Analysis of fibre reinforced concrete for road pavements on very weak soils

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Research Paper

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In this paper, the effects of steel fibre usage on concrete pavement thickness and cost were investigated. Prepared fibrous concrete specimens were subjected to physical and mechanical tests. From the experiments, it was determined that as the steel fibre ratio increased, the workability and compressive strength of the specimens decreased, but the flexural and splitting tensile strengths increased. In addition, according to calculations made using the AASHTO 1993 design method, the concrete pavement thickness decreased in the range of 4.35 to 18.66 % with an increase in steel fibre, but the pavement cost increased by 56.50 to 74.07 %.

Key words:

concrete road pavement, steel fibre, AASHTO method, mechanical properties, cost analysis

Prethodno priopćenje

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Analiza betona ojačanog vlaknima za betonske kolnike na slabo nosivom tlu

U ovom su radu analizirani učinci primjene čeličnih vlakana u betonu na debljinu i trošak gradnje betonskog kolnika. Ispitana su fizikalna i mehanička svojstva uzoraka betona ojačanog vlaknima. Rezultati ispitivanja su pokazali da se povećanjem udjela čeličnih vlakana smanjuje obradljivost i tlačna čvrstoća uzoraka, ali se povećava njihova čvrstoća na savijanje i vlačna čvrstoća cijepanjem. Osim toga, prema proračunima metode AASHTO 1993, s povećanjem udjela čeličnih vlakana u betonu, debljina betonskog kolnika smanjuje se od 4,35 % do 18,66 %, a trošak gradnje kolnika povećava se za 56,50 % do 74,07 %.

Ključne riječi:

betonski kolnik, čelična vlakna, AASHTO metoda, mehaničke karakteristike, analiza troška

1. Introduction

Owing to rapid developments in concrete technology in recent years, researchers have investigated the effects of additives that can be used in concrete for the high-strength properties of concrete and different materials to be substituted for concrete on the physical and mechanical properties of concrete.

In light of these studies, artificial pozzolans, such as fly ash, silica fume, blast furnace slag, and steel fibre, have become quite common as additives in concrete road pavements [1, 2]. Artificially used pozzolans protect natural resources and the environment, and reduce the cost of concrete [3, 4]. Among them, fly ash is a mineral-derived thermal power plant waste material with pozzolanic features. Fly ash grains are generally preferred because of their spherical structure, as well as the fact that they improve the workability of concrete, reduce bleeding in fresh concrete, and reduce the hydration heat of concrete [5]. Silica fume is an industrial waste material containing a large amount of silica, generally comprising glassy and smooth-surfaced spherical particles. Silica fume grains fill the voids in the mixture, reduce the number of $C_a(OH)_2$ crystals, and increase the compressive strength of cement and concrete. Blast furnace slag is a waste product generated during iron production; it also has some binding properties, as it contains high amounts of calcium oxide. This waste material not only increases the compressive strength and workability of fresh concrete, but also reduces sweating [6, 7].

The steel fibres used in concrete significantly improve its properties, such as flexural strength, toughness, energy absorption capacity, and durability, and prevent crack formation. However, steel fibres make concrete more durable by slowing down the progress of these cracks in the concrete and transferring the stresses at the end of the crack to themselves and solid areas, preventing the loss of strength that the crack would cause in the concrete [8, 9]. The amount of fibre used in the mixture and the fibre slenderness also have significant effects on the flexural strength, fracture energy, and toughness of steel fibre concrete. The extent to which steel fibres can be used when mixed into concrete depends on the geometric shape of the fibre and the interlock distribution between the fibre and the concrete matrix. Therefore, steel fibres are produced and used in many different geometric forms. In studies examining the effect of fibre size, it has been observed that short-length fibres increase the tensile strength by delaying the first crack formation in concrete, whereas long fibres significantly increase the final rupture strength by providing load transfer and ductility in concrete [10]. Owing to these advantages, fibrous concrete has a wider range of applications than conventional concrete [11]. Fibrous concrete continues to be increasingly used in tunnels, shotcrete pavements, road pavements in airport runways and highways, and industrial and water structures owing to its high abrasive and tensile strengths, stabilisation of slopes and retaining wall construction, earthquake-resistant structures, and repair and reinforcement of bearing elements of buildings and engineering structures [12]. In particular, steel fibre reinforced concrete pavement roads have high fatigue and impact strength, as well as sufficient strength against repeated loads and impacts from vehicle wheels. Therefore, steel fibres make brittle concrete structures flexible and durable because they act as bridges between microcracks and transfer stress over a large area. As a result, the stress distribution within the concrete changes, and the load-carrying capacity significantly increases [13-15].

In studies on steel fibre concrete, it has been determined that fibres have an effect of approximately ±25 % on the compressive strength of concrete; however, the effect of fibres on flexural strength is higher than that on tensile and compressive strengths. The final flexural strength becomes up to 50 % higher than that of normal concrete, and the tensile strength is also higher than that of conventional concrete [16-18]. Similarly, it has been determined that fibres do not have a significant effect on the compressive strength of concrete and decrease strength by 5.10 % to 9.59 %, and increase the flexural strength by up to 21.15 % [19, 20]. In addition, in very few studies in the literature, it has been observed that steel fibre reinforced concrete reduces the concrete pavement thickness by up to 20.50 % with the addition of 0.5 % steel fibre depending on the project traffic load, reliability coefficient, and bearing strength of the soil [21]. Most existing studies using steel fibre only aimed to improve the strength properties of concrete. However, these studies failed to apply a multidisciplinary approach or ignored the use of steel fibre concrete as road pavement. For this reason, the potential for the use of steel fibre reinforced concrete as road pavement for different traffic and soils and the thickness-cost effect have not been thoroughly addressed until today.

In this study, unlike in the limited number of previous studies, the use of concretes containing different ratios of steel fibre on very weak soils such as plastic clay under different traffic loads was investigated. For this purpose, specimens of fibrous concrete were subjected to a series of tests, including workability, compressive, flexural, splitting tensile strength, and freeze-thaw tests, under a variety of curing conditions. In addition, using the AASHTO 1993 design method, the thicknesses of the road pavements for steel fibre reinforced concrete were determined, and current cost analyses were performed according to these thicknesses.

2. Materials and methods

2.1. Materials

In this study, the concrete mixture was composed of crushed sand, crushed stone, Portland cement, mixing water, steel fibres, and a superplasticiser. In all mixtures, 0-5 mm crushed sand (specific gravity 2.77 kg/m³), 5-11 mm crushed stone-I (specific gravity 2.79 kg/m³), and 11-22 mm crushed stone-II (specific gravity 2.80 kg/m³) were used at rates of 22 %, 38 % and 40 %, respectively. The particle size distribution of the aggregate mixture according to the TS EN 933-1 [22] standard limits is shown in Figure 1. Portland cement (CEM I 42.5R) with a specific

gravity of 3.08 g/cm³, specific surface of 3.720.00 cm²/g, SiO₂ content of 19.41 %, and 7-day compressive strength of 57.40 % was used in the mixtures. Tap water of Tekirdağ/Çorlu country was used as the mortar mixing water. Steel fibres with a length of 60 mm, diameter of 0.90 mm, and slenderness of (L/d) 65 with hook ends were used in the production of concrete (Figure 2). The tensile strength of the steel fibres with a density of 7.85 gr/cm³ was 1150 N/mm² according to the TS EN 14889-1 [23] standard.
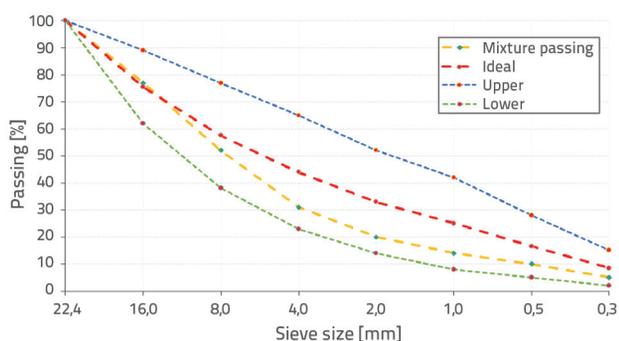
Figure 1. The particle size distribution of the aggregate mixture

As a chemical additive, 1.34 % superplasticiser with a specific gravity of 1.11 g/cm³ was used to increase the workability of fresh concrete, which became harder with the addition of steel fibres and to provide ideal performance.

Figure 2. Steel fibre used in concrete specimens

2.2. Preparation of concrete mix specimens

The water/cement ratio was taken as 0.40 in all mixtures with and without steel fibres, and this ratio was kept constant. Steel fibres were added to the concrete at rates of 0, 0.75 %, 1.00 %, 1.25 %, and 1.50 % by weight, and five series of mixtures were produced with four different fibre-volume ratios of steel fibres and fibre-free control concrete. The control and steel fibre reinforced mixture specimens produced were coded as follows, and the material ratios in the mixtures are listed in Table 1.
- (K-C): Control concrete specimens that do not include steel fibre
- (0.75SF+C): Concrete specimens including 0.75 % steel fibre
- (1SF+C): Concrete specimens including 1 % steel fibre
- (1.25SF+C): Concrete specimens including 1.255 % steel fibre
- (1.50SF+C): Concrete specimens including 1.50 % steel fibre.

The mixing process was initiated by dry mixing of cement, sand, and crushed stones based on the mixing ratios listed in Table 1; then, half of the plasticiser and half of the water were added after being mixed in another place. The remaining amounts of plasticiser and water were added in a controlled manner to ensure the homogeneity of the mixture. After the concrete entered a flowing state, steel fibres were added to the mixture and sprinkled in the last stage, and the mixing was continued until they were homogeneously dispersed. The mixing was completed after 15 min. An image of the fresh steel fibre concrete mixture is shown in Figure 3.

Figure 3. Fresh concrete mixture with steel fibre

Table 1. Material ratios in mixtures

Mixture code	Cement [kg/m³]	Aggregate [kg/m³]			Steel fibre [kg/m³]	Water [kg/m³]	Superplasticiser [kg/m³]	Water/Binder [%]
		0-5 [mm]	5-11 [mm]	11-22 [mm]				
(K-C)	450	410	709	746	0	180	6.00	0.40
(0.75SF+C)		406	701	738	58.88			
(1SF+C)		404	698	735	78.50			
(1.25SF+C)		403	695	732	98.13			
(1.50SF+C)		401	693	729	117.75			

The produced concrete specimens were compacted after being placed in moulds of different sizes for each experiment (Figure 4). After approximately 24 hours, the specimens were removed from the moulds and cured by being kept in a water-filled curing pool at 23±2°C for 7, 28, and 90 days. At the end of the curing process, all specimens were kept in a laboratory environment and turned into saturated surface dry (SSD). Hardened concrete experiments were performed on the SSD specimens.
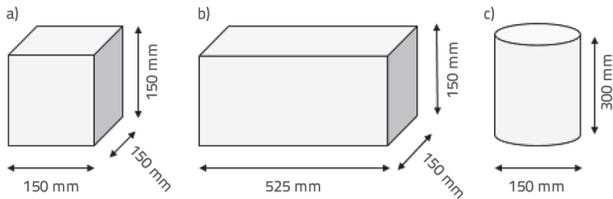
Figure 4. Specimen forms and sizes: a) Compressive strength; b) Flexural strength; c) Splitting tensile strength

2.3. Methods

2.3.1. Experimental methods

Workability and fluidity properties of concrete

A slump test was applied to the mixture specimens according to the TS EN 12350-2 [24] standard to determine the consistency and workability of the fresh concrete. The experiment was conducted by measuring the amount of collapse of the fresh concrete placed in the cone after the cone was lifted in the vertical direction under its own weight (Figure 5).

Figure 5. Determination of the slump size of fresh concrete

Compressive strength

The compressive strength of concrete is its ability to resist the influence of an axial compressive load before breaking. An experiment was performed to determine the load that a unit area of the specimen could carry. The compressive strength of concrete specimens is determined by selecting the loading rate in the range of 0.2–1.0 MPa/s (N/mm^2. s), according to the TS EN 12390-4 [25] standard. The compressive strength test setup is shown in Figure 6.
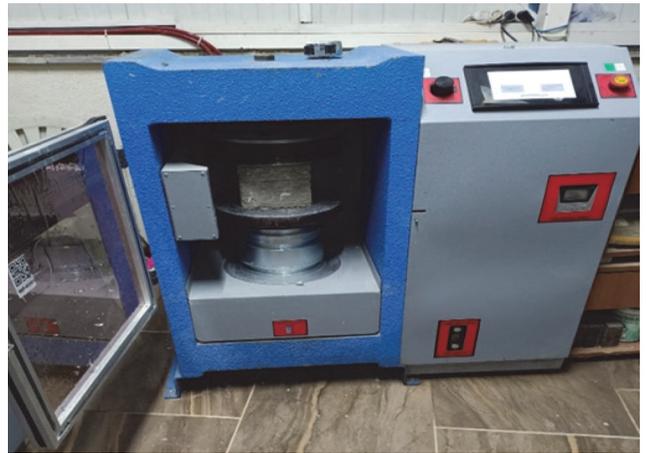
Figure 6. Compressive strength test

The compressive strengths of concrete specimens are calculated by using equation (1).

$$f_c = F/A_c \tag{1}$$

where:
f_c - Compressive strength [MPa]
F - Highest load reached at the time of fracture [N]
A_c - Cross-sectional area of the specimen on which the compressive load was applied [mm^2].

Flexural strength test

Flexural strength is a measure of the tensile strength of the outer fibres of a material. This property is determined by applying loads to cylindrical or prismatic specimens until the material breaks, using installing mechanisms that apply loads at three or four points. The experiment was performed at a loading rate of 0.04–0.06 MPa/s (N/mm^2·s) in accordance with the TS EN 12390-5 [26] standard. The flexural strength test setup is shown in Figure 7. The flexural strengths of the concrete specimens were calculated using equation (2).

$$\sigma = P \times L/(b \times h^2) \tag{2}$$

where:
σ - Flexural strength [MPa]
P - Maximum load [N]

L   - Distance between two supports [mm]
b   - Width of the specimen [mm]
h   - Height of the specimen [mm].
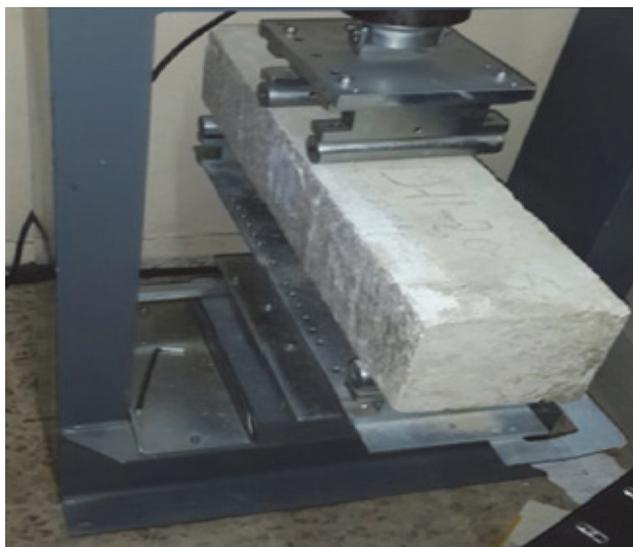
Figure 7. Flexural strength test

Splitting tensile strength test

Knowledge of the splitting-tensile strength of concrete is critical for crack and structural analysis. Tensile strength is important for preventing cracks in mass concrete, water tanks, nuclear power plants, airports, prestressed concrete, and road construction. Based on the TS EN 12390-6 [27], a load was applied to the specimen placed in the test device, as shown in Figure 8. Tensile strengths were formed perpendicularly to the compressive stresses along the linear load applied to the specimen. The concrete specimen underwent shortening where the load was applied and elongation along the horizontal axis in the middle region. The applied load was continued until the specimen broke parallel to the loading direction, and the fracture load was measured [19].

Figure 8. Splitting tensile strength test

The splitting tensile strengths of the concrete specimens were calculated using equation (3):

$$\sigma = 2 \times P_c / (\pi \times L \times d) \tag{3}$$

where:
σ - Splitting tensile strength [MPa]
P_c - Fracture load [N]
L   - Distance between specimen contact line and loading section [mm]
d   - Cross-sectional size of the specimen [mm]

Freeze-thaw resistance test

This experiment was conducted to determine the performance of concrete against the environmental conditions to which it will be exposed during its service life. Specimens produced within the scope of the experiment were tested for freeze-thaw resistance according to the TSE CEN/TS 12390-9 [28] standard. The freeze-thaw cabinet in which the specimens were placed and the test cycles are shown in Figure 9.

Figure 9. a) Freeze-thaw cabinet; b) cycle time
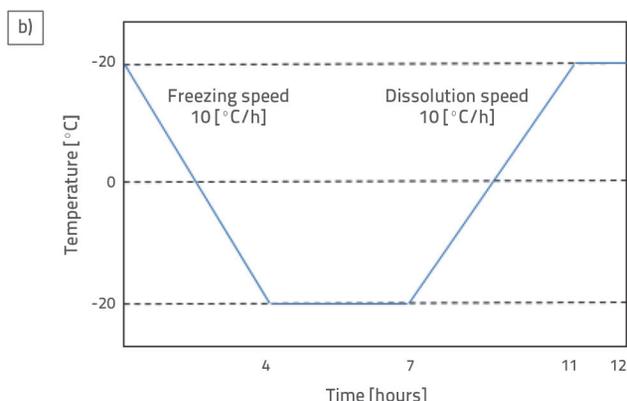
Table 2. Parameter values selected in the AASHTO 1993 design method [29, 30]

Symbol	Unit	Description	Explanation
$W_{8,2}$	-	Total standard axle load repetitions (8,2 t)	$1 \cdot 10^6$, $10 \cdot 10^6$, $100 \cdot 10^6$, $200 \cdot 10^6$
R	-	The engineering effect that brings the project closer to the goal	The recommended (R) values for the designs to be made for Turkey are expected to be 95% for state roads and highways, and 85% for provincial roads. In this study, R = 95 % was taken.
Z_R	-	Standard normal deviation	In the calculations made in this study, for highways and state roads, the R value was 95% and the ZR value was -1,645 depending on the selected R value.
S_0	-	Combined standard error of traffic forecast and performance forecast	For rigid pavements, it is recommended to take the total standard deviation (So) as 0.35. In this study, So was taken as 0.35.
d	(inc) (0,0254 m)	Plate thickness of the pavement (inches) (1 in = 0,0254 m)	-
ΔPSI	-	The difference between the initial design service capability (p_o) and the final service capability index (p_t)	According to the AASHTO 1993 method, the (p_o) value was determined as 4.5 for rigid pavements. In the calculations made for the study, p_0 = 4.5 and p_t = 2.5 were selected.
S'_c	(psi) ($6,8950 \cdot 10^3$ Pa)	Flexural strength value of concrete	The flexural strength value was obtained as a result of the four-point flexural strength test.
J	-	Load transfer coefficient	Load transfer coefficients according to design conditions are given in AASHTO 1993 Design Guide. In this study, J=2.7 was used for all calculations.
C_d	-	Drainage coefficient	The Cd value was taken as 1 in calculations in accordance with AASHTO 1993 Design Guidelines.
E_c	(psi) ($6,8950 \cdot 10^3$ Pa)	Modulus of elasticity of concrete	It has been suggested by AASHTO to calculate this using the equation $E_c = 6750 \times S'_c$.
k	(pci) ($27679,9$ kg/m³)	Subgrade effective reaction module	The 'k' value may vary depending on the bearing capacity, density, moisture content, and type of the soil. Commonly used values for 'k' are in the range of $150 \leq k \leq 550$. The 'k' value was taken as 150 in calculations in accordance with the AASHTO 1993 Design Guidelines.

According to the standard, the resistance of specimens to the effect of freeze-thaw is determined by weighing the mass loss caused by flaking after 28 freeze-thaw cycles at -20°C for 4 hours and at +20°C for 4 hours. The particles separated from the specimen mass were weighed and their count per square meter of the specimen surface was calculated using equation (4) to measure the amount of flaking.

$$m_n = (\sum \mu_s / A) \times 10^6 \qquad (4)$$

where:
m_n - Weight loss [g/m²]
μ_s - Amount of broken specimen in cycles [g]
A - Surface area [m²]

2.3.2. Design methods

In highway pavement design, many parameters, such as traffic load, bearing capacity of the subgrade, properties of the materials used, regional climatic conditions, service life of the road, and service quality, are considered. Because the AASHTO 1993 method has been used for rigid and flexible pavements and road design on Turkish highways for years, this study included calculations based on the AASHTO 1993 method for rigid pavement design.

In this context, the AASHTO 1993 equation for the performance of a concrete pavement, which is obtained by considering the effect of the 8.2-ton standard equivalent single-axle load repetition number ($W_{8,2}$) on the performance of the pavement, is given in equation 5. Concrete pavement thickness (d) is calculated with the help of this equation [29].

$$
\begin{aligned}
\text{Log}_{10}W_{8.2} = {} & Z_R * S_0 + 7.35 * \log_{10}(d+1) - 0.06 \\
& + [\log_{10}\Delta PSI/(4.5-1.5)]/[1+(1.624*10^7)/(d+1)^{8.46}] \\
& + (4.22-0.32*p_t)*\log_{10}[(S'_c*C_d*(d^{0.75}-1.132)) \\
& /(215.63*J*d^{0.75}*(18.42/(E_c/k^{0.25}))]
\end{aligned} \qquad (5)
$$

The meanings of the parameters given in Equation 5 and the values selected in this study in accordance with the AASHTO 1993 design criteria are listed in Table 2.

3. Results

3.1. Experimental results

3.1.1. Slump test results

The consistency and workability properties of the fresh concrete mixture specimens were determined by a slump test according to the TS EN 12350-2 [24] standard, and the slump values of the specimens are shown in Figure 10. Figure 10 shows that the slump value decreases as the steel fibre content in the concrete mixtures increases; in other words, the workability decreases. It was determined that the workability of concrete reinforced with fibres decreases with an increase in fibre volume, especially after the rate of 0.75 % steel fibre, and the degree of slump entered the S3 consistency class at the rate of 1.50 % steel fibre. The results of the current study are compatible with those in the literature [31], as it has been observed in the literature that the workability of concrete mixtures decreases after a 0.8 % steel fibre ratio in studies using different ratios of steel fibres [32, 33].
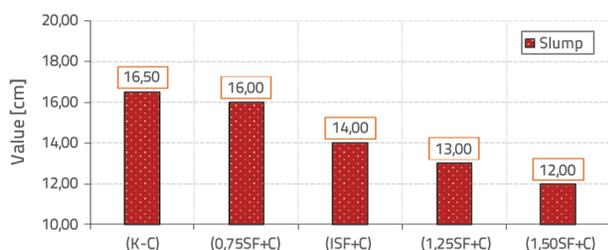
Figure 10. Effect of steel fibre on the slump values of fresh concrete

3.1.2. Compressive strength test results

The control and fibre-added mixtures were placed in cubic moulds measuring 150×150×150 mm and kept in the laboratory for 24 h. Afterwards, the hardened specimens were removed from the moulds and kept in the curing pool at 23±2 °C for 7, 28, and 90 days. All specimens were removed from the pool at the end of the curing period and turned into saturated surface dry (SSD) in a laboratory environment. These specimens were tested using a 300-ton compression capacity press with a loading speed of 0.50 MPa/s. The variation in the compressive strength of the specimens, which were prepared in triplicate for each ratio, together with the steel fibre additive ratio and curing time, is shown in Figure 11.

As shown in Figure 11, the compressive strength values of the concrete specimens decreased compared to those of the control specimens for all curing times, depending on the amount of steel fibre. These reductions in compressive strength were 2.07 %, 4.16 %, 8.33 %, and 12.49 % for the specimens subjected to curing for 28 days, respectively. This can be attributed to steel fibres having a higher specific gravity compared to aggregates within the scope of this study. Similarly, Soroushian and Bayasi [34] stated that fibres with a high slenderness rate negatively

affect workability. In the literature, it has been stated that the use of steel fibres with three different slenderness (L/d) values such as 80, 65, and 55 in concrete production, as well as steel fibre with hook ends with different slenderness values and proportions, reduces the compressive strength of concrete. However, it has been reported that it significantly increases tensile and flexural strengths, and when up to 1.5 % steel fibre is used in concrete, the compressive strength of concrete varies by up to ±25 % compared to that of non-fibre concrete [35-41].
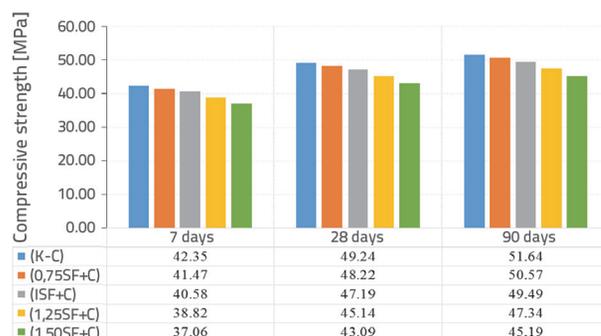
Figure 11. Compressive strengths of control and steel fibre reinforced specimens

Because it is recommended to choose the minimum C30/37 MPa concrete strength class according to the TCK Concrete Road Pavements Technical Specifications, the compressive strengths of the 28-day specimens in the study were compared with this value, and the results are shown in Figure 12.
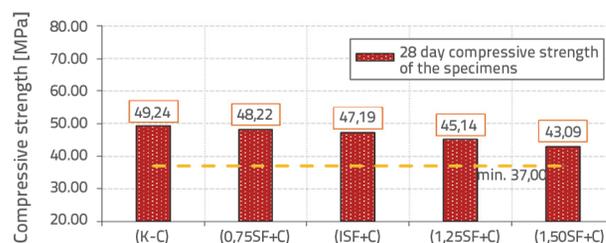
Figure 12. Compressive strength design criterion of specimens

Figure 12 shows that at the end of the 28-day compressive strength test, all specimens met the minimum characteristic compressive strength (C 30/37) requirement according to the TCK Specifications.

3.1.3. Flexural strength test results

The prepared 150×150×525 mm concrete beam specimens were subjected to a four-point flexural strength test after 7, 28, and 90 days of curing. The test was conducted in a 20-ton bending capacity press at a loading speed of 0.05 MPa/s. The variation in the flexural strengths of the control and steel fibre reinforced specimens with the additive ratio is shown in Figure 13.

As shown in Figure 13, the flexural strength values of the concrete specimens with the steel fibre additive were higher than those of the control specimens. Considering the 28-day curing period of the concrete, it was observed that this increase in flexural strength occurred at higher rates of 9.77 %, 17.48 %, 28.37 %, and 39.10 %, respectively, compared to the control concrete. The reason for this is thought to be the ductile behaviour under bending, which is the most important feature of steel fibre reinforced concrete. In previous studies, it was observed that the addition of steel fibres to concrete increased its flexural strength by 31.75 % [42].
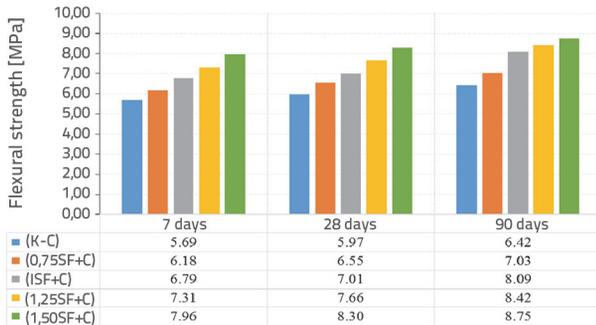
Figure 13. Flexural strengths of control and steel fibre reinforced specimens

According to the TCK Concrete Road Pavements Technical Specifications [43], the 28-day flexural strength of concrete roads must be higher than 4.50 N/mm². In this study, the flexural strengths of the 28-day-old specimens were compared with the specifications, and the results are shown in Figure 14.
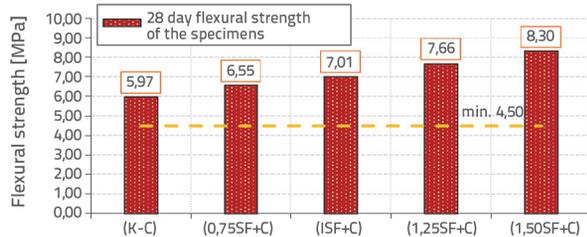
Figure 14. Flexural strength design criteria chart of specimens

Figure 14 shows that the 28-day flexural strength of the fibrous specimens met the minimum characteristic flexural strength (4.50 N/mm²) required by the TCK Technical Specifications.

Load-deflection curves and flexural toughness test results

The mid-load-span deflection curves obtained from the four-point flexural test of steel fibre reinforced specimens were prepared using the data obtained after recording with the image recorder at the time of the test. The toughness values obtained by calculating the areas under these curves shown in Figure 15 are shown in Figure 16.
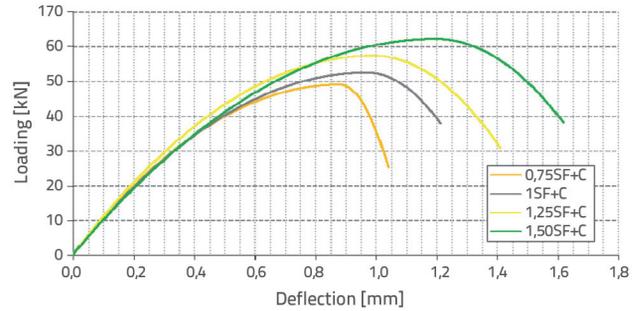
Figure 15. Load-deflection curves of steel fibre reinforced specimens

Figure 16. Fracture toughness values of specimens

The addition of steel fibres increased the fracture toughness values of all specimens. The fracture toughness values were highest for the specimens containing 1.50 % steel fibres. This is because they increased the toughness of the concrete owing to the high tensile strength of the steel fibres in the concrete and the adherence between them and the matrix.

The highest toughness values belonged to the 57.46 kNmm and 1.50SF+C specimens. The lowest toughness values were observed for the 0.75SF+C specimens with 30.18 kNmm. Increasing the amount of steel fibre from 0.75 % to 1.50 % by volume increased the toughness (energy absorption capacity) of the concrete by 90.38 %. It was determined that increasing the steel fibre ratio added to the mixtures increased the toughness values and thus improved the mechanical properties of the concrete. In addition, studies have shown that increasing the amount of fibre from 0.03 % to 0.90 % by volume increased the toughness by 100 % [42].

3.1.4. Splitting tensile strength test results

To determine the splitting tensile strength of the control and steel fibre reinforced mixtures at the end of 7, 28, and 90 days of curing, three cylindrical specimens with dimensions of Ø150x300 mm were tested for each ratio. The experiment was conducted at a loading speed of 1.6 kN/s using a press with a compression capacity of 300 tons. The variation in the splitting tensile strength of the specimen with the steel fibre additive ratio is shown in Figure 17.

As shown in Figure 17, there was a significant increase in the splitting tensile strength values of the concrete specimens with

the steel fibre additive compared to the control specimens. This increase in the 28-day splitting tensile strength occurred at rates of 10.96 %, 21.71 %, 25.50 %, and 29.08 %, respectively, compared to the control concrete. It is thought that the reason for this is that long fibres have a higher adherence to the cement matrix and transfer the tensile stresses formed in the concrete more effectively compared to short fibres. In the literature, it has been observed that the splitting tensile strength increases by up to 35 % compared to the control concrete with the use of steel fibres, and this increase varies in parallel with the increase in the rate of steel fibres added to the concrete [14, 44].
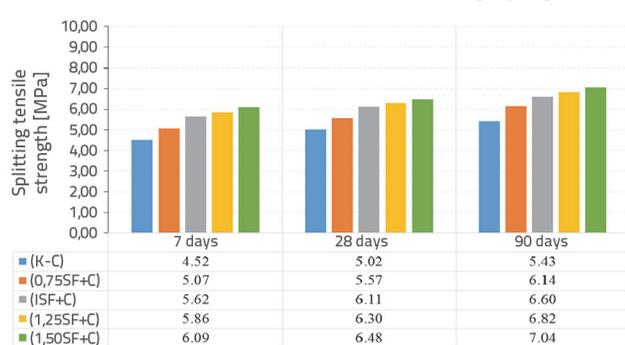
Figure 17. Splitting tensile strengths of control and steel fibre reinforced specimens
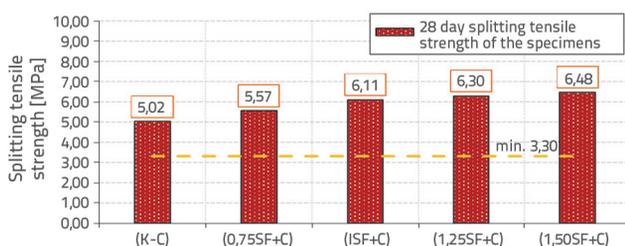
Figure 18. Splitting tensile strength design criteria chart of the specimens

According to the TCK Technical Specifications, the 28-day splitting tensile strength values of the concrete pavement specimens were compared based on a minimum value of 3.30 N/mm², and the results are shown in Figure 18.

Figure 18 shows that the 28-day splitting tensile strength of the fibrous specimens meets the minimum characteristic splitting tensile strength (3.30 N/mm²) required by the TCK Technical Specifications.

3.1.5. Freeze-thaw resistance test results

A freeze-thaw experiment was conducted to determine the resistance of the steel fibre reinforced concrete pavement as a result of freeze-thaw periods during its service life. Control and steel fibre reinforced concrete specimens were subjected to a freeze-thaw resistance test based on the Capillary suction of deicing solution and freeze-thaw test (CDF) method, according to the TSE CEN/TS 12390-9 [28] standard. According to Table 3, specified in accordance with the TCK Technical Specifications [43] in Turkey, the freeze-thaw resistance category was taken as FT2, depending on the climatic conditions of the region where the study was conducted.

Before the experiment, after the fresh concrete was placed in the moulds, the moulds were protected against drying at 20±2°C for one day, and after 24±2 hours, the specimens were removed from the moulds and placed in a curing pool filled with tap water at a temperature of 20±2°C. Specimens were removed from the curing pool on the 7th day and kept in a curing room at 20±2°C and 65±5 % relative humidity for 21 days until testing began. Specimens cured for 28 days were saturated with a test liquid (97 % tap water and 3 % NaCl by mass) capillary for 7 days, and the experiment started when the specimens were 35 days old. At the end of 28 freeze-thaw cycles, entailing freezing for 4 hours at -20°C and thawing for 4 hours at +20°C, the specimens produced were evaluated by scaling the

Table 3. Freeze-thaw resistance categories

Category	Mass loss (28 days)
FT0 (Freeze-thaw-free places)	-
FT1 (Freeze-thaw places)	Average < 1,0 kg/m² Individual value < 1.5 kg/m²
FT2 (Places with freeze-thaw and where defrosting agents are used)	Average < 0.5 kg/m²

Table 4. Freeze-thaw test results of the specimens

Mixture code	Mass loss [g/m²] 28 freeze-thaw cycles	Reduction in weight loss compared to control specimen [%]
(K-C)	342	-
(0.75SF+C)	339	0.88
(1SF+C)	341	0.29
(1.25SF+C)	339	0.89
(1.50SF+C)	334	2.34

masses they lost. The mass loss values of the specimens were calculated using Equation (4), and the results are given in Table 4. The changes in mass loss are shown in Figure 19.
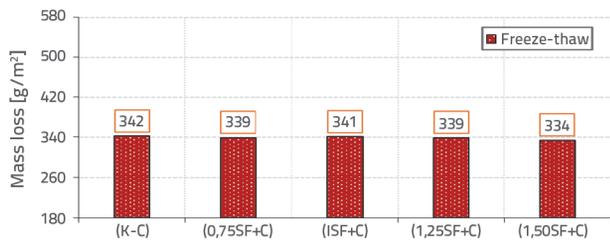
Figure 19. Freeze-thaw mass loss graph of the specimens

Table 4 shows that according to the specification [43], the requirement for all specimens to have a mass loss of less than 0.50 kg/m^2 after 28 cycles was met. The highest mass loss among the specimens occurred in concrete containing 1.50 % steel fibre (1.50SF+C). Compared to the control specimens, it was observed that the mass losses decreased by 0.88 %, 0.29 %, 0.88 % and 2.34 %, respectively, and thus the freeze resistance increased. This is considered to have occurred because of the lower internal stress that occurs in concrete as a result of freezing due to the higher bond strength of steel fibre reinforced specimens. However, in previous studies, it has been reported that specimens with steel fibre do not have a positive effect in terms of compressive strength, but the mass loss of specimens decreases (freeze-thaw resistance increases) as the amount of steel fibre increases according to the freeze-thaw test [45].

3.2. Design results

3.2.1. Concrete pavement thickness design results using the AASHTO method

Highway concrete pavement design was carried out according to the AASHTO 1993 design guide, based on 0 %, 0.75 %, 1.00

%, 1.25 %, and 1.50 % steel fibre reinforced concrete specimens. The traffic of four different projects for soil with a very low bearing capacity (plastic clay) was considered in the calculations. In traffic selection, $1×10^6$ standard axle load repetitions were considered as light vehicle traffic, where the annual average daily heavy vehicle traffic (AADHVT) is less than 500; in other words, $W_{8.2}$ was less than $3,1×10^6$. For heavy vehicle traffic, $10×10^6$, $100×10^6$, and $200×10^6$ standard axle load repetitions with AADHVT values greater than 500 were used.

In accordance with the TCK Concrete Road Technical Specifications, the minimum strength requirements used in the design of concrete road pavements are listed in Table 5 [43].

The S'_c and E_c values used in the design of the control and fibre reinforced specimens are listed in Table 6.

In soils with a very weak bearing capacity (k=150 pci), the pavement thicknesses for different project traffic loads were determined using Equation 5, and the results are shown in Figure 20.

	1 x 10^6	10 x 10^6	100 x 10^6	200 x 10^6
(K-C)	14.064	21.204	30.307	33.614
(0,75SF+C)	13.363	20.221	28.976	32.146
(1SF+C)	12.883	19.528	28.044	31.118
(1,25SF+C)	12.291	18.641	26.868	29.82
(1,50SF+C)	11.439	17.548	25.568	28.421
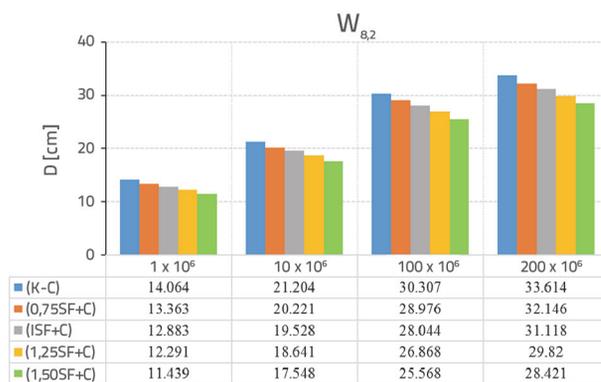
Figure 20. Concrete pavement thickness values for mixture specimens

Figure 20 shows that in soils with a very low bearing capacity, steel fibre reinforced specimens showed a decrease in concrete pavement thickness compared to the control specimens. This reduction is as follows for the

Table 5. Minimum strength values for concrete road pavement design [43]

Characteristic cube compressive strength, f$_{ck}$ [N/mm^2]	Flexural strength, f$_{cbt}$ [N/mm^2]	Splitting tensile strength f$_{sk}$ [N/mm^2]	Freeze-thaw, mass loss (28-days) [kg/m^2]
Min. C 30/37	Min. 4.50	Min. 3.30	0.50

Table 6. S'$_c$ and E$_c$ values of control and fibre added specimens

Mixture code	Characteristic cube compressive strength (28 day) [MPa]	Splitting tensile strength (28 day) [MPa]	Flexural strength (28 day) [MPa]	S'$_c$ (psi)	E$_c$ (psi)
(K-C)	49.24	5.02	5.97	865.44	5.841.719.70
(0.75SF+C)	48.22	5.57	6.55	950.00	6.412.479.31
(1SF+C)	47.19	6.11	7.01	1.016.71	6.862.821.37
(1.25SF+C)	45.14	6.30	7.66	1.110.99	7.499.174.28
(1.50SF+C)	43.09	6.48	8.30	1.203.81	8.125.737.14

Table 7. Unit prices for cost analysis

Materials	Unit	Unit price [$]
Cement (3.80 g/cm³)		129.40
Water		1.06
0-5 mm aggregate (2.77 g/cm³)		31.45
5-11 mm aggregate (2.79 g/cm³)	$/t	27.40
11-22 mm aggregate (2.80 g/cm³)		28.80
Chemical additive (1.08 g/cm³) (a new generation of superplasticise)		1.100.00
Steel fibre (7.85 g/cm³)		850.00

Table 8. Unit prices of control and steel fibre added specimens

Mixture code	Cement [kg/m³]	Aggregate [kg/m³]			Steel fibre [kg/m³]	Water [kg/m³]	Superplasticiser [kg/m³]	Total cost [$]	The cost of 1 m², layer thickness 1 cm [$]
		0-5 [mm]	5-11 [mm]	11-22 [mm]					
(K-C)		410	709	746	0			118.83	1.19
(0.75SF+C)		406	701	738	58.88			196.13	1.96
(1SF+C)	450	404	698	735	78.50	180	6.00	212.49	2.12
(1.25SF+C)		403	695	732	98.13			228.88	2.29
(1.50SF+C)		401	693	729	117.75			245.26	2.45

1×10^6, 10×10^6, 100×10^6, and 200×10^6 project traffic loads, respectively:
- (0.75SF+C) specimen: 4.98 %, 4.64 %, 4.39 %, and 4.37 %
- (1SF+C) specimen: 8.40 %, 7.91 %, 7.47 %, and 7.43 %
- (1.25SF+C) specimen: 12.61 %, 12.09 %, 11.35 %, and 11.29 %
- (1.50SF+C) specimen: 18.66 %, 17.24 %, 15.64 %, and 15.45 %.

It was determined that the experimentally calculated compressive, flexural, and splitting tensile strength results met the concrete pavement design criteria, and the steel fibres added to the concrete increased the flexural strength of the concrete compared to that of the control concrete, resulting in a decrease in the concrete pavement thickness. In very few studies in the literature, it has been determined that the addition of 0.5 % steel fibre reduces the concrete pavement thickness by 20.50 %, depending on variable criteria such as project traffic and bearing strength of the soil [21].

3.2.2. Cost analysis

Because construction cost prices are constantly changing globally, the US dollar was used for cost calculation for road concrete pavement thickness of the control and steel fibre reinforced specimens. Because the 20 cm thick plant mix foundation (PMF) application recommended by AASHTO under the concrete slab was performed for all specimens, it was not included in the scope of this cost analysis. The unit prices used in the cost analysis are listed in Table 7. In the cost analysis, only the effect of steel fibre on the cost of concrete pavement material was considered, and the cost and environmental impact of construction activities were not considered.

The unit prices of the control and steel fibre reinforced specimens were calculated using Table 7 and are listed in Table 8.
The costs of the control and steel fibre specimens within the scope of this study are shown in Figure 21.

	1 x 10⁶	10 x 10⁶	100 x 10⁶	200 x 10⁶
(0,75SF+C)	56.5	57.07	57.47	57.51
(ISF+C)	63.19	64.07	64.85	64.92
(1,25SF+C)	68.18	69.18	70.6	70.71
(1,50SF+C)	67.46	70.38	73.69	74.07
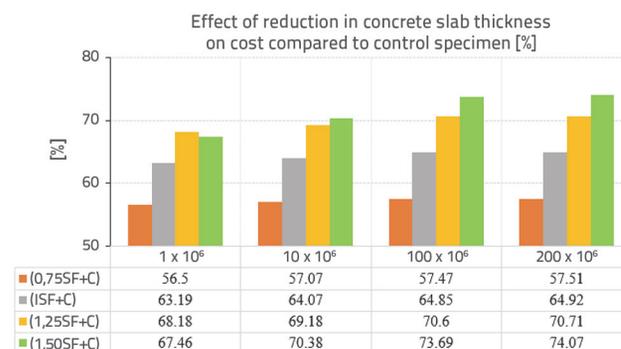
Figure 21. Cost analyses for concrete specimens

As Figure 21 shows, if steel fibre reinforced concrete is used instead of control specimens in the design of the concrete pavement thickness, a cost increase of 56.50-74.07 % can be obtained according to the pavement layer thickness for different project traffic loads. In previous studies, it was determined that the addition of steel fibre to concrete at a rate of 0.25 % to 1.00 % by volume increases the unit cost of the concrete by 60.10-139.80 % [21]. In another study, it was observed that the service life of steel fibre reinforced concrete was 6.5 times longer than that of concrete without additives. However, considering the same service life, it has been determined that even when the

pavement thickness of concrete is decreased by approximately 50 % with the addition of steel fibres, its cost increases by 41 % [46]. Because concrete pavement roads are often exposed to harsh environmental conditions throughout their service life, it is thought that the addition of steel fibre to concrete will be more cost effective in the long run because it increases the resistance and ductility of concrete against crack development; has a significant effect on flexural strength, fracture energy, and toughness; increases wear strength depending on the increased fibre content; and increases the durability of the pavement.

4. Conclusions

In this study, the effects of using different ratios of steel fibres in concrete pavements built on soils (plastic clays) with a very weak bearing capacity on the pavement thickness and cost were investigated, and the following results were obtained:

- It was observed that the slump value of the concrete mixes decreased, which indicated that the concrete became less workable as the percentage of steel fibres in the mixture increased.
- Depending on the amount of steel fibre, the compressive strength values of the concrete specimens decreased compared to those of the control specimens. The reductions in compressive strength were 2.07 %, 4.16 %, 8.33 %, and 12.49 % for the 0.75 %, 1.00 %, 1.25 %, and 1.5 % steel fibre reinforced specimens, respectively. These results are due to the use of steel fibres with a specific gravity higher than that of the aggregate in the scope of this study.
- The flexural strength values of the concrete specimens were higher than those of the control concrete. Considering the 28-day curing period of the concrete, these increases in flexural strength were found to occur at high rates of 9.77 %, 17.48 %, 28.37 %, and 39.10 % for specimens with steel fibre additives of 0.75 %, 1.00 %, 1.25 %, and 1.5 %, respectively, compared to the control concrete. This can be explained by

the fact that the steel fibres added to the mixtures prevented and delayed crack initiation and growth by bridging the cracks in the matrix.
- There was an increase in the splitting tensile strength values of the concrete specimens with the steel fibre additive compared to the control concrete. These increases in the 28-day splitting tensile strength were 10.96 %, 21.71 %, 25.50 %, and 29.08 % for specimens with steel fibre additives of 0.75 %, 1.00 %, 1.25 %, and 1.5 %, respectively, compared to the control concrete. This is thought to be because long fibres have a stronger bond with the cement matrix compared to short fibres, and transfer the tensile strength formed in concrete more effectively than short fibres.
- The calculations showed that the concrete pavement thickness of the steel fibre reinforced specimens to be built on soils with a very low bearing capacity (plastic clay) decreased by an average of 4.37-18.66 % at different traffic loads (1×10^6, 10×10^6, 100×10^6, and 200×10^6), but as a result, the costs increased within the range of 56.50-74.07 %.

Thus, it was observed that the physical and mechanical requirements required for the design of concrete pavements are met when steel fibres are added to concrete built on very weak soils. In addition, rigid road pavement layer thicknesses decreased, but construction costs increased. However, considering the curative effect of steel fibre additives on the properties of concrete and the fact that concrete pavements are often exposed to harsh environmental conditions during their long service life, it is considered that the cost increase will not have a negative impact.

Acknowledgements

REFERENCES

[1] Abut, Y., Yildirim, S.T., Ozturk, O., Ozyurt, N.: A comparative study on the performance of RCC for pavements casted in laboratory and field, International Journal of Pavement Engineering, 23 (2020) 6, pp. 1777–1790, doi: 10.1080/10298436.2020.1823391

[2] Kazemi, M.T., Golsorkhtabar, H., Beygi, M.H.A., Gholamitabar, M.: Fracture properties of steel fiber reinforced high strength concrete using work of fracture and size effect methods, Construction and Building Materials, 142 (2017), pp. 482–489, doi: 10.1016/j.conbuildmat.2017.03.089

[3] Paiva, H., Velosa, A., Cachim, P., Ferreira, V.M.: Effect of pozzolans with different physical and chemical characteristics on concrete properties, Materıales De Construccıon, 66 (2016) 322, doi: 10.3989/mc.2016.01815

[4] Shafigh, P., Hashemi, M., Nam, B.H., Asadi, I.: Laboratory comparison of roller-compacted concrete and ordinary vibrated concrete for pavement structures, GRAĐEVINAR, 72 (2020) 2, pp. 127-137, doi: https://doi.org/10.14256/JCE.2572.2018

[5] Setina, J., Gabrene, A., Juhnevica, I.: Effect of pozzolanic additives on structure and chemical durability of concrete, Procedia Engineering, 57 (2013), pp. 1005-1012, doi: 10.1016/j.proeng.2013.04.127

[6] Hassan, A.A.A., Lachemi, M., Hossain, K.M.A.: Effect of metakaolin and silica fume on the durability of self-consolidating concrete, Cement and Concrete Composites, 34 (2012) 6, pp. 801–807. doi: 10.1016/j.cemconcomp.2012.02.013

[7] Alhozaimy, A.M., Soroushian, P., Mirza F.: Mechanical properties of polypropylene fiber reinforced concrete and the effects of pozzolanic materials, Cement and Concrete Composites, 18 (1996) 2, pp. 85-92, doi: 10.1016/0958-9465(95)00003-8

[8] Song, P.S., Hwang, S.: Mechanical properties of high-strength steel fiber-reinforced concrete, Construction and Building Materials, 18 (2004) 9, pp. 669–673, doi: 10.1016/j.conbuildmat.2004.04.027

[9] Naghibdehi, M.G., Naghipour, M., Rabiee, M.: Behaviour of functionally graded reinforced concrete beams under cyclic loading, GRAĐEVINAR, 67 (2015) 5, pp. 427-439, doi: 10.14256/JCE.1098.2014

[10] Li, Z., Zhu, H., Zhen, X., Wen, C., Chen, G.: Effects of steel fiber on the flexural behavior and ductility of concrete beams reinforced with BFRP rebars under repeated loading, Composite Structures, 270 (2021), pp. 114072, doi: 10.1016/j.compstruct.2021.114072

[11] Sirijaroonchai, K., El-Tawil, S., Parra-Montesinos, G.: Behavior of high performance fiber reinforced cement composites under multi-axial compressive loading, Cement & Concrete Composites, 32 (2010) 1, pp. 62–72, doi: 10.1016/j.cemconcomp.2009.09.003

[12] Lee, J.H.: Influence of concrete strength combined with fiber content in the residual flexural strengths of fiber reinforced concrete, Composite Structures, 168 (2017) pp. 216–225, doi: 10.1016/j.compstruct.2017.01.052

[13] Bencardino, F., Rizzuti, L., Spadea, G., Swamy, R.N.: Swamy, Experimental evaluation of fiber reinforced concrete fracture properties, Composites Part B: Engineering, 41 (2010) 1, pp. 17–24, doi: 10.1016/j.compositesb.2009.09.002

[14] Holschemacher, K., Mueller, T., Ribakov, Y.: Effect of steel fibres on mechanical properties of high-strength concrete, Materials and Design, 31 (2010) 5, pp. 2604-2615, doi: 10.1016/j.matdes.2009.11.025

[15] Abbass, A., Abid, S., Özakça, M.: Experimental investigation on the effect of steel fibers on the flexural behavior and ductility of high-strength concrete hollow beams, Advances in Civil Engineering, (2019), pp. 13, doi: 10.1155/2019/8390345

[16] Kang, M.C., Yoo, D., Gupta, R..: Machine learning-based prediction for compressive and flexural strengths of steel fiber-reinforced concrete, Construction and Building Materials, 266 (2021), doi: 10.1016/j.conbuildmat.2020.121117

[17] Han, J., Zhao, M., Chen, J. Lan, X.: Effects of steel fiber length and coarse aggregate maximum size on mechanical properties of steel fiber reinforced concrete, Construction and Building Materials, 209 (2019), pp. 577-591, doi: 10.1016/j.conbuildmat.2019.03.086

[18] Xu, B.W., Shi, H.S.: Correlations among mechanical properties of steel fiber reinforced concrete, Construction and Building Materials, 23 (2009) 12, pp. 3468–3474, doi: 10.1016/j.conbuildmat.2009.08.017

[19] Choi, Y., Yuan, R.L.: Experimental relationship between splitting tensile strength and compressive strength of GFRC and PFRC, Cement and Concrete Research, 35 (2005) 5, pp. 1587–1591, doi: 10.1016/j.cemconres.2004.09.010

[20] Lin, W.T., Wu, Y.C., Cheng, A., Chao, S.J., Hsu, H.M.: Engineering properties and correlation analysis of fiber cementitious materials, Materials, 7 (2014) 11, pp. 7423–7435, doi: 10.3390/ma7117423

[21] Ozturk, O., Ozyurt, N.: Sustainability and cost-effectiveness of steel and polypropylene fiber reinforced concrete pavement mixtures, Journal of Cleaner Production, 363 (2022) 1, doi: 10.1016/j.jclepro.2022.132582

[22] TS EN 933-1.: Experiments for geometric properties of aggregates Part 1: Determination of particle size distribution-sieving method. Turkish Standards Institute, 2012.

[23] TS EN 14889-1: Fibers - for use in concrete - Part 1: Steel fibers - Definitions, properties and suitability, Turkish Standards Institute, 2006.

[24] TS EN 12350-2.: Concrete - Fresh concrete tests - Part 2: Slump test, Turkish Standards Institute, 2019.

[25] TS EN 12390-4: Concrete - Tests of hardened concrete - Part 4: Compressive strength - Specification of test machines, Turkish Standards Institute, 2019.

[26] TS EN 12390-5: Concrete - Hardened concrete tests - Part 5: Determination of flexural strength of test specimens, Turkish Standards Institute, 2021.

[27] TS EN 12390-6: Concrete - Hardened concrete tests - Part 6: Determination of splitting tensile strength of test specimens, Turkish Standards Institute, 2010.

[28] TSE CEN/TS 12390-9: Concrete - Tests of hardened concrete - Part 9: Freeze-thaw resistance-Surface incrustation (superficial wear), 2012.

[29] AASHTO Guide for Design of Pavement Structures: American Association of State Highway and Transportation Officials, Washington, D.C., 1993.

[30] TCK Concrete Road Pavements Project Guide.: Turkey, 2019.

[31] Frančić Smrkić, M., Damjanović, D., Baričević, A.: Application of recycled steel fibres in concrete elements subjected to fatigue loading, GRAĐEVINAR, 69 (2017) 10, pp. 893-905, doi: 10.14256/JCE.2059.2017

[32] Holschemacher, K., Mueller, T., Ribakov, Y.: Effect of steel fibers on mechanical properties of high strength concrete, Materials & Design, 31 (2010) 5, pp. 2604–2615, doi: 10.1016/j.matdes.2009.11.025

[33] Mahdi, A., Falah, M.W., Hafedh, A.A., Khafaji, Z.A.: Evaluation the influence of steel-fiber on the concrete characteristics, Periodicals of Engineering and Natural Sciences, 10 (2022) 3, pp. 368-379, doi: 10.21533/pen.v10i3.3111

[34] Soroushian, P., Bayasi, Z.: Fiber type effects on the performance of steel fiber reinforced concrete, ACI Materials Journal, 88 (1991) 2, pp. 129-134.

[35] Jhatial, A.A., Sohu, S., Bhatti, N.K., Lakhiar, M.T., Oad, R.: Effect of steel fibres on the compressive and flexural strength of concrete, International Journal of Advanced and Applied Sciences, 5 (2018) 10, pp. 16-21, doi: 10.21833/ijaas.2018.10.003

[36] Sharaky, I.A., Eldin, H.K.S., Shehata, M.M., Mohamed, H.A.: Flexural Response of RC beams cast with normal and steel fibre concrete internally reinforced with various types of FRP bars, GRAĐEVINAR, 72 (2020) 12, pp. 1117-1130, doi: 10.14256/JCE.3009.2020

[37] Dudek, D., Kadela, M., Malek, M.: Effect Steel Fibre Content on the Load-Carrying Capacity of Fibre-Reinforced Concrete Expansion Anchor, Materials (Basel), 14 (2021) 24, doi: 10.3390/ma14247757

[38] Yazıcı, S., Inan, G., Tabak, V.: Effect of aspect ratio and volume fraction of steel fiber on the mechanical properties of SFRC, Construction Building Material, 21 (2007), pp. 1250–1253. doi: 10.1016/j.conbuildmat.2006.05.025

[39] Mansur, M.A., Chin, M.S., Wee, T.H.: Stress–strain relationship of high strength fiber concrete in compression, Journal of Materials in Civil Engineering, 11 (1999) 1, pp. 21–29, doi: 10.1061/(ASCE)0899-1561(1999)11:1(21)

[40] Nili, M., Afroughsabet, V.: Combined effect of silica fume and steel fibers on the impact resistance and mechanical properties of concrete, International Journal of Impact Engineering, 37 (2010) 8, pp. 879–886, doi: 10.1016/j.ijimpeng.2010.03.004

[41] Nyström, U., Gylltoft, K.: Comparative numerical studies of projectile impacts on plain and steel-fibre reinforced concrete, International Journal of Impact Engineering, 38 (2011) 2, pp. 95–105, doi: 10.1016/j.ijimpeng.2010.10.003

[42] Jang, S.J., Yun, H.D.: Combined effects of steel fiber and coarse aggregate size on the compressive and flexural toughness of high-strength concrete, Composite Structures, 185 (2017) pp. 203–211, doi: 10.1016/j.compstruct.2017.11.009

[43] TCK Concrete Road Pavements Technical Specification.: Turkey, 2019.

[44] Blagojević, P., Blagojević, N., Kukaras, D., Živković, D., Šutanovac, A.: Mechanical flexural properties of concrete with melt-extract stainless steel fibres. GRAĐEVINAR, 72 (2020) 12, pp. 1155-1164, doi: :10.14256/JCE.2992.2020

[45] Zhang, Q., Xu, W., Sun, Y., Ji, Y.: Investigation on Mechanical and Microstructure Properties of Steel Fiber Reinforced Concrete, Advances in Materials Science and Engineering, (2022), pp. 1-18, doi: 10.1155/2022/3681132

[46] Kamel, M.A.: Quantification of Benefits of Steel Fiber Reinforcement for Rigid Pavement, American Journal of Civil Engineering and Architecture, 4 (2016) 6, pp. 189-198, doi: 10.12691/ajcea-4-6-1