15]. Change in dry density is from 4% up to 14%. Therefore, utilization of carpet wastes has negative impact on both the compressive and flexural strength of the concrete. Water absorption of carpet waste added samples is at the range of 6,8% and 9.3%. Obviously, water absorption of concrete has increased significantly. Higher porosity of the carper waste can be considered as the main reason for high water absorption.

Basalt fiber is another additional material, that recently used to lightweight concrete in Besides increasing both compressive and flexural strength, basalt fibers can also enhance toughness together with the fracture energy in the cement matrix composite applications [16]. Due to its similar chemical properties, it shows better binding performance with the cement. In terms of cost, it is cheaper than the other widely used chemical fibers in civil engineering researches [17]. Even though, there is a great number of researches on steel fibers addition to LWC, number of researches on basalt fiber addition to LWC is limited. Existing researches on basalt fiber added conventional concrete focused on mechanical properties of the composites. According to the existing researches, the optimum percentage of basalt fiber addition is 0.5% by volume. Furthermore, this percentage might change depending upon the type of concrete [18-20]. The main advantage of basalt fiber can be considered as a shift from a brittle failure behavior to more ductile one for conventional concrete mixes under compressive loads [20], and literature suggests that basalt fiber addition can significantly increase the tensile strength of concrete [21]. It has been also proved that basalt fiber containing

concrete shows higher toughness. It is not easy to evaluate the relative advantages of it as various test methods are used [22].

3. Materials and method

3.1. Pre-Optimization Experimental Studies and Results

The material used for lightweight pumice concrete were Pumice Aggregates (PA), Fine Aggregates (river sand; FA), commercially available Betocarb® and CEM I 42.5 R Cement. The particle size distributions of the combined aggregates are presented in Fig. 1.

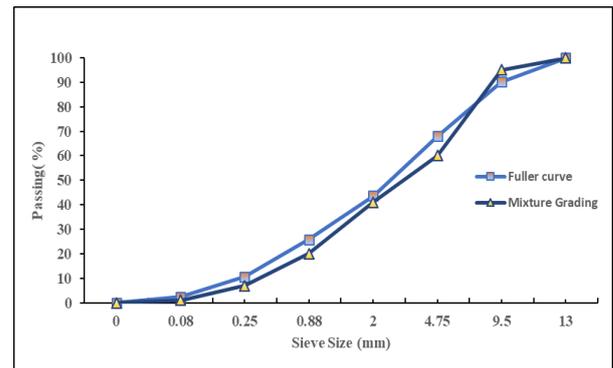


Fig. 1 - Fuller curve and aggregate gradation

Physical properties of the PA and FA, and material properties of the BF are given in Table 1 and Table 2, respectively. 6 mm length BFs were utilized with the volume fractions of 0.25%, 0.5%, 0.75% and 1% in the experimental study. Polycarboxylic type hyper plasticizer was also added to all prepared mixture at the rate of 1.25% of cement by weight.

Table 1

Physical properties of the aggregates		
Aggregates/property	FA	PA
Particle size (mm)	0- 4	2-12
Particle density (g/cm ³)	2.73	2.21

Table 2

Material properties of the BFs	
Technical property	
Elasticity module, MPa	90
Tensile strength, MPa	4832
Melting point, C°	1452
Application temperature, C°	-220/+980
Chemical composition	Percentages (%)
SiO ₂	51.2-58.9
Al ₂ O ₃	14.5-18.2
Fe ₂ O ₃	5.7-9.6
MgO	3.0-5.4
FeO + Fe ₂ O ₃	9.2-14.0
TiO ₂	0.8-2.25
Na ₂ O + K ₂ O	0.8-2.25
Others	0.08-0.14

Material properties of Cement and Betocarb® are given in Table 3. A good bonding can be expected between the cement and BFs

Table 3

Physical properties and chemical compositions of cement, PA and Betocarb®

Material property	Cement	PA	Betocarb®
Fe ₂ O ₃ , %	3.52	1.5	
CaO, %	60.21	0.2	
SiO ₂ , %	.19	75.84	
MgO, %	2.32	0.4	
SO ₃ , %	2.61	0.5	
Al ₂ O ₃ , %	4.32	12.54	
Free CaO, %	1.7	-	
Loss on ignition	2.85	5.63	
Specific gravity	3.12	2.35	
Specific surface (cm ² /g)	3,618	-	>30,000
Blue value	-	-	<3
d50%	-	-	3

Table 4

Mixture proportions of the specimens

Trail no.	Mixture code	Fine Aggregates (kg/m ³) (FA)	Pumice Aggregates (kg/m ³) (PA)	Basalt Fiber (volume fraction, %)	GCC (kg/m ³)	Cement (kg/m ³)	Water (kg/m ³)	Superplasticizer(kg/m ³)
	R	741	450	0	0	170	80	2.50
1	LC ₁	891	300	0.25	0	170	80	2.50
2	LC ₂	841	350	0.5	8.5	161.5	80	2.50
3	LC ₃	791	400	0.75	17	153	80	2.50
4	LC ₄	741	450	1	25.5	144.5	80	2.50
5	LC ₅	891	300	0.25	8.5	161.5	80	2.50
6	LC ₆	841	350	0.5	0	170	80	2.50
7	LC ₇	791	400	0.75	8.5	161.5	80	2.50
8	LC ₈	741	450	1	17	153	80	2.50
9	LC ₉	891	300	0.25	17	153	80	2.50
10	LC ₁₀	841	350	0.5	17	153	80	2.50
11	LC ₁₁	791	400	0.75	0	170	80	2.50
12	LC ₁₂	741	450	1	8.5	161.5	80	2.50
13	LC ₁₃	891	300	0.25	25.5	144.5	80	2.50
14	LC ₁₄	841	350	0.5	25.5	144.5	80	2.50
15	LC ₁₅	791	400	0.75	25.5	144.5	80	2.50
16	LC ₁₆	741	450	1	0	170	80	2.50

according to their similar chemical compositions as it is shown in Table 2 and Table 3 [9].

Mix proportions of the prepared specimens are presented in Table 4. The reference and 16 lightweight pumice concrete samples (LC₁₆ design) were mixed with a pan mixer. The pan mixer rate was kept constant as 250 r/min in order to prevent the breaking of the BFs.

The effects of FA to PA ratio, BF inclusion and utilizing GCC as supplementary cementitious material on the physical, durability and mechanical properties of the lightweight composites were investigated within the scope of laboratory tests. Consistency of the blends was recorded with slump test. Slump tests were repeated three times with 20 min. intervals in order to investigate slump losses in an hour. Bulk density and water absorption of the samples were recorded according to the ASTM C 642 standard [23]. Sorptivity characteristics of the specimens were recorded as per the requirements of ASTM C 1585 [24]. Disc specimens (Ø100/50) were prepared for the bulk density, sorptivity and water absorption tests. Compressive strength tests were performed on the Ø150/300 mm cylindrical specimens according to ASTM C 469 standard [25]. Flexural strength tests.

were conducted with 100 x 100 x 500 mm prismatic samples according to the EN 14651 [26]. Prismatic specimens were notched prior to the flexural strength tests. Sulfate attack on lightweight pumice concrete was investigated with compressive strength losses of the samples. Two groups of specimens were prepared during the sulfate attack tests. One group was left in curing water, and the second group was kept in 10 % of magnesium sulfate containing solution. Magnesium sulfate concentration was renewed every 20 days until the end of test time (180 days). Compressive strength losses were recorded at 7,28,90 and 180 days.

Slump test results are presented in Fig. 2. BF inclusion decreased the spread diameter of the mixtures. BF addition in concrete generally worsens the slump test results [27]. However, both utilization of BF and GCC limited the decrease in spread diameter. As it is shown in Fig 2., LC₁₃ sample includes same BF and aggregate content with LC₁, but spread diameter of the LC₁₃ sample was higher compared to the LC₁. This result can be attributed to the GCC content of LC₁₃ sample. SEM image of utilized GCC is presented in Fig. 3. As seen in Fig .3 partially rounded shape of GCC,

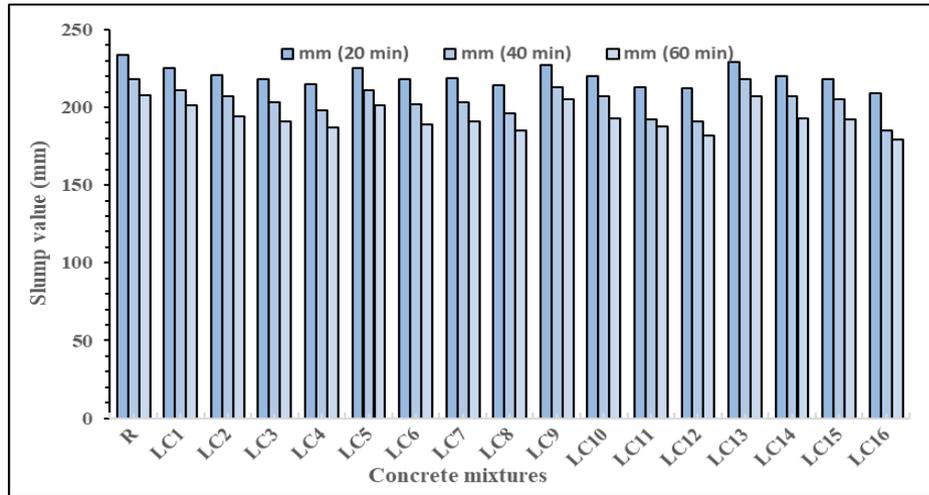


Fig. 2 - Spread the diameter of lightweight concretes.

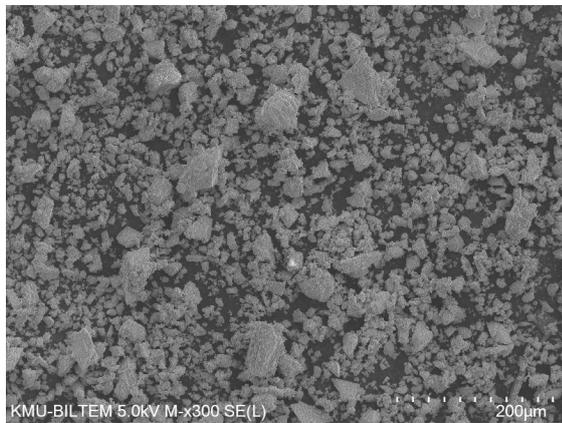


Fig. 3 - SEM images of GCC particles.

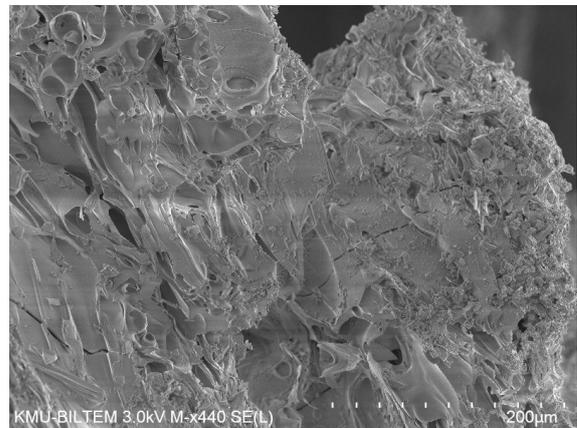


Fig. 4 - SEM images of PA particles.

and its fineness (Table 3) can improve the spreading behavior of the prepared mixtures. The presence of PA had negative effect on consistency of the concrete mixtures (Fig. 2.). An increase in PA content of the lightweight concrete mixtures resulted in decreased spread diameters, since used PAs have a porous microstructure (Fig. 4).

Water absorption and dry bulk density of the lightweight pumice concrete at 7,28,90 and 180 days are presented in Fig. 5 Fig. 6, respectively.

The water absorption rate of all samples was gradually decreased at later ages as it is shown in Fig. 5. Both GCC and BF addition reduced the water absorption ratios at 7,28,90 and 180 days. This can be attributed to filling of voids by GCC particles and BFs. Dry bulk density values of the samples increased with the curing time. GCC inclusion increased the dry bulk density test results of all ages. In most cases, lower water absorption rates and denser microstructures were obtained during the

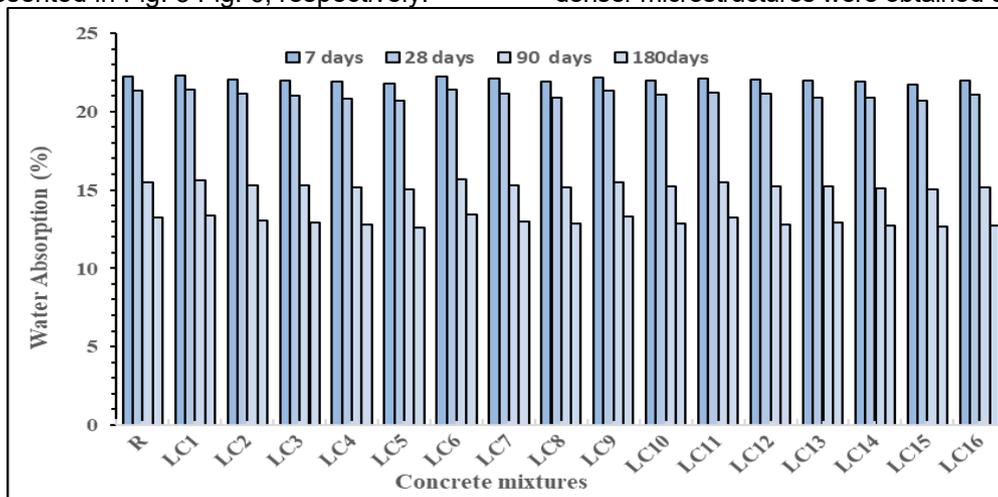


Fig. 5 - Water absorption test results.

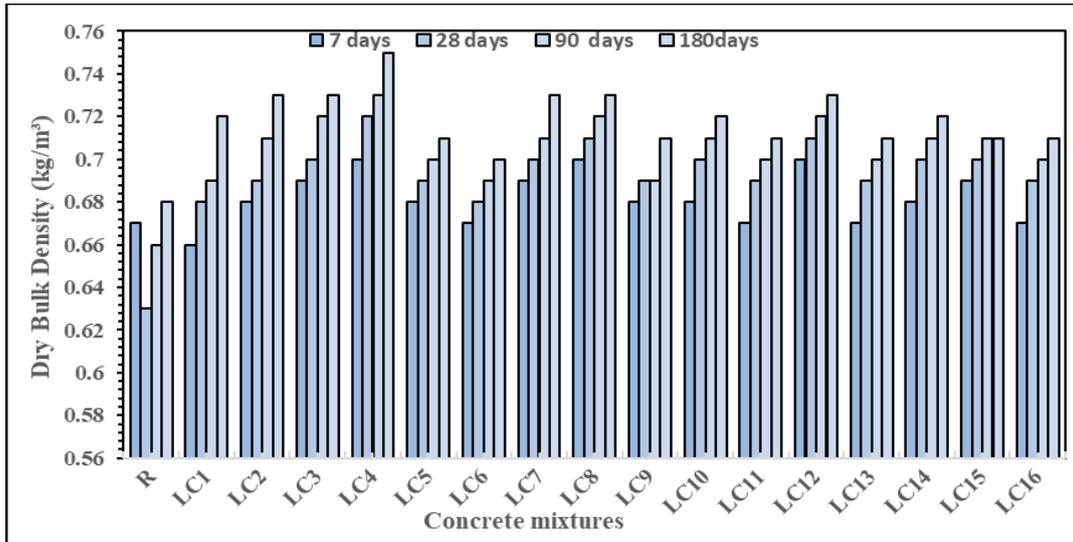


Fig. 6 - Bulk density test results.

Table 5

Compressive strength test results

Mixture Code	Compressive strength (MPa)			
	7 days	28 days	90 days	180 days
R	11.16	14.88	15.97	17.61
LC ₁	11.89	15.26	16.84	17.68
LC ₂	12.36	15.14	16.59	17.72
LC ₃	12.64	15.60	16.72	17.74
LC ₄	10.74	14.66	16.00	17.57
LC ₅	12.49	15.02	16.08	17.67
LC ₆	12.33	16.12	16.66	17.63
LC ₇	12.32	15.54	16.78	17.71
LC ₈	13.08	16.69	17.41	17.72
LC ₉	12.63	15.68	16.73	17.68
LC ₁₀	12.67	15.81	16.96	17.69
LC ₁₁	12.38	15.87	16.40	17.67
LC ₁₂	12.64	15.64	16.88	17.71
LC ₁₃	10.30	14.21	15.56	17.57
LC ₁₄	10.72	14.75	16.25	17.52
LC ₁₅	10.71	14.81	16.17	17.54
LC ₁₆	13.40	15.98	17.90	17.56

Table 6

Flexural strength test results

Mixture Code	Flexural strength (MPa)			
	7 days	28 days	90 days	180 days
R	0.70	1.09	1.32	1.44
LC ₁	0.91	1.28	1.49	1.60
LC ₂	0.95	1.32	1.52	1.64
LC ₃	1.01	1.38	1.58	1.69
LC ₄	0.76	1.06	1.31	1.39
LC ₅	0.90	1.28	1.52	1.63
LC ₆	1.17	1.55	1.76	1.89
LC ₇	1.13	1.49	1.70	1.80
LC ₈	1.17	1.54	1.75	1.85
LC ₉	1.08	1.46	1.67	1.78
LC ₁₀	1.12	1.48	1.69	1.79
LC ₁₁	1.09	1.47	1.68	1.79
LC ₁₂	1.09	1.46	1.67	1.77
LC ₁₃	0.68	0.98	1.16	1.13
LC ₁₄	0.73	1.03	1.26	1.27
LC ₁₅	0.74	1.05	1.28	1.37
LC ₁₆	1.09	1.49	1.73	1.83

physical tests. The main effect behind these improvements can be explained with GCC inert mineral filler role, as reported in previously concluded researches [28, 29].

The compressive strength test results at

7,28,90 and 180 days are presented in Table 5. Cement replacement with GCC up to 10 % and BF inclusion increased the compressive strength test results compared to the reference mixture. GCC addition at certain amounts also increased the

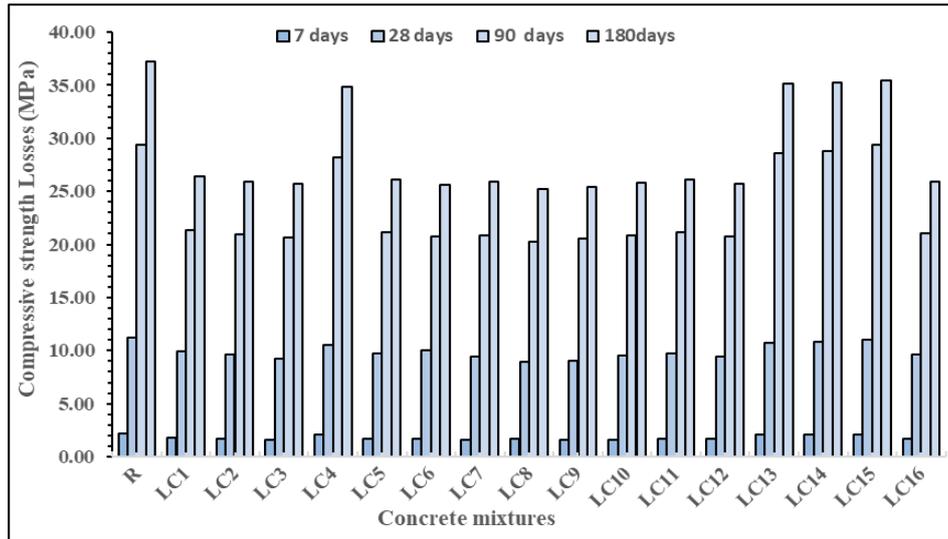


Fig. 7 - Bulk density test results.

Table 7

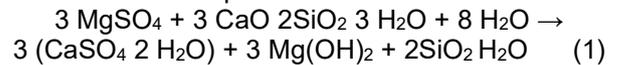
Experimental factors and their levels used in Taguchi Design				
Factors	Level 1 (%)	Level 2 (%)	Level 3 (%)	Level 4 (%)
GCC	0	5	10	15
PA	25	30	34	38
BF	0.25	0.5	0.75	1

early strength development of the samples. Strength improvements can be attributed to the GCC interaction with aluminate phases in the cement and more ettringite production as a result of this reaction. Denser microstructure can be formed, and this mechanism leads to strength enhancements. BFs addition of 1 % by volume fraction showed better performances compared to the other mixtures. Many studies reported that BF usage up to 0.5 % by volume is beneficial [30]; however, test results can be notably varied with respect to the produced concrete types [31].

Table 6 shows the flexural test results of the lightweight concretes. Samples containing more than 10 % replaced cement content showed lower performance compared to the other mixtures. A gradual increase in curing time was also obtained. “LC₈” sample showed the best flexural test results performance. BFs additions increased the flexural test results. Mechanical performance improvement of samples can be attributed to the filler effect of GCC and BF contribution to the flexural behavior of the samples.

Magnesium sulfate attack on concretes can result in the C-S-H gel to non-cementitious M-S-H gel transformation (Eq.1) [32,35-37]. For this reason, sulfate resistance of concrete has been widely studied [33]. Magnesium sulfate resistance of specimens decreased with the exposure time as it is shown in Fig. 7. The most deleterious effect was obtained for the reference mixtures for all ages. BFs inclusion improved the resistance against the sulfate solution. GCC addition more than 10 % of the cement weight decreased the resistances compared to the samples (except

reference mixtures). According to the sulfate resistance test results, low permeable lightweight concrete samples were produced compared to the reference mixtures. LC₁₃, LC₁₄ and LC₁₅ showed higher compressive strength losses against sulfate attack at 180 days as 35.11, 35.24 and 35.42 %, respectively. This value was obtained as 37,20 % for the reference specimen.



3.2. Taguchi Optimization

The Taguchi design of experiment method was used to determine optimal mixtures of the ingredients of BF reinforced lightweight pumice concrete to maximize strengths and sulfate resistances while preserving water absorption, bulk density and consistency properties. Three factors related to the strengths and durability properties such as GCC (%) and PA (%) contents and BF (%) addition ratios were evaluated in this study. Table 7 shows the experimental factors and their levels utilized in the Taguchi optimization. PA (%) levels in all mixtures were calculated by the weight of pumice aggregate (W_{PA}) divided by the sum of PA (W_{PA}) and fine aggregate (W_{FA}) as shown in the Eq. (2):

$$\text{PA content (by weight) (\%)} = W_{PA} / (W_{PA} + W_{FA})$$

In the Taguchi method, Signal to Noise ratios was applied as “Larger is better” for compressive and flexural strength determination [34]. However, “Smaller is better” ratio was utilized for sulfate resistances with respect to minimizing compressive strength losses.

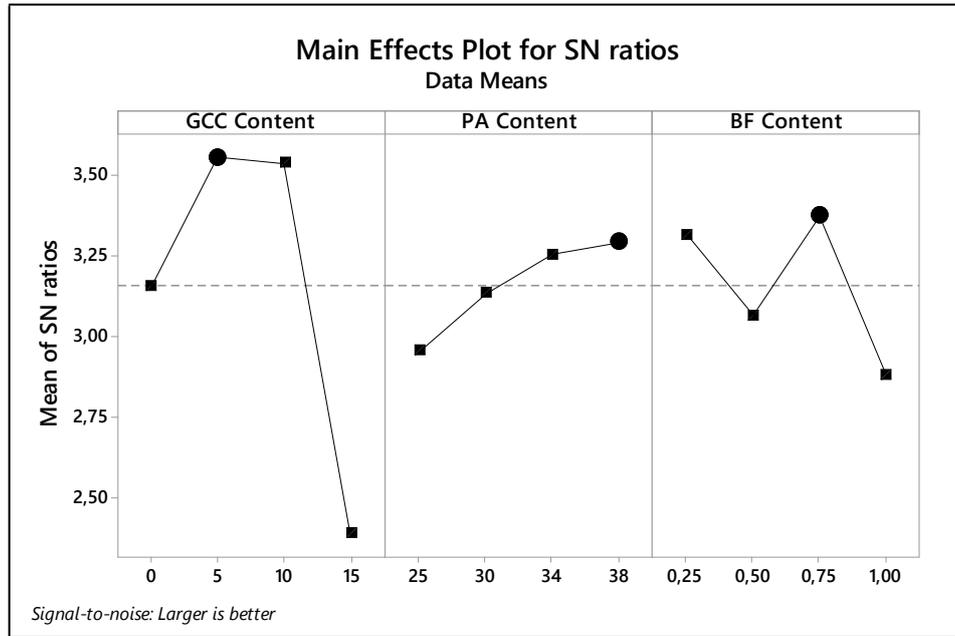


Fig. 8 – Result of compressive strength Taguchi design.

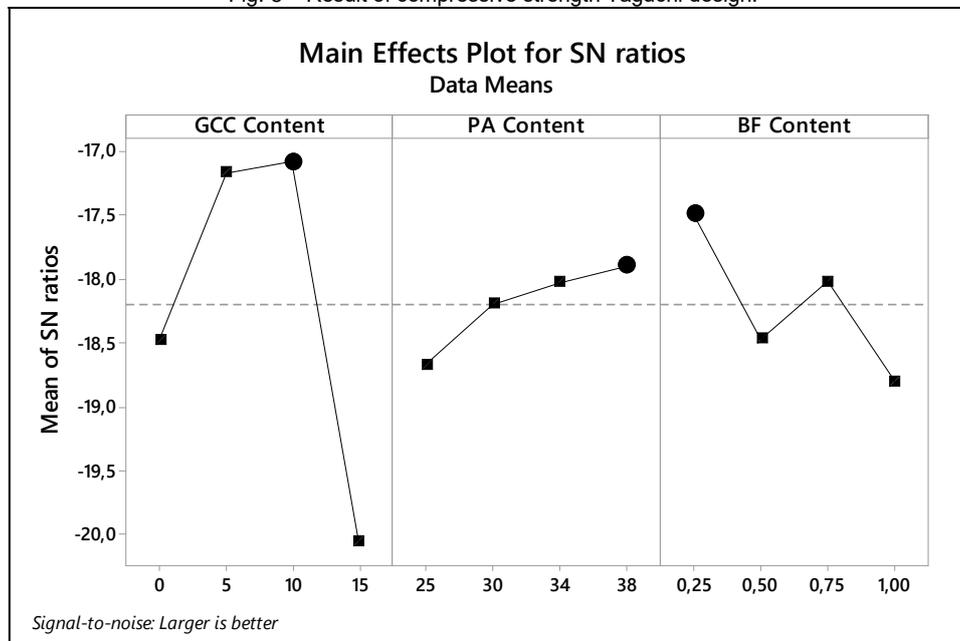


Fig. 9 - Result of flexural strength Taguchi design.

4. Results and discussion

4.1. Taguchi and ANOVA results

GCC, BF and PA contents were considered as control factors for the Taguchi optimizations, as mentioned before. The Taguchi method examined the variations of compressive strength, flexural strength and sulfate resistance using chosen Signal to Noise ratios. Compressive strength optimization results are plotted in Fig. 8., where $GCC_{0,5}PA_{38}BF_{0,75}$ for the 28th day compressive strength.

According to the Taguchi design results, Flexural strength optimum conditions were obtained as $GCC_{15}PA_{25}BF_1$ as it is shown in Fig 9. In strength optimization results, GCC content is more important than PA and BF contents; in other

words, S/N ratio of GCC was higher than any other ratios.

Sulfate resistance optimization results based on the 180 days test results are depicted in Fig. 10. The optimum solution was obtained as $GCC_{15}PA_{25}BF_1$ in parallel with the flexural strength test results. The analysis states that GCC was the key factor for sulfate resistance improvement with the lowest S/N ratio compared to the other factors.

F-value analysis results are statistically used for the determination of the effect of each parameter on the process [35]. Table 8-10 show the ANOVA results for the compressive and flexural strength at 28 days, sulfate resistance at 180 days. GCC content was the most effective parameter on compressive and flexural strength results as seen in Table 8 and Table 9. GCC F-value was greater compared to

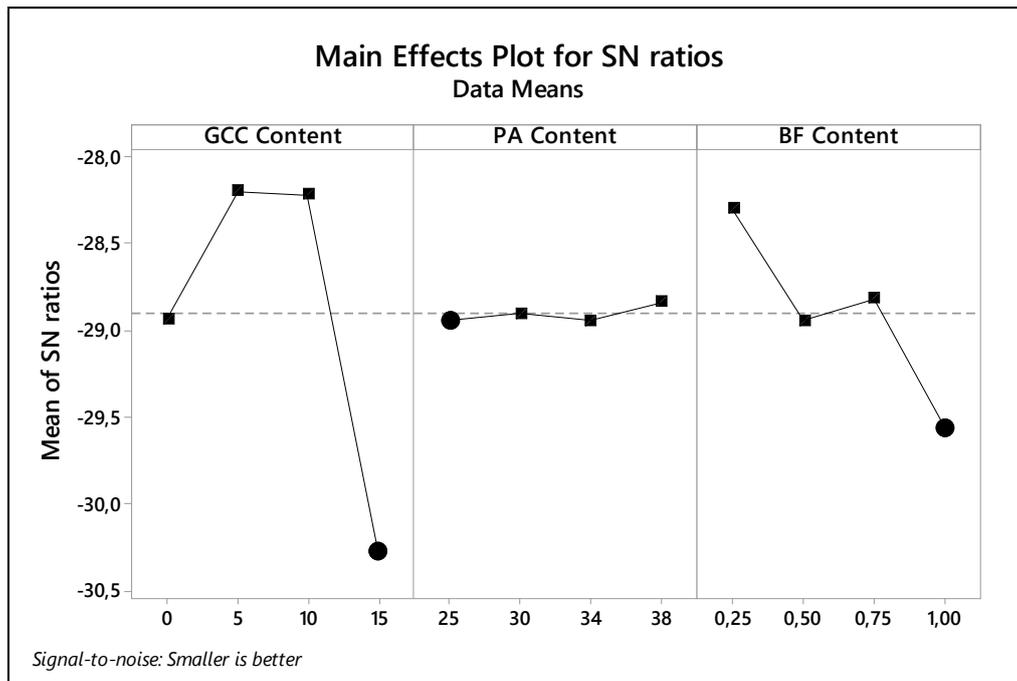


Fig. 10 - Results of sulfate resistance Taguchi design.

Table 8

ANOVA Results for Compressive Strength at 28 days

Factor	df	Sum of Square (SS)	Adj mean of square (MS)	F-Value	P-Value
GCC content, %	3	224.31	74.770	15.10	0.003
PA content, %	3	32.46	10.819	2.19	0.191
BF content, %	3	12.78	4.261	0.86	0.511
Error	6	29.70	4.95	-	-
Total	15	299.25	-	-	-

Table 9

ANOVA Results for Flexural Strength at 28 days

Factor	df	Sum of Square (SS)	Adj mean of square (MS)	F-Value	P-Value
GCC content, %	3	0.31625	0.10542	4.47	0.057
PA content, %	3	0.04085	0.01362	0.58	0.651
BF content, %	3	0.09220	0.03073	1.30	0.357
Error	6	0.14160	0.02360	-	-
Total	15	0.59090	-	-	-

Table 10

ANOVA Results for Sulfate Resistance at 180 days

Factor	df	Sum of Square (SS)	Adj mean of square (MS)	F-Value	P-Value
GCC content, %	3	0.054875	0.018292	5.50	0.037
PA content, %	3	0.0016775	0.000558	0.17	0.914
BF content, %	3	0.003075	0.001025	0.31	0.819
Error	6	0.019950	0.003325	-	-
Total	15	0.079575	-	-	-

Table 11

Mixture proportions of the validation samples

Trail no.	Mixture code	Fine Aggregate s (kg/m ³) (FA)	Pumice Aggregate s (kg/m ³) (PA)	Basalt Fiber (volume fraction, %)	GCC (kg/m ³)	Cement (kg/m ³)	Water (kg/m ³)	Superplast icizer(kg/m ³)
1	V _{CS}	741	450	0.75	8.5	161.5	80	2.50
2	V _{FS}	741	450	0.25	17	153	80	2.50
3	V _{SR}	891	300	1.00	25.5	144.5	80	2.50

the other parameter analysis results. It contributed to the compressive strength due to its effects on early strength development.

Besides, GCC was the finest material among the other concrete ingredients used in this research. Utilization of GCC as cement replacement material

Table 12

Validation Test Results			
Sample code	Mean Compressive Strength at 28 days, MPa	Mean Flexural Strength at 28 days, MPa	Sulfate attack compressive strength Loss (%)
V _{CS}	17.68	-	-
V _{FS}	-	1.78	-
V _{SR}	-	-	25.10

showed filler effect and contributed to the strength enhancement as reported in previously concluded studies [38-39].

After the optimisation process, concrete specimens were prepared in the laboratories based on the data gathered from this process. Later on, these specimens were tested. Compressive, flexural strength at 28 days and sulfate resistance validation test results are presented in Table 12. Optimum results for compressive and flexural strength, and sulfate resistance behavior of concrete specimens are also presented in Table 12. The test results indicate that Taguchi method can be applied to the concrete specimens to optimize the BF reinforced pumice concrete properties

5. Conclusions

In this study, BF reinforced GCC added lightweight pumice concrete was designed and optimized with the Taguchi method. Based on the results of the research, the following conclusions can be drawn:

- (1) The most influential factor in compressive, flexural strengths and sulfate resistance is GCC content according to the Taguchi optimization and ANOVA results.
- (2) BF inclusion decreased the spread diameter of the mixtures; however, BF utilization together with the GCC reduced the slump value reduction.
- (3) The mechanical and durability properties of the reference specimens were significantly improved with the GCC and BF inclusions.
- (4) Water absorption rate of all samples were gradually decreased at later age. Both GCC and BF additions reduced the water absorption ratios.
- (5) The outcomes of this research can be useful to analyze mechanical and durability properties of BF added lightweight pumice concrete under industrial conditions.

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MANIFESTĂRI ȘTIINȚIFICE / SCIENTIFIC EVENTS

International Conference on “Cement-based materials tailored for a Sustainable Future” in honour of Prof. Surendra P. Shah and Prof. Turan Özturan , 7-8.05.2020, Boğaziçi University, Istanbul, Turkey

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