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Research Article

Investigating the usability of kevlar and steel fibers as a hybrid in concrete pavements

Erhan MOLA[1], Osman Ünsal BAYRAK[1,*], Fatih İrfan BAŞ[2], Halim Ferit BAYATA[2]

[1]Department of Civil Engineering, Faculty of Engineering, Ataturk University, Erzurum, 25240 Türkiye
[2]Department of Civil Engineering, Faculty of Engineering, Erzincan Binali Yildirim University, Erzincan, 24002, Türkiye

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ABSTRACT

In this study, the hybrid usage of Kevlar and steel fiber in concrete pavements was investigated. For this purpose, the concrete was designed using the water/binder ratio (0.40, 0.45, 0.50), silica fume (instead of cement 0, 5, 10%), Kevlar fiber (0 gr/m^3, 500 gr/m^3, 1000 gr/m^3) and steel fiber (0 gr/m^3, 500 gr/m^3, 1000 gr/m^3). Taguchi method was used as the experimental design, and optimum levels of parameters were determined for 28-days compressive strength, flexural strength, and toughness. According to the experiments and observations, the positive effect of Kevlar fiber upon energy absorption capacity (toughness), compressive and flexural strength of concrete was determined. Using only Kevlar fiber increasing up to 5.1% in compressive strength and up to 14.5% in flexural strength were observed. Considering the obtained results, Kevlar was noticed as a possible recycling material to be introduced into the economy by adding concrete.

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INTRODUCTION

Concrete pavements have a structure of transferring the loads to the subgrade by spreading over a wider area. They are high-standard superstructures which provide driving safety and comfort in airports and highways with high traffic volumes [1]. Concrete pavements have started to be used as an alternative to flexible pavements since the 1990s due to the import of asphalt in Turkey, increased maintenance costs, and external dependencies. The popularity of concrete pavements has gradually increased hence, significant researches have been carried out about rigid pavements in Turkey as in Europe and United States of America.

The service life of concrete pavements depends on external factors, and most of these factors are correlational. Because the emergence of any negative factor affects the other factors, this leads to some disadvantages. For example, there is a possibility of fracture due to heavy vehicle load. Therefore, penetration increases by causing fractures in pavements due to road base and ground deformation [2]. Although the concrete has several advantages, it is generally weak in post-crack abrasion resistance, flexural strength,

***Corresponding author.**
*E-mail address: unsalb@atauni.edu.tr

This paper was recommended for publication in revised form by Regional Editor Ahmet Selim Dalkilic and load-bearing capacity as a brittle material [3, 4]. Mainly dynamic wheel loads cause cracks in the edges and sides of the concrete, quickly spreading due to low flexural strength.

Tensile stresses occur under the concrete pavement and compressive stresses above the concrete pavement due to positive temperature differences. Concrete pavements are exposed to these tensile stresses caused by the positive temperature gradient longer than the axle loads. As the thickness of the concrete increases, the tensile stresses arising from the temperature difference also increase [5]. Therefore, the thickness of concrete pavement can be reduced by using fibers [6]. Adding fiber to concrete is possible to increase the tensile strength, ductility, and power holding capacity of concrete [7-11].

Several studies were conducted on fiber-reinforced concretes (FRC) to evaluate their properties. Song and Hwang [12] reported that an increase in the steel fiber volume fraction up to 2% led to an increase up to 98% in the splitting tensile strength of FRC compared to that of control concrete. Iqbal et al. [13] declared that increasing the volume fraction of steel fibers in high strength lightweight self-compacting concrete reduced the compressive strength while improving the splitting tensile strength, flexural strength, and flexural toughness of the concrete. Sharbatdar and Rahmati [14] reported that steel fibers with 20 kg/m^3 improved flexural strength, tensile strength and impact resistance respectively by 83%, 20% and 270%. Kamil et al. [15] evaluated the effects of polypropylene and aramid fibers on the performance characteristics of concrete. It was seen that many problems of pavements such as permanent deformation, fatigue cracking and thermal cracking might be solved by fiber-reinforcement. Yildirim et al. [16] concluded that HFRC impact performance increased with an increase in steel fibers proportion under repeated impact loads. They also concluded that the hybrid fibers had a positive effect on the performance of concrete. Bhogone and Subramaniam [17] studied the early-age fracture response of concrete with steel and hybrid blend of steel and macro polypropylene fibers. They concluded that plastic shrinkage cracking was reduced by 90.4% using a hybrid blend of steel and macro polypropylene fibers. Scorza et al. [18] studied the fracture behavior of roller-compacted concrete pavements using hybrid fibers. They stated that the combination of 0.2% short copper-coated steel fibers and 0.5% medium polymeric fibers increased the fracture toughness by 16.3% concerning plain specimens. According to the results of Lee and Cho [10], the equivalent flexural strength ratio increased with the increase in the fiber volume fraction but decreased with the increase in the concrete strength. Yousefieh et al. [19] investigated the effect of fibers on drying shrinkage in restrained concrete. Fibers in concrete not only reduced the drying shrinkage cracking but also increased the initial cracking time of FRC concerning plain concrete. Sukontasukkul et al. [20] investigated the effects of steel and polypropylene fiber hybridization on the flexural performance of fiber-reinforced geopolymer. The results indicated that the hybridization of steel fiber could improve the flexural response, toughness, and residual strength of polypropylene fiber reinforced geopolymer to different degrees. Almusallam et al. [21] studied the impact resistance of hybrid fiber reinforced concrete (HFRC) casted using steel and plastic fibers with different ratios. The impact penetration test results showed that the usage of hybrid fibers reduces scabbing and spalling damage. Khamar and Kumar [22] investigated the effects of a hybrid fiber between steel and micro polypropylene (PP) fiber on properties including compressive, flexural, and splitting tensile strengths. Their results showed that the optimum volume fractions of micro PP fiber were 20% for compressive strength and 30% for flexural strength. It is evident from the literature that hybridization of two or more precisely selected fibers with different sizes and types can develop concrete with more attractive engineering properties [23-25].

Fiber optical cable is made from glass or plastic sending light signals, and it includes an outer protective cover strengthened with Kevlar and glass fiber as the strength element (Figure 1). Its popularity has gradually increased through technological developments and has become a frequently-used product in the communication sector. These cables with 20-year economic life have been replaced with the new ones, and the olds have been scrapped. The economic usability of these scrapped ones is not possible. Kevlar in fiber optic cables are considered to be used in road concretes that have an essential place in the transportation sector.

Kevlar, a waste material, has a synthetic chemical structure and is highly resistant to impact and heat due to its structure. This material is used to manufacture armor (protective gloves, vests, fireproof clothing, parachutes, etc.) and sports equipment. As a waste material, Kevlar is not being used for recycling since it does not have any usage area.

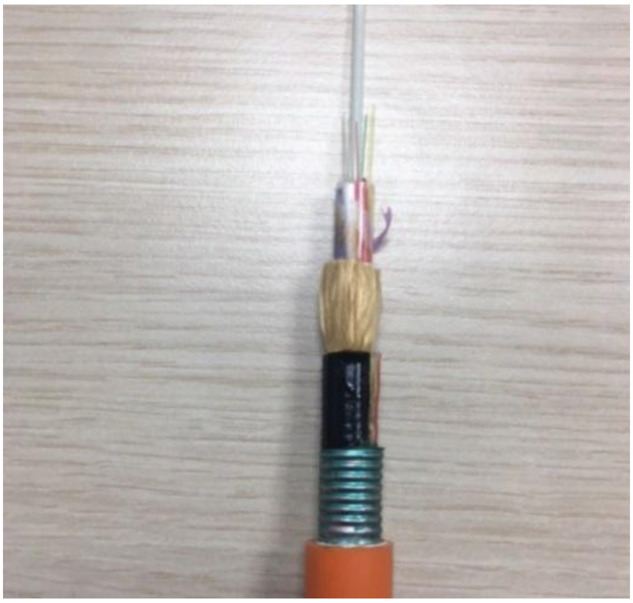

Figure 1. Kevlar in fiber optic cable.

In the conventional approach of experimental studies, while one factor is kept varying, all other factors are constant. Therefore, when the number of mixing variables increases, the number of experiments also increases. Hence, the quantity of materials, money, and time increase in the conventional design of experiments. The Taguchi method can decrease the number of experiments for such experimental studies. One of the advantages of the Taguchi method over the conventional experimental design is keeping the experimental cost at a minimum level.

A concrete pavement design aims to determine the thickness of the layers and the quality of the materials and ensure the tensile stresses occurring under the pavement in order not to exceed the flexural strength of the concrete [5]. The current study aimed to increase the flexural strength, which is one of the essential parameters in a concrete pavement design. For this purpose, four parameters, each having three different levels, were considered for the experimental design. These factors and levels were: steel fiber (0, 500 g/m^3, 1000 g/m^3), Kevlar (0, 500 g/m^3, 1000 g/m^3), silica fume (0, 5%, 10%), water/binder ratio (0.40, 0.45, 0.50). Compressive and flexural strength and the flexural toughness of specimens were determined for 28 days of curing age. The Taguchi optimizations for each compressive and flexural strength and flexural toughness using the L_9 orthogonal array were carried out. The findings of this research had potential significance for the optimization of the hybrid FRC in different structural applications.

MATERIAL AND METHODS

In the study, CEM I 42.5R cement produced in Erzurum Aşkale Cement Plant and conforming to TS EN 197–1 standard was used. The chemical properties of CEM I 42.5R cement are presented in Table 1, and the physical and mechanical properties are presented in Table 2.

Table 1. Chemical properties of the cement

Chemical Analyses	
SiO_2	18.10
Al_2O_3	4.48
Fe_2O_3	3.09
CaO	63.65
MgO	2.58
SO_3	2.84
Ignition loss	3.90
K_2O	0.62
Na_2O	0.21
(Na_2O); Na_2O+0,658x K_2O	0.62
Cl	0.015
Imponderable	0.52
CaO (free lime)	0.44
Insoluble matter	0.55

The RC 80/60 BN type, hooked end, low carbon, and uncoated steel fiber supplied from Sancak Kimya San. A.Ş. were used. The technical properties of steel fiber are given in Table 3.

Kevlar fibers were added into the mixture at a length of 4 cm (Figure 2). The physical properties of Kevlar fiber are given in Table 4.

Table 2. Physical and mechanical properties of cement

Physical and Mechanical Tests	
Slenderness 45m sieve	7.15%
Specific gravity (g/cm^3)	3.12
Specific surface (cm^2/g)	3698
Initial set (hour-minute)	2h-31min
Final set (hour-minute)	3h-11min
Volume expansion (mm)	1
Compressive strength 2 Days (MPa)	27.9
Compressive strength 28 Days (MPa)	58.0
Water requirement (%)	29.5

Table 3. Technical properties of steel fiber

Technical Property	Value
Fiber type	RC 80/60 BN
Length (mm)	60
Diameter (mm)	0.75
Aspect Ratio (l/d)	80
Performance Class	80
Min. Tensile Strength (N/mm^2)	1050

Figure 2. Kevlar fibers added into the mixture.

Table 4. Technical properties of Kevlar

Fiber Type	Aramid	HM
Linear density	D_{tex}	3160
Sizing rate	%	0.8
Elongation at break	%	2.5
Tensile strength	MPa	2926
Tensile force	N	325
Elasticity module	GPa	110
Flammability	LOI-Index	0.29
Warm-air contraction (15min at 190°C)	%	0.1
Temperature resistance (48h at 200°C)	%	90
Degradation temperature	C	> 450
Thermal expansion Kts.	109K	-3.5

Pozzolanic materials are used for filling in the micropores in the binder. These materials contribute to the strength of the binder due to their pozzolanic reactions [26-29]. Accordingly, silica fume was used in addition to cement in the study. Technical properties of silica fume are presented in Table 5.

ZYLA 645 super-plasticizer concrete admixture produced by GCP Applied Technologies firm was used in poured concrete samples in the study. This admixture was a ready-to-use plasticizer concrete mixture. It was the aqueous solution of the hydroxyl organic components that

Table 5. Technical properties of silica fume

Amorphous SiO_2	Min 93% (real 96.1%)
H_2O (humidity)	Max 0.3% (real 0.19%)
Ignition loss	(L.O.I max 3.5%) (real 1.81%)
Above +45 micron	Max 2.5% (real 0.58%)
Volume density	0.55-0.65 kg/dm^3(D)
BET	min.1 5-28 m^2/gr (real 23.36 m^2/gr)

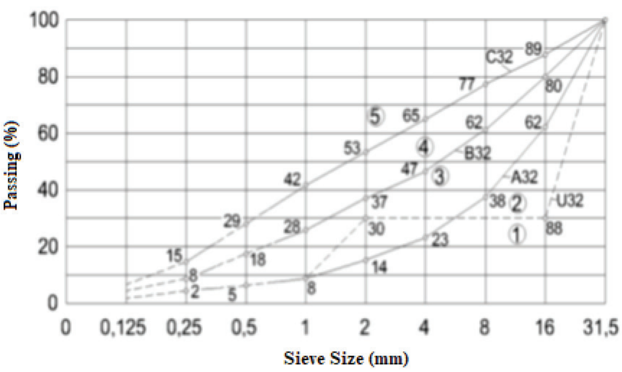

Figure 3. Aggregate gradation curve [30].

Table 6. The sieve analysis after aggregate admixture

Sieve (mm)	Sieved (%)
0.25	7.50
0.5	11.78
1	18.21
2	29.89
4	46.75
8	61.13
16	78.48
32	100

had effects upon the final properties of concrete. It was produced under active control to provide the estimated performance as standard. It did not include calcium fluoride. It was conforming to TS EN 934-2 standards. The angular aggregate used in the study was procured from the facility established for aggregate production of the Aşkale Cement Plant close to Tercan district of Erzincan province. The gradation curve of the aggregate mixture used was given in Figure 3 within the limits specified by TSE 3526-3529 standards. The results of the sieve analysis are given in Table 6.

Experimental Approach

All other factors are fixed in conventional experimental design while changing one specific factor. As the factors and levels in the experimental design increase, the number of experiments to be conducted increases. Accordingly, practicing such a design leads to material, time, and labor difficulties. Furthermore, in the case of inner interaction among the factors, the optimum conditions obtained according to the conventional experimental design's not being in actual optimum conditions. Taguchi method as one of the experimental design techniques has successfully been conducted for the optimization in systematic designs [28, 31-33].

This method enables a systematic approach for optimizing performance and quality designs. The optimizations to be performed using the Taguchi method are fulfilled in 8 steps:

1. Determining the parameters to be assessed
2. Determining the levels of these parameters and their possible inner-interactions
3. Determining the appropriate orthogonal sequence
4. Adapting outputs of the experiment into method depending upon the orthogonal sequence
5. Calculating performance statistics
6. Evaluating outputs with variance analysis using performance characteristics
7. Choosing optimum levels
8. Confirming the outputs

The Taguchi method uses performance statistics (S/N) as the optimization criterion. There are three types of performance statistics, the biggest–the best, nominal–the best, and the smallest-the best. Using the data obtained from the experiments, the S/N values were calculated according to equation 1 depending upon the bigger the better performance statistics.

$$\frac{S}{N_L} = -10Log\left[\frac{1}{n}\sum_1^n \frac{1}{Y_i^2}\right] \tag{1}$$

Here;

S/NL: Performance statistics

n: The number of repetitions performed in an experimental combination

Yi: i^{th} the performance statistic of the experiment.

The parameter levels maximizing S/NL are optimum. However, the experiment providing optimum parameter levels for the Taguchi method may not exist in the experimental design. Accordingly, the performance value corresponding to optimum conditions can be estimated by equation 2.

$$Y_t = \mu + X_i + e_i \tag{2}$$

Here;

μ: General average for the performance value,

X_i: Fixed effect of the parameter-level combination in the experiment,

e_i: i. random error in the experiment

Here, the Y_t value calculated depending upon the experimental outputs is a point estimate. Accordingly, a confidence interval at a specific level of error should be created to determine whether verification experiments were significant or not. The confidence interval for the chosen level of error was calculated by equation 3. [34, 35],

$$\mu \mp \sqrt{F_{\alpha;1;DF_{MSe}} MS_e \left[\frac{1+m}{N} + \frac{1}{n_i}\right]} \tag{3}$$

Here;

$F_{\alpha;1;DF_{MSe}}$: Table value,

α: Level of error,

DF_{Mse}: Total degree of freedom for the error mean square,

m: Degree of freedom for the parameters used in mean estimation,

n_i: The number of repetitions for verification experiments

In the study, CEM I 42.5 R Type cement produced in Aşkale Cement Plant and aggregate produced in Aşkale Cement Plant Tercan facility were used as the main component. The steel fiber of RC 80/60 BN with the hooked end was procured from Sancak Chemistry firm, Kevlar fiber procured from the cables scrapped by Türk Telekom A.Ş., silica fume (SF) and ZYLA 645 super-plasticizer concrete admixture were used. Tap water was used to provide the water necessary for the concrete mix. Cement dosage was kept constant, and SF, water/binder ratio, steel fiber ratio, and Kevlar fiber ratio were used as the parameters.

The cement content for rigid pavements was suggested to be above 350 kg/m³ according to the concrete pavement technical specifications [30] released in 2016. Accordingly, the cement content was determined as 350 kg/m³, and silica fume was added as 0%, 5%, and 10% of the cement weight as an additive. Steel fiber and Kevlar fiber were used at the rate of 0 g/m³, 500 g/m³, and 1000 g/m³. The plasticizer was kept constant for all samples and used at a rate of 1.5%. Considering all factors, a total of 9-groups samples were prepared. The parameters and their levels are given in Table 7, and the experiment plan prepared according to the L9 orthogonal array is given in Table 8 [36].

Table 7. Parameters and their levels

Parameters	Levels		
	1	**2**	**3**
(A) water/binder rate	0.40 (A1)	0.45 (A2)	0.50 (A3)
(B) SF (%)	0.00 (B1)	5.00 (B2)	10.00 (B3)
(C) Kevlar (g/m³)	0.00 (C1)	500 (C2)	1000 (C3)
(D) Steel Fiber (g/m³)	0.00 (D1)	500 (D2)	1000 (D3)

Table 8. L_9 orthogonal array

Group No	Water/Binder Ratio	SF (%)	Kevlar (g/m³)	Steel Fiber (g/m³)
1	A1	B1	C1	D1
2	A1	B2	C2	D2
3	A1	B3	C3	D3
4	A2	B1	C2	D3
5	A2	B2	C3	D1
6	A2	B3	C1	D2
7	A3	B1	C3	D2
8	A3	B2	C1	D3
9	A3	B3	C2	D1

Three 500 *x* 500 *x* 500 mm cube and 70 *x* 70 *x* 280 mm prismatic specimens were cast according to Table 8. The samples poured with determined admixture rates were kept in water curing for 28 days. The samples were taken away from water curing and were dried for 24 hours. After then, compressive and flexural strength and toughness were determined in the Ataturk University Construction laboratory.

RESULTS AND DISCUSSION

The compressive and flexural strengths obtained from the experiments according to the L9 orthogonal array are presented in Table 9. In this Table, the average of three samples obtained from the experiments in terms of MPa was presented with S/N values calculated by equation (1) [36]. According to the Taguchi method, average S/N effects should be calculated to determine optimum conditions. After calculating S/N values by equation (1), the average S/N values were calculated via these values and presented in Tables 10 and 14. In these tables, the maximum value of each parameter indicates the optimum level of that parameter. To understand better the values in the Tables, the optimum conditions obtained with these values are presented in Figures 4, 5, and 7. The optimum conditions for compressive and flexural strength and the contribution ratios of parameters to S/N calculated using analysis of variance are given in Tables 11 and 14.

Evaluation of Compressive Strength

When Figure 4 was analyzed, it was noticed that optimum levels for compressive strength were A2, B3, C3, and D3. According to Table 12, the parameters that had the highest effect upon compressive strength were silica fume, Kevlar fiber ratio, water/binder ratio, and steel fiber ratio, respectively. When the experimental plan presented in Table 8 was considered, the design with the optimum values was not present in the experimental plan. Therefore, a sample was prepared according to the relevant parameter values (A2, B3, C3, D4) to verify the result, and the sample was tested again after 28-day curing conditions. A 60.58 MPa of compressive strength was obtained at the end of the verification experiment. The S/N value corresponding

Table 9. Compressive and flexural strength results

Group No	Compressive Strength		Flexural Strength	
	(MPa)	S/N	(MPa)	S/N
1	46.63	33.372	6.63	16.436
2	49.10	33.822	8.46	18.542
3	58.81	35.389	9.26	19.336
4	54.70	34.760	9.98	19.983
5	52.16	34.346	9.29	19.356
6	60.72	35.667	9.35	19.416
7	56.89	35.100	10.95	20.788
8	53.08	34.499	9.54	19.586
9	56.35	35.018	6.93	16.815
Average		34.664		18.918

Table 12. Optimum conditions maximizing the compressive strength and estimation of performance

Factors	Level	Contribution to S/N
Water/Binder	A2	0.260
Silica Fume	B3	0.694
Kevlar	C3	0.281
Steel Fiber	D3	0.219
Contribution of all factors (S/N)		1.454
Average performance statistic (S/N)		34.664
Expected value at optimum conditions (S/N)		36.118
Result of verification test (S/N) / (MPa)		35.65 / 60.58
Confidence interval (α=95%) (S/N)		35.070 - 37.166

Table 10. Average S/N effects for compressive strength

	Water/Binder	Silica Fume	Kevlar	Steel Fiber
1stLevel	34.194 (A1)	34.411 (B1)	34.513 (C1)	34.245 (D1)
2ndLevel	34.924 (A2)	34.222 (B2)	34.533 (C2)	34.863 (D2)
3rdLevel	34.872 (A3)	35.358 (B3)	34.945 (C3)	34.883 (D3)

Table 11. ANOVA table for compressive strength

Factors	DOF	Sums of Squares	Variance	F-Ratio	Pure Sum	Percent (P)
Water/binder	2	0.993	0.497	-	0.99	22.70
Silica Fume	2	2.229	1.115	-	2.23	50.94
Kevlar	2	0.365	0.183	-	0.37	8.34
Steel Fiber	2	0.789	0.395	-	0.79	18.01
Error	0.00	0.00	0.00			0.00
Total	8	4.38				100.00

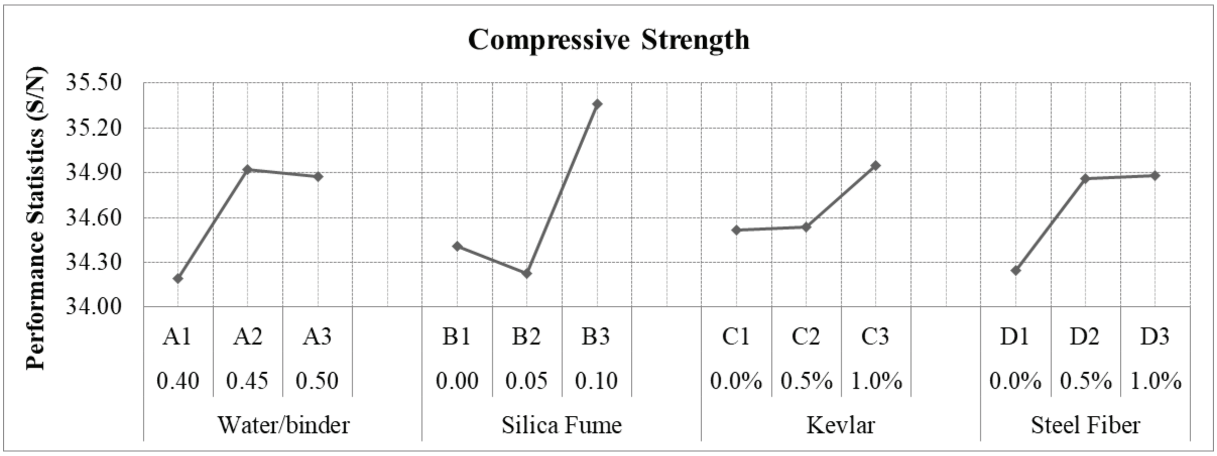

Figure 4. The effect of parameters on compressive strength.

to this result is 35.65. This value should be between 35.070 and 37.166 intervals at a 95% confidence level (Table 12). Hence, it can be said that the result is accurate at a 95% confidence level.

The ANOVA table for compressive strength was calculated according to the Taguchi Method. It can be seen from Table 11 that the most effective parameter on the compressive strength is silica fume with a rate of 50.94%. This is followed by water/binder with 22.70%, steel fiber with 18.01% and Kevlar fiber with 8.34%.

When the results are analyzed, it can be realized that the maximum compressive strength was obtained at the 2nd level of the water/binder ratio, 3rd level of the silica fume, 3rd level of the Kevlar ratio, and 3rd level of the steel fiber ratio. Through the increase in the water/binder ratio, the compressive strength of concrete increased after a specific value [37]. However, according to the results, the maximum compressive strength was obtained at a 0.45 water/binder ratio which was the second level of this parameter. SF, which is a very fine material, increased the water requirement and decreased the workability of the concrete. Therefore, the 0.40 water/binder ratio was insufficient for the cement hydration. Accordingly, the compressive strength of concrete decreased at a 0.40 water/binder rate.

Although it had similarities with polypropylene fiber, Kevlar fiber showed a similar effect to steel fiber in this study. It can be seen that there is an increase in the compressive strength with the increase of the Kevlar fiber ratio, which is thought to be used for the first time in rigid pavements. It is known that an increase in compressive strength is provided through adding steel fibers into concrete up to 1% [38]. Similarly, an increase in compressive strength was provided by increasing the steel fiber ratio in this study. Moreover, Yaka [39] reported that the effects of fiber quantity upon the compressive strength were both negative and positive.

Evaluation of Flexural Strength

The flexural strength results (both as MPa and S/N unit) are given in Table 9. Average S/N effects calculated via these values are given in Table 14. The ANOVA table for flexural strength was calculated according to the Taguchi Method. It can be seen from Table 13 that the most effective parameter on the flexural strength is steel fiber with a rate of 52.38%. This is followed by Kevlar with 22.67%, water/binder with 20.63% and silica fume with 4.32%.

According to the results obtained from flexural strength experiments, it was noticed that the parameter

Table 13. ANOVA table for flexural strength

Factors	DOF	Sums of Squares	Variance	F-Ratio	Pure Sum	Percent (P)
Water/Binder	2	3.384	1.692	-	3.38	20.63
Silica Fume	2	0.709	0.355	-	0.71	4.32
Kevlar	2	3.720	1.860	-	3.72	22.67
Steel Fiber	2	8.594	4.297	-	8.59	52.38
Error	0.00	0.00	0.00			0.00
Total	8	16.41				100.00

Table 14. Average S/N effects for flexural strength

	Water/Binder	Silica Fume	Kevlar	Steel Fiber
1stLevel	18.105 (A1)	19.069 (B1)	18.479 (C1)	17.536 (D1)
2ndLevel	19.585 (A2)	19.161 (B2)	18.447 (C2)	19.825 (D2)
3rdLevel	19.063 (A3)	18.522 (B3)	19.827 (C3)	19.635 (D3)

Table 15. Optimum conditions maximizing the flexural strength and estimation of performance

Factors	Level	Contribution to S/N
Water/Binder	A2	0.667
Silica Fume	B3	0.243
Kevlar	C3	0.909
Steel Fiber	D3	0.717
Contribution of all factors (S/N)		2.536
Average performance statistic (S/N)		18.918
Expected value at optimum conditions (S/N)		21.454
Result of verification test (S/N) / (MPa)		21.68 / 12.14
Confidence interval (α=95%) (S/N)		20.804 - 22.104

Table 16. The values of toughness

Experiment No	Toughness (Nmm)
1	367.84
2	5776.21
3	10020.15
4	10518.52
5	2455.63
6	6833.94
7	8380.95
8	9440.25
9	1832.87

levels maximizing flexural strength were A2, B3, C3, and D3. When Table 15 was analyzed, it could be seen that the most significant parameter that affected flexural strength was the Kevlar fiber rate. The followings were steel fiber, water/binder rate, and silica fume, respectively. When the experimental plan in Table 8 was analyzed, the combination providing maximum flexural strength was not included in the experimental design. The sample was prepared according to the relevant parameter values (A2, B3, C3, D4) to test the result, and the sample was tested again after 28-day curing conditions. At the end of the verification experiment, 12.14 MPa flexural strength was obtained. The S/N value corresponding to this result was 21.68. This value should be between 20.804 and 22.104 intervals at a 95% confidence level. This value was noticed to be accurate at a 95% confidence level. In flexural strength experiments performed for each sample group in different admixture rates, the effects of parameters upon strength are presented in Figure 5.

Evaluation of Toughness

Toughness is one of the most remarkable properties characterizing fiber-reinforced concretes. This concept depends on the role (distribution, size, slenderness, etc.) of fibers in concrete and is considered while evaluating the workability of fiber concrete. This property is affected by fiber quantity, slenderness ratio, fiber length, fiber geometry, loading ratio, and sample size of fiber concrete. The measurement of power holding capacity was determined in JSCE-SF4 Japan, ASTM 1018 USA, TS 10515 standards and found as calculating the area below

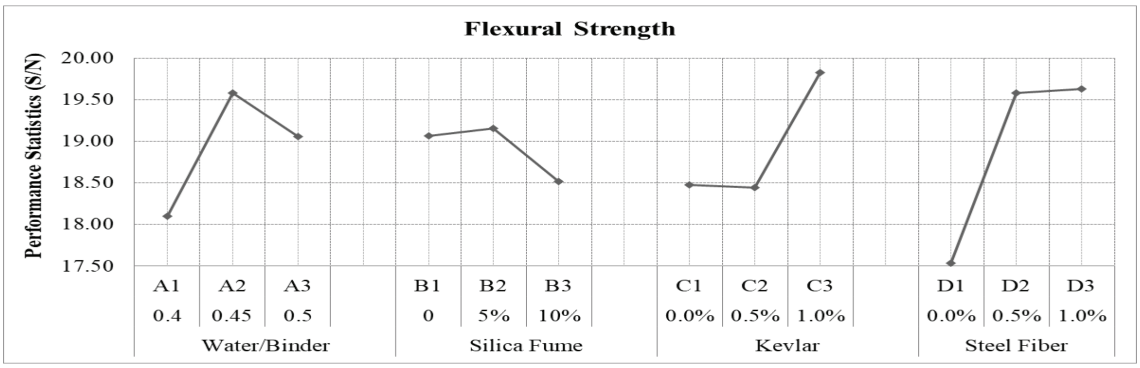

Figure 5. The effect of parameters on flexural strength.

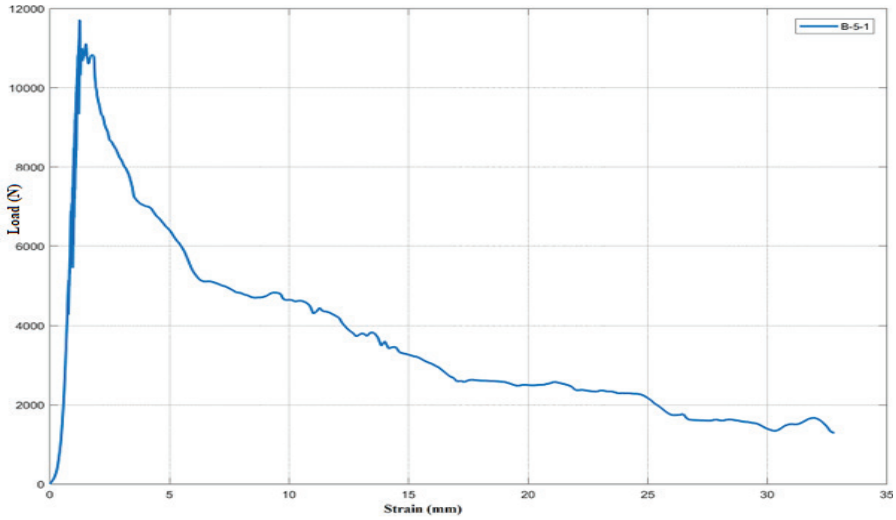

Figure 6. The load strain curve.

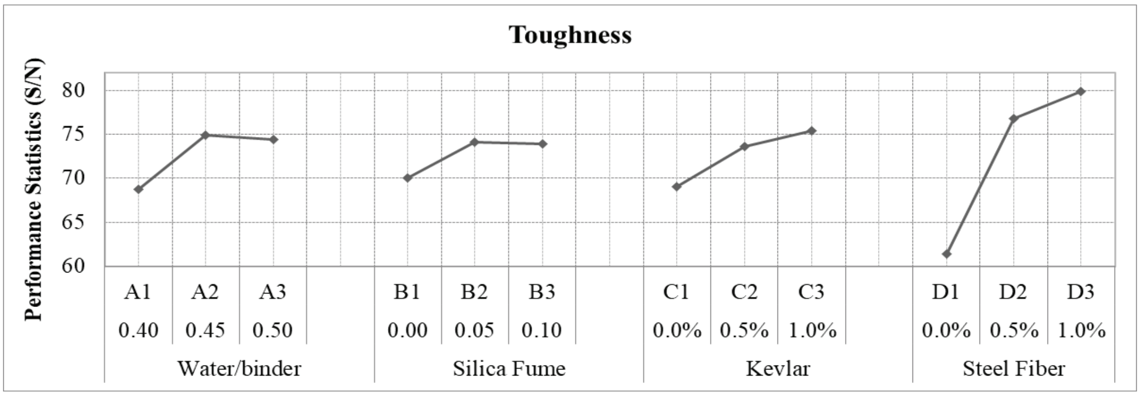

Figure 7. The effect of parameters on toughness.

the load-deformation curve. The toughness of concrete increases by increasing fiber content in concrete and growth in fiber length and slenderness ratio. Compression stress depends upon the quality of concrete rather than the role of fibers, and toughness and flexural strength depend upon the performance of fibers. As the toughness of concrete increases, its behavior under the earthquake loads becomes more ductile [40]. In the studies on stress-strain behaviors of steel, fiber-reinforced concretes under compression, it was reported that the type and quantity of fiber had a remarkable effect on the toughness value of concrete [41]. Due to the reasons mentioned before or during the study, it is beneficial to obtain fracture mechanics parameters (toughness, fracture energy) studying with size effect principles upon especially special concretes and, accordingly, fiber concretes. Rehabilitation appears in various material criteria (fracture mechanics parameters), such as toughness and fractures energy by mixing steel fibers with a higher modulus of elasticity rather than concrete. After the concrete begins to break, that is, after moving away from the linear-elastic area, the fibers play a more active role and increase the fracture energy. The load-strain curves obtained for one of the experiments is presented in Figure 6. Toughness values obtained from the experiments are presented in Table 16.

Effects of parameters upon toughness were presented in Figure 7.

The ANOVA table for toughness was calculated according to the Taguchi Method. It can be seen from Table 17 that the most effective parameter on the flexural strength is steel fiber with a rate of 78.28%. This is followed by water/binder with 9.13%, Kevlar with 8.30%, and silica fume with 4.29%.

When Figure 7 was analyzed, the highest toughness value was determined in the 2nd level of water/binder ratio (A2), in the 2nd level of silica fume (B2), 3rd level of Kevlar fiber (C3), and 3rd level of steel fiber (D3). As can be understood from the Figure, the concrete had higher ductility as the rate of fiber increased, and the energy it absorbed increased [38]. According to Taguchi's analysis results, it was determined that energy holding capacity increased

Table 17. ANOVA table for toughness

Factors	DOF	Sums of Squares	Variance	F-Ratio	Pure Sum	Percent (P)
Water/binder	2	68.689	34.345	-	68.69	9.13
Silica Fume	2	32.248	16.124	-	32.25	4.29
Kevlar	2	62.407	31.204	-	62.41	8.30
Steel Fiber	2	588.608	294.304	-	588.61	78.28
Error	0.00	0.00	0.00			0.00
Total	8	751.95				100.00

at the rate of 206% compared with concrete using Kevlar fiber. Similarly, an 845% increase was observed in the case of using only steel fiber. Caf [38] stated that an increase at 100-1200% was possible to appear in toughness in terms of technical properties of fiber concretes.

CONCLUSION

The concrete road pavement usage has gradually increased in our country and in the world. These are environmental-friendly, long-life rigid pavements resisting heavy vehicle load rather than flexible pavements. Due to increasing fuel rates, concrete pavements have started to compete with flexible pavements in terms of their initial manufacturing, maintenance, and repair costs. Compared to the flexible pavements, the most important property of concrete pavements is their spreading capability of the traffic loads on the ground to a larger area. They have more resistance against larger flexural strength due to their high rigidity and elasticity modules. Concrete is a structural material that is weak in flexural strength but strong in compressive strength. Accordingly, most of the studies on concrete pavements have been carried out to improve the flexural strength of concrete. This study aimed to investigate the usability of Kevlar fiber obtained as waste material from fiber optic cables in concrete pavements. For this purpose, the effect of Kevlar fiber was evaluated with steel fiber, which is known to contribute to the flexural strength of concrete. In the experimental plan, four parameters, including three levels in each, were used, and the effects of these parameters were evaluated according to the Taguchi method. The results obtained from the study were as below:

- Unit weight was observed to decrease even slightly in Kevlar fiber-reinforced concrete. This was considered Kevlar's having less unit weight than the conventional concrete has. Unit weight was observed to increase in concrete with steel fiber admixture. This increase was relatively more than Kevlar. This could be explained as the unit weight difference between steel fiber and concrete was much more than the unit weight difference between Kevlar fiber and conventional concrete, and fiber quantity in the admixture was much more.
- In the study, 46.62 MPa compression and 6.63 MPa flexural strength were obtained from the control sample produced with aggregate, water, cement, and plasticizer.
- In the case of only Kevlar fiber presence in concrete (in case of not using SF and steel fiber), an increase up to 5.1% was observed in compressive strength (48.99 MPa). In the case of adding just steel fiber in concrete, nearly 7% more increase was provided than the control concrete (50.17 MPa). Maximum compressive strength was obtained in the third level of steel fiber rate. However, it was possible to mention that compressive strength obtained from the second and third levels were close to each other, and accordingly, both levels could be used. In the case of using 1000 g Kevlar fiber and 10% SF per 1 m^3, an increase up to 14.67% was observed in compressive strength. In the case of using both steel fiber and Kevlar fiber in the admixture, the highest compressive strength value of 63.96 MPa was obtained.
- In the case of only Kevlar fiber presence in concrete (in case of not using SF and steel fiber), an increase up to 14.5% was determined in flexural strength (7.75 MPa). In the case of adding only steel fiber in concrete, nearly 21.5% more increase was provided than the control concrete (8.45 MPa). Maximum flexural strength was obtained in the third level of steel fiber rate. However, it was possible to mention that flexural strength obtained from the second and third levels were very close to each other, and accordingly, both levels could be used.
- In the case of increase in water/binder ratio, approximately an 8% increase was noticed in compressive strength (50.70 MPa). However, roughly equal compressive strengths were obtained in the second and third levels of the water/binder ratio. This meant that both effects were nearly similar in the design to be conducted, and accordingly, both were possible to be used. In the case of increase in water/binder ratio, approximately a 15.8% increase was noticed in flexural strength (7.87 MPa).
- In the case of only using Kevlar fiber, energy holding capacity was determined to increase up to 206% more than standard concrete, and an 845% increase was observed in the case of using only steel fiber.

The construction of flexible pavements has become increasingly unsustainable due to rising life cycle costs.

For this reason, concrete pavements should be preferred throughout the world and in our country. Concrete is a structural material that is strong in compressive strength but weak in flexural strength. For this reason, the concrete pavement design is aimed to ensure that the tensile stresses caused by the axle loads and positive temperature gradient remain below the flexural strength of the concrete. According to the results obtained, the flexural strength of the concrete was improved by the usage of hybrid fibers. Using waste Kevlar material in concrete pavements will reduce the amount of expensive fiber types required to increase flexural strength. And it will also reduce concrete thicknesses. Thus, it will contribute to the country's economy and the environment.

AUTHORSHIP CONTRIBUTION

Concept: Osman Ünsal Bayrak, Erhan Mola; Design: Osman Ünsal Bayrak, Halim Ferit Bayata; Literature research: Erhan Mola; Materials: Erhan Mola, Fatih İrfan Baş; Data analysis: Osman Ünsal Bayrak, Fatih İrfan Baş, Halim Ferit Bayata; Writing: Erhan Mola, Fatih İrfan Baş

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DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

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

ETHICS

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

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