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Experimental investigation of steel fibers' effect on the improvement of mechanical properties of concrete segmental lining in mechanized tunneling

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Preliminary communication

Hamid Chakeri[1], **Mohammad Darbor**[2], **Farid Sh. Maleki**[3], **Tohid Minaee**[4]
Department of Mining Engineering, Sahand University of Technology, Tabriz, Iran, ORCID 0000-0002-5734-5347
Department of Mining Engineering, Sahand University of Technology, Tabriz, Iran, ORCID 0000-0001-7854-9077
Department of Mining Engineering, University of Tehran, Tehran, Iran
Department of Mining Engineering, Sahand University of Technology, Tabriz, Iran

Abstract

The lining system, used in tunnel boring machines, is made of precast concrete segments. The use of steel fibers in this kind of support system can not only decrease production time and costs but also can improve compressive, tensile as well as flexural behaviors. A study has been carried out to examine the mechanical properties of segments in the Tabriz metro line-2 project using three types of steel fibers: 3D, 4D, and 5D. Various experiments were investigated to monitor the workability of Steel Fiber Reinforced Concrete (SFRC) under various loads. The results confirmed an improvement in the specimens' mechanical properties because of these types of steel fibers. 5D, 4D, and 3D fibers provided the greatest effect on the tensile and flexural strength of steel fiber-reinforced concrete, respectively. The 28-day compressive, tensile, and flexural strengths of the specimens are incremented by 13%, 68%, and 154%, respectively. In addition, by conducting tests on the orientation of steel fibers, placing the fibers perpendicular to the load can improve the compressive strength of concrete by almost 18%.

Keywords:
segments; steel fibers; mechanical properties of concrete; cracking; rupture mode

1. Introduction

The world's most widely used building material is concrete. Being economical, accessible, and the high compressive strength of this mixture have caused it to receive more and more attention. On the other hand, concrete has a very low tensile strength, turning it into a brittle material. To fix this defect, reinforced concrete is mainly used. Using rebar not only makes the project time-consuming but also increases the cost. In recent decades, thin fibers and strands have been used in concrete to solve this problem. The dispersion of fibers in concrete and their almost uniform placement in all directions causes concrete, known as a brittle material, to become a ductile one (**Holschemacher et al., 2010**). The behavior of fiber-reinforced concrete improves significantly after cracking. The crack-controlling feature in fiber-reinforced concrete is more effective than the rebar-reinforced one (**Tiberti et al., 2014**). The existence of fiber in the whole volume of the element prevents crack propagation by using the bridging mechanism (**Abbas et al., 2014**) and (**Plizzari et al., 2006**). The existence of cracks can be considered one of the significant reasons for permeability in the concrete that can be declined by preventing openings and their propagation. This action not only leads to a plummet in permeation of destructive material inside the concrete and a significant reduction of rebars' corrosion probability but can also provide an enhancement in its durability (**Kepler et al., 2000**). Cement-based matrixes have been reinforced with a variety of fibers in the past. Fibers can be synthetic organic (such as propylene or carbon), synthetic inorganic (such as steel or glass), natural organic (such as cellulose material), or natural inorganic (such as asbestos) (**Portland Cement Association, 1990**). The functions of different types of fibers are provided in **Table 1**.

The investigations, done by Romuladi, Batson, and Mandi in late 1950 and early 1960, provided the first steps towards developing Steel Fiber Reinforced Concrete (SFRC) manufacturing technology. Although official permits were issued for different types of steel-reinforced concrete from the beginning of the 20th century, the development of steel fiber-reinforced concrete technology did not progress much until the late 1950s. Since then, steel fibers have been slightly optimized to be used in concrete. In addition, the technologies of mixing, concreting, and polishing these types of concrete have been improved (**Vazifekhah et al., 2012**).

Corresponding author: Mohammad Darbor
e-mail address: darbor@sut.ac.ir

Table 1: Application of different types of fibers (**Vazifekhah et al., 2012**), (**Hansel et al., 2011**)

Fiber Type	Applications	Main advantages
Glass	Precast Panels, Wastewater Piping, Concrete Shell Roofs	Relatively low price Improving the flexibility High tensile strength High chemical resistance Low weight Very low coefficient of thermal expansion Electrical insulation Resistance to corrosive environments
Steel	Roads' Cover, Bridges' Floor, Explosion Resistant Structures, Machinery Foundation, Sea Structures, Tunnels' Lining, Ships' Body Structure	Increasing tensile strength Improving the flexural strength of concrete Inhibition of concrete cracks Increasing the ductility of concrete Improving the durability of concrete
Carbon	Flooring Wavy Units, Wavy Separators, Boats' Body, Scaffolding Boards	Low specific weight High tensile strength Low coefficient of thermal expansion High resistance to corrosive chemicals High resistance to heat and fire High resistance to fluctuating loads
Nylon, Propylene	Piles, Pretensioned Piles, Façade Panels, Floating Units to Pass Evacuate Loads at Sea, Pavement Repair, Concrete Slabs, Surface Coating of Underwater Pipes	Very low weight Reducing costs Increasing bending, tensile and shear strengths Increasing wear and chemical resistance of concrete Decrease of thermal stresses Control of deep and superficial cracks in the final volume of concrete Increasing the concrete toughness Reducing breakage, cutting, and spalling of concrete during storage, handling, or delivery

The first steel fibers, used in concrete, were round and smooth. In recent years, the use of smooth fibers has become obsolete to a large extent. Most of the fibers currently being used have rough surfaces with two hooked ends or they are wavy along their length. These specifications improve the ability to resist pulling out fibers from cement-based matrices. Steel fibers have different shapes and diameters, and the way they are made is also different. Due to the malleability of steel, it is easy to fix the fibers in concrete. Accordingly, it is possible to produce different shapes of fibers, such as curved ends, hooked ends, wide tails, wavy ends, etc. Samples of steel fibers are shown in **Figure 1**.

Figure 1: Schematic of steel fibers in different shapes

One of the functions of steel fiber concrete in construction is the full-scale tunneling method's lining system, having been used mainly in Europe and Australia since the early 1990s (**Hansel et al., 2011**). These advantages have been highly beneficial, especially in prefabricated elements. In terms of structural aspects, fiber reinforcements have significantly enhanced the tensile strength of materials. Also, increasing the hardness and improving the crack propagation control are assumed as other applications of utilizing fibers in pre-fabricated parts (**Caratelli et al., 2011**).

The purpose of using steel fibers and reinforcements is different. Steel reinforcements are generally used to change the cracking characteristics of concrete when ruptures occur. In ordinary concrete under loading, microcracks are formed that become integrated and get more extensive with the continuation of loading. However, in fiber-reinforced concrete, the fibers connect the two sides of the crack like a bridge and prevent crack propagation. As a result, the presence of fibers affects the mechanical behavior of concrete. Concrete gets considerable strength after cracking by adding steel fibers so that its content can be considered in the designing phase (**Shokrchizadeh et al., 2014**).

According to the results obtained by Alwan et al. in 1999, using fibers with bent ends increases their pull-out strength compared to lying fibers (**Alwan et al., 1999**). Previous research shows that the presence of steel fibers does not significantly affect the compressive strength of concrete. However, because of the role of fibers in stitching the cracks, it prevents brittle rupture and failure of the sample. The failure of the fiber-reinforced concrete is associated with ductility, and the specimen maintains its continuity until failure (**Afshin et al., 2013**). The bending test can be assumed to obtain the endurance of concrete containing steel fibers. A load-displacement diagram is used to calculate endurance. Compared to plain concrete, the strength of fiber-reinforced concrete can increase significantly, depending on the volume of fibers, the aspect ratio, and the resistance between fibers and concrete. In high-strength concretes, due to the high bond strength between concrete and fibers, the fibers can get yielded before pulling out of the concrete. In this case, the expected final hardness capacity cannot be obtained (**Lee 2017**).

The use of steel bars and fibers in producing precast concrete segments has evolved significantly, especially in large sections (**De la Fuente et al., 2013**) and (**Plizzari et al., 2007**). In 1999, Konig and Kutzing performed tests on the specimens of plain concrete as well as fiber-reinforced ones and found that the latter provides significantly high compressive strength after cracking (**Konig et al., 1999**). Therefore, it can result in the prevention of lateral displacements owing to the existence of fibers in the concrete.

In 2012, Koksal et al. implemented the tests of compressive and tensile strengths as well as toughness considering the water-to-cement ratio of 0.45 and 0.70., so that the curved ends steel fibers were used with the volumetric percentage of 0.26, 0.51, and 0.78, as well as different appearance ratios for each of the mixing plans. The toughness of the concrete, including fibers, improves with an increase in the appearance ratio and the volumetric percentage of steel fibers. The highest toughness is obtained at about 1849 Joules, at which the water-to-cement ratio, fiber volumetric percentage, and appearance ratio are 0.45, 0.76, and 65, respectively. In addition, the toughness is acquired 1618 Joules when the variables mentioned above turn to 0.7, 0.78, and 80, respectively. The existence of fiber cannot recuperate the compressive strength significantly but can improve the tensile strength exceptionally (**Koksal et al., 2013**).

In 2018, Meng et al. investigated the mechanical properties of steel fibers and the cracks on precast concrete segments in a tunnel while loading in China. According to the results, the cracks' distance average increased by adding more fibers (30 kg/m^3) to the concrete. In addition, assuming equal loads, the width of the created cracks is smaller in concrete containing more steel fibers. In 2018, Zhang and Yun concluded that the difference between the tensile behavior of fiber concrete and plain concrete is quite evident by conducting compressive and tensile experiments on the former ones. Also, by adding fibers, the tensile strength of concrete increases (**Jang et al., 1999**). In 2018, Wasim Abbass et al. investigated the effect of bent steel fibers with various appearance ratios and volumetric percentages on concrete with different strengths. Ordinary concrete contains three water-to-cement ratios 0.25, 0.35, and 0.45 (**Abbass et al., 2018**).

In this study, the effect of steel fibers on the improvement of mechanical properties of precast concrete segments was investigated. Mechanical experiments were carried out to investigate how steel fibers can affect the concrete used in the segmental lining. To conduct the experiments, three types of 3D, 4D, and 5D steel fibers were utilized with volumetric percentages of 0.5%, 1%, and 1.5% in the concrete, respectively. In addition to examining the effect of these three types of fibers on the mechanical properties of concrete, analyzing the influence of the orientation of the fibers on the strength of the concretes used in precast concrete segments is one of the other issues discussed in this paper. Finally, an investigation was conducted on the influence of these three types of fibers on concrete slump, which is a significant parameter for concrete efficiency.

2. The specimens and experiments

Fiber-reinforced concrete specimens have been studied using different types and percentages of steel fibers to determine how they react to the applied forces. The compressive, tensile, and flexural experiments were done on 7- day and 28-day specimens. In this study, the compressive strength of upper 40 MPa and a slump of 10 to 12 cm was considered as a criterion to select the fiber-reinforced concrete mixture for further experiments, assuming the existing design presumptions of the Tabriz Metro Line-2 project. After experimenting on three different plans, mixing plan number 2 was selected as the final one (see **Table 2**). Sand and 5 mm gravel were chosen based on the ASTM C 136-848 standards for this study (see **Figure 2**).

This study used Portland type 2 cement. To enhance the efficiency and strength of concrete, polycarboxylate ether (Carboxal HF500) was utilized as a new-generation super-plasticizer in the mixture. The 3D, 4D, and 5D steel fibers in the experiments differ in appearance and the degree of bends at their ends. As shown in **Figure 3**, the mentioned fibers include two, three, and four

Table 2: The materials used in mixtures for each cubic meter

Constituent materials	**Mix Label**		
	1	**2**	**3**
cement (kg)	430	470	530
gravel (kg)	670	640	610
sand (kg)	1180	1160	1120
water (kg)	135	140	159
additive (kg)	2.5	2.5	3
w/c ratio	0.313	0.297	0.3

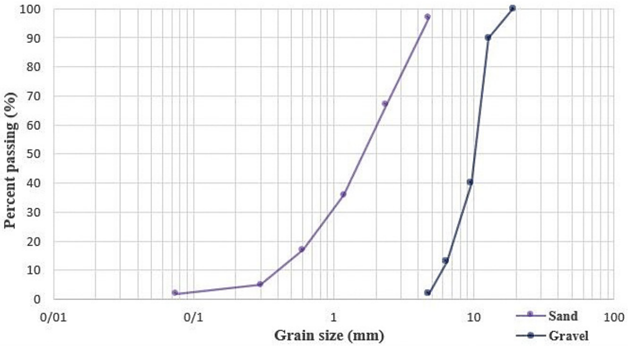
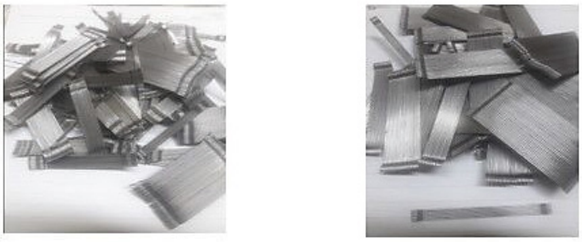


Figure 2: The grain size distribution of sand and gravel used in mixtures

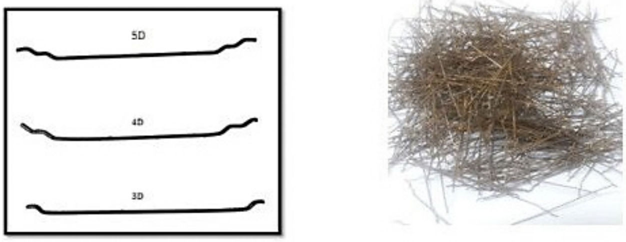
bends at both ends, respectively. The length and diameter of the fibers are the same, and only the number of fiber bends (3D fibers have two bends, 4D fibers have three bends, and 5D fibers have four bends at the end), which represents the effect of the shape of the fibers, is different. The characteristics of these three types of fibers are given in **Table 3** according to the catalog provided by their manufacturer. The fiber content used in concrete specimens was 25, 30, and 35 kg/m^3. In this study, the molds with dimensions of 15×15×15 cm and the prisms with a cross-section of 10×10 cm along with a length of 40 cm were utilized for compressive and flexural strength experiments, respectively. By conducting coring operations on the cubic specimens, the cylindrical ones were provided to do the tensile strength test. Both sides of the specimens were cut. The diameter and length of cylindrical samples were 54 mm and 130 mm, respectively.

Table 3: The utilized fibers' properties

Property	3D, 4D, 5D Fibers
Cross-section	Circle
Length (mm)	60
Diameter (mm)	0.9
L/D Ratio (Appearance Ratio)	66.66



4D Steel Fiber **3D Steel Fiber**



3D, 4D, 5D Steel Fibers **5D Steel Fiber**

Figure 3: The steel fibers

To examine the impact of fiber orientation, the fiber content of 30 kg/m^3 was used. Steel fibers were placed inside the concrete specimens in three directions vertical, horizontal, and oblique, to the main axis, connecting the ends of the specimens. After adding gravel, sand, and cement into the concrete mixer and mixing them for 30 seconds, water was added to this mix, and after a short time, the additives, mixed in the water, were added. After about 7 minutes, the concrete was placed into cubic molds. As the standard molding, concrete should be placed in three stages, and about 5 cm of concrete should be placed into the mold in each series. To create the specimens, including fibers with vertical orientation, first a 5cm layer of concrete was placed into the mold, and then the fibers were placed vertically inside it. The concrete compaction operation, which should be done every three stages, was carried out before placing the fibers in each row. Locating the fibers in the oblique form was done in the same way.

To construct specimens in cubic and prismatic molds similar to the ones mentioned above, firstly, cement, gravel, sand, and fibers were poured into the mixer. After mixing for 30 seconds, water and additive materials, dissolved in water, were added. The only difference from the previous condition is that the fibers are irregularly distributed inside the concrete.

To compact the cubic specimens, a square cross-section steel rod with dimensions of 25×25 mm was used after pouring each layer of concrete to provide 35 impacts on it. The impact should not be intense; otherwise it can cause the material inside the concrete to be damaged. After compacting the concrete with the steel rod, a plastic hammer was used to make a slight impact on each side of the mold. This was done for all the three pouring layers, and finally, a trowel was used to smooth the concrete surface (**British Standards, 2000**).

For the sake of compacting the prismatic specimens, a steel rod with a diameter of 5.8 mm was used. The concrete was poured in two layers in the prismatic molds, and each layer got impacted 28 times with the steel rod. Subsequently, a plastic hammer was used to hit each side of the mold slightly (**American Society for Testing and Materials, 2002**). The specimens were kept at a temperature of 18 to 22°C for 24 hours after molding. To prevent the specimens from evaporating, a wet sack was placed on them. The specimens were removed from the molds after 24 hours and placed in a 20°C water basin.

To investigate the concrete workability, the slump test was utilized. To perform this experiment, concrete was poured into the cone in 3 steps and compacted using a specific rod. Subsequently, the cone was slowly pulled upwards. After removing the cone, the concrete had some slump. Finally, the amount of concrete slump was measured, and the obtained number was introduced as the slump number (**International Organization for Standardization, 1980**).

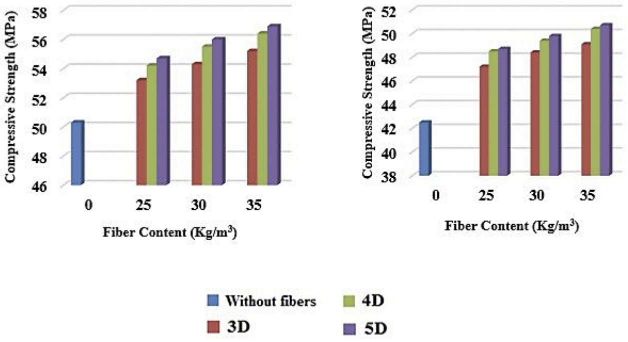
The compressive strength evaluation was done on the 7-day and 28-day concrete specimens. For the tensile strength test, the specimens prepared by the core drilling machine were used. The four-point flexural test was done to evaluate concrete flexural strength using specimens with dimensions of 40×10×10 cm.

3. Analysis of laboratory results and discussion

This section contains the results of compressive, tensile, flexural, and slump tests, presented and discussed. The processed concrete specimens were placed in the water basin, at a temperature of 20°C and, after 7 and 28 days, were taken out to perform the experimental tests on them, and the results are provided separately.

3-1. Effect of fiber content on compressive strength in mechanized tunneling

A comparison of all three types of steel fibers' compressive strength is shown in **Figure 4**. Plain concrete (without fibers) has a compressive strength of 42.5 MPa and 50.3 MPa after 7 and 28 days, respectively. According to **Figure 4**, it can be inferred that the compressive strength is not dependent on the type of steel fiber, having an equal amount in the specimens. However, the 5D steel fibers have the most effect, and the 3D one has the least effect on the compressive strength. However, it is not noticeable enough to be considered in the calculations. The Uniaxial Compressive Strength (UCS) increase amount for 3D, 4D, and 5D steel fibers is presented in **Table 4**. A plain concrete specimen ruptured entirely under the compressive force is shown in **Figure 5-a**, which demonstrates a wedge failure. The method of failure in specimens containing steel fibers is different from that of plain ones. Accordingly, the steel fibers prevent wedge failure in concrete specimens but cause the creation of cracks parallel to the loading direction. As illustrated in **Figure 5-b**, the existence of steel fibers can change the failure mechanism in the concrete specimens, and the greater the number of fibers, the greater their effect.



28-Days Compressive Strength

7-Days Compressive Strength

Figure 4: The variation of compressive strength of concrete without steel fibers and fiber-reinforced concrete using 3D, 4D, and 5D fibers

Table 4: The variation of concrete UCS, including steel fibers

Fiber content (kg/m^3)	The amount of UCS increased in 7-day steel fiber concrete in comparison to plain concrete (%)		
	3D Fiber	**4D Fiber**	**5D Fiber**
25	11	14	14
30	13	16	17
35	15	18	19
Fiber content (kg/m^3)	**The amount of UCS increased in 28-day steel fiber concrete in comparison to plain concrete (%)**		
	3D Fiber	**4D Fiber**	**5D Fiber**
25	5	7	8
30	7	10	11
35	10	12	13

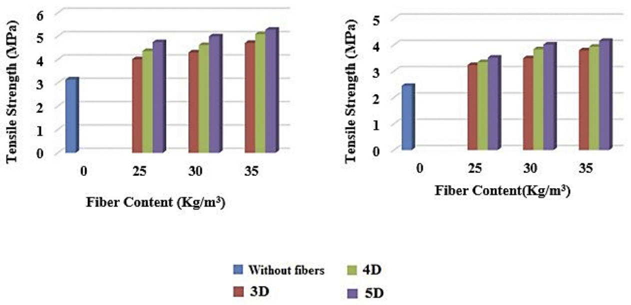
a. Without steel fibers

b. Including steel fibers

Figure 5: The failure mechanism of concrete under the compressive load

3-2. The investigation of steel fiber number effect on the concrete tensile strength in mechanized tunneling

The tensile strength of concrete after 7 and 28 days with three types of steel fibers, including 25, 30, and 35 kg/m^3 fibers, is presented in **Figure 6**. The tensile strength of plain concrete (without steel fibers) is 2.44 MPa and 3.14 MPa for 7-day and 28-day concrete, respectively. According to the figure, steel fibers improve the tensile strength of concrete containing steel fibers when added. The effect of each of the 3D, 4D, and 5D steel fibers on the tensile strength of concrete is different. In a certain number of utilized fibers, 5D, 4D, and 3D fibers have the greatest impact on the tensile strength of 7-day and 28-day concrete, respectively. For example, using the content of 35 kg/m^3 of steel fibers, 5D fibers increased the 28-day tensile strength of concrete by



28-day tensile strength 7-day tensile strength

Figure 6: Variation of steel fiber concrete tensile strength using 3D, 4D, and 5D fibers

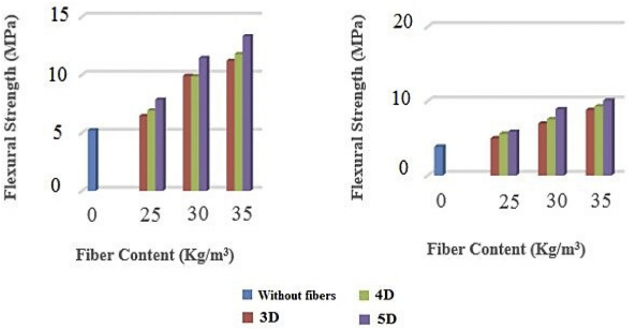
Table 5: The variation of concrete tensile strength, including identical steel fibers

Fiber content (kg/m^3)	The amount of tensile strength enhancement in 7-day steel fiber concrete in comparison to plain concrete (%)		
	3D Fiber	**4D Fiber**	**5D Fiber**
25	32	37	44
30	43	57	64
35	55	61	70
Fiber content (kg/m^3)	**The amount of tensile strength enhancement in 28-day steel fiber concrete in comparison to plain concrete (%)**		
	3D Fiber	**4D Fiber**	**5D Fiber**
25	27	36	51
30	37	47	59
35	50	62	68

a. Failure mode of plain concrete b. Failure mode of steel fiber concrete

Figure 7: The failure mode of plain and steel fiber-reinforced concrete in the Brazilian test

6% more than 4D fibers and 18% more than 3D fibers. On the other hand, increasing the number of fibers in concrete increases its tensile strength.



28-day flexural strength 7-day flexural strength

Figure 8: Variation of concrete flexural strength using 3D, 4D, and 5D fibers

Table 6: The variation of concrete flexural strength, including identical steel fibers

Fiber content (kg/m^3)	The amount of flexural strength enhancement in 7-day steel fiber concrete in comparison to plain concrete (%)		
	3D Fiber	**4D Fiber**	**5D Fiber**
25	29	45	51
30	79	94	129
35	127	139	160
Fiber content (kg/m^3)	**The amount of flexural strength enhancement in 28-day steel fiber concrete in comparison to plain concrete (%)**		
	3D Fiber	**4D Fiber**	**5D Fiber**
25	23	32	50
30	77	88	119
35	114	125	154

Steel Fiber-Reinforced Concrete Plain Concrete

Figure 9: The failure mode of plain concrete (without fiber) and steel fiber-reinforced concrete under the 4-point bending experiment

Table 5 shows the variation of steel fiber-reinforced concrete compared to the plain one. As it is evident, 5D fibers have the most influence on improving concrete tensile strength. In addition to the growth in the concrete tensile strength, the failure mechanism is changed while using steel fibers in concrete. The failure of plain concrete and the steel fiber-reinforced one in the Brazilian test is shown in **Figure 7**. In the Brazilian test, the concrete specimens, including steel fibers, show high strength when the first crack is created, and after that, the presence of fibers prevents them from further failure, in such a way that the fibers act like a bridge between the cracks and prevent crack propagation.

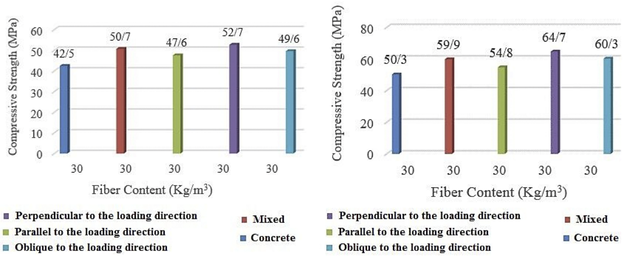
3-3. The investigation of steel fiber number effect on the concrete flexural strength in mechanized tunneling

In this section, the effect of fibers on the flexural strength of concrete in mechanized tunneling has been studied. **Figure 8** illustrates the effects of 3D, 4D, and 5D fibers in concrete on the 7-day and 28-day flexural strengths. Plain concrete has a flexural strength of 3.883 MPa at 7 days and 5.236 MPa at 28 days. The influence of 3D, 4D, and 5D steel fibers on the concrete flexural strength is presented in **Table 6**. As is evident, by increasing the number of fibers inside the concrete, its flexural strength is improved. On the other hand, it can result that the 5D steel fibers have the most effect on the flexural strength. Considering an identical content of 35 kg/m^3 of fibers, the increased amount of 28-day flexural strength using 5D, 4D, and 3D fibers is 154%, 125%, and 114%, respectively. 5D fibers affect the flexural strength of concrete by 29% more than 4D fibers and 40% more than 3D fibers.

Under the bending test, **Figure 9** shows the failure modes of plain concrete and steel fiber-reinforced concrete. To illustrate the application of fibers, the crack of residual concrete was opened with a specific tool. When plain concrete is under a 4-point bending experiment, it fails suddenly; however, when using steel fibers as the reinforcement inside the concrete matrix, the failure starts with cracks, and does not happen suddenly. Fibers in concrete increase flexural strength and prevent crack propagation.

3-4. The influence of 5D steel fiber orientation on the compressive strength of concrete in mechanized tunneling

In this part of the study, the influence of 5D steel fiber orientation on concrete in mechanized tunneling has been analyzed. **Figure 10** shows the 7-day and 28-day compressive strength of concrete using various orientations of 5D steel fibers, distributed inside the concrete, with a content of 30 kg/m^3. According to the diagram, it is determined that the maximum compressive strength is obtained when the fibers are perpendicular to the loading direction compared to the other modes. The variation of concrete compressive strength using 5D steel fibers in specific directions is presented in **Table 7** compared to



7-day Compressive Strength

28-day Compressive Strength

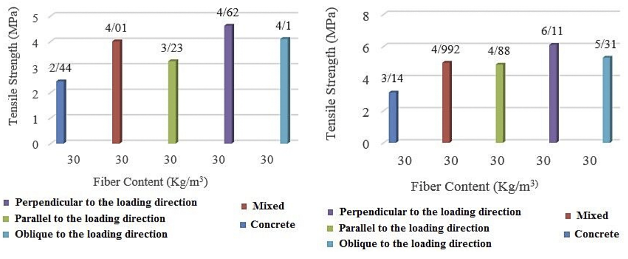
Figure 10: The effect of 5D steel fibers' orientation on the 7-day and 28-day compressive strength of concrete

Table 7: The variation of concrete compressive strength using 5D steel fibers in a specific direction

Specimen	Orientation	Fiber Content (kg/m^3)	Increased 7-day strength (%)	Increased 28-day strength (%)
1	Mixed	30	19	13
2	Parallel to the loading direction	30	12	8
3	Perpendicular to the loading direction	30	24	29
4	Oblique	30	17	20

Table 8: The variation of concrete tensile strength using 5D steel fibers in a specific direction

Specimen	Orientation	Fiber Content (kg/m^3)	Increased 7-day strength (%)	Increased 28-day strength (%)
1	Mixed	30	64	59
2	Parallel to the loading direction	30	32	55
3	Perpendicular to the loading direction	30	89	94
4	Oblique	30	68	69



7-day Compressive Strength

28-day Compressive Strength

Figure 11: The effect of 5D steel fibers' orientation on the 7-day and 28-day tensile strength of concrete

plain concrete. Accordingly, when the fibers are perpendicular to the loading direction, the 28-day compressive strength is significantly increased by about 29% compared to the plain concrete.

The variation of concrete tensile strength using 5D steel fibers in a specific direction is provided in **Table 8**. As is evident, the presence of fibers inside the concrete increases its tensile strength considerably. However, this enhancement mainly occurs when the orientation of fibers is perpendicular to the cracks. In this case, the 28-day tensile strength of concrete grows by about 94%. The 7-day and 28-day tensile strength of concrete using 5D steel fibers with specific orientations are demonstrated in **Figure 11**.

3-5. *Slump Experiment results*

According to **Table 9**, the slump amount for the plain concrete (without fibers) is 15 cm. If steel fibers are used, the amount of slump decreases by about 3 to 5 cm. In addition, it can result that the 3D, 4D, and 5D steel fibers do not affect the concrete slump. **Figure 12** illustrates slump test results for plain concrete, 3D, 4D, and 5D steel fiber-reinforced concrete. Adding steel fiber to concrete reduces the slump compared to the sample without fiber.

Table 9: The slump test results in centimetres

Fiber Content (kg/m³)	Plain Concrete	Concrete with 3D steel fibers	Concrete with 4D steel fibers	Concrete with 5D steel fibers
0	15	-	-	-
25	-	12	12	12
30	-	12	12	11
35	-	10	10	10

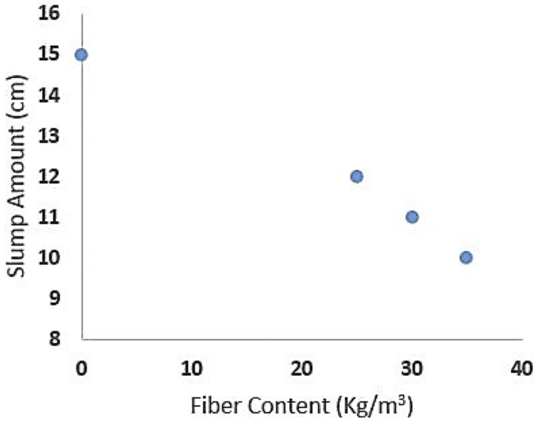


Figure 12: Slump test results for plain concrete and fiber-reinforced ones.

4. Conclusion

In this study, the effect of fiber shape on the mechanical properties of precast concrete used as segmental lining in mechanized tunneling was investigated. The three types of steel fibers (3D, 4D, and 5D) used have no difference in the length and diameter of the fibers and only differ in the number of bends at both ends (3D fibers have two bends, 4D fibers have three bends and 5D fibers have four bends at the end). The results of the experimental studies show that:

- The compressive, tensile, and flexural strengths of concrete are increased when steel fibers are added.
- Compressive strength increases by 19% for 7-day concrete and 13% for 28-day concrete.
- The effect of 3D, 4D, and 5D steel fibers on the compressive strength of concrete does not vary significantly from one another, and the maximum difference between them is about 3% while using equal content of them inside the concrete.
- The 7-day compressive strength of steel fiber-reinforced concrete exceeds plain concrete's 28-day strength.
- Steel fibers make the concrete rupture mode different from plain concrete in the compressive strength experiment, so that fibers prevent crack propagation and concrete fragmentation in mechanized tunneling.
- Steel fibers make the concrete rupture mode different from plain concrete in the tensile strength experiment, so that fibers prevent sudden failure of concrete in mechanized tunneling.
- 5D, 4D, and 3D fibers provide the greatest effect on the tensile and flexural strength of steel fiber-reinforced concrete, respectively.
- The presence of steel fibers makes the concrete rupture mode different compared to plain concrete in the flexural strength experiment so that fibers prevent sudden failure of concrete in mechanized tunneling.
- Fibers' orientation provides a significant influence on the compressive strength of the concrete in mechanized tunneling, so that if the fibers are located inside the concrete perpendicular to the loading direction, the most influence on the compressive strength is obtained.

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SAŽETAK

Utjecaj čeličnih vlakana na poboljšanje mehaničkih svojstava betonske segmentne obloge

Sustav obloge koji se koristi u strojevima za bušenje tunela izrađen je od predgotovljenih betonskih segmenata. Upotreba čeličnih vlakana u ovoj vrsti potpornoga sustava ne samo da može smanjiti vrijeme i troškove proizvodnje, već također može poboljšati tlačna, vlačna i savojna svojstva. U ovoj studiji istražen je učinak triju vrsta (3D, 4D i 5D) čeličnih vlakana na mehanička svojstva segmenata u projektu linije 2 metroa Tabriz. U tu svrhu provedeni su pokusi tlačne, vlačne i savojne čvrstoće te test slijeganja. Rezultati su potvrdili poboljšanje mehaničkih svojstava uzoraka zbog prisutnosti ove vrste čeličnih vlakana, a također povećanjem sadržaja vlakana 28-dnevna tlačna, vlačna i savojna čvrstoća uzoraka povećava se za 13 %, 68 % odnosno 154 %. Osim toga, provođenjem ispitivanja orijentacije čeličnih vlakana utvrđeno je da se pomoću njih može povećati tlačna čvrstoća betona za oko 18 %, tako da postavljanje vlakana u smjeru okomitom na opterećenje ima najveći učinak.

Ključne riječi:
segmenti, čelična vlakna, mehanička svojstva betona, pukotine, test slijeganja

Author's contribution

Hamid Chakeri (1) (Ph.D., Associate Professor) proposed ideas and guided the research. **Mohammad Darbor (2)** (Ph.D., Assistant Professor) guided the research. **Farid Sh. Maleki (3)** (MSc of Mining Engineering) Performed experimental tests and **Tohid Minaee (4)** (MSc of Mining Engineering) processed their results.