ESCUELA DE CONSTRUCCIÓN CIVIL
FACULTAD DE INGENIERÍA
Revista de la Construcción
Journal of Construction

Research Article

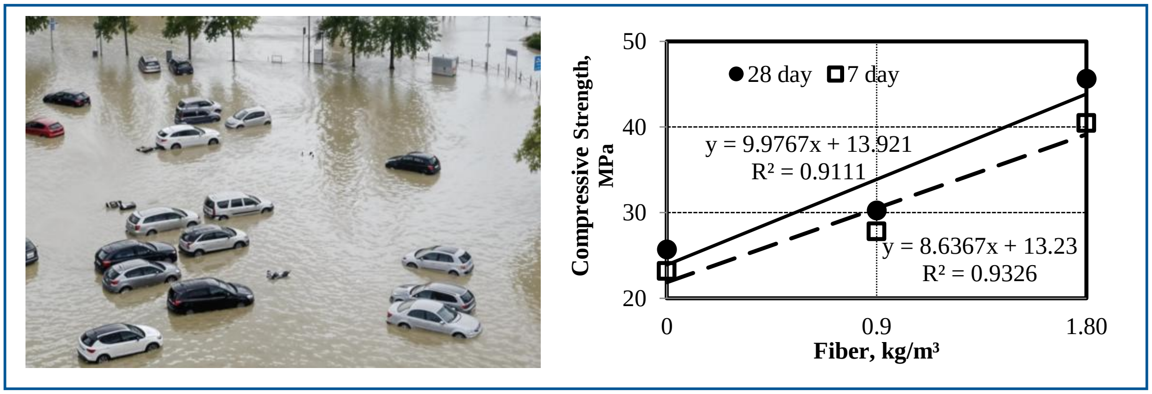
Effect of polypropylene fibers on strength and durability of permeable concrete road as urban drainage alternatives

Nuh Mehmet Polat [1], **Polat Yalınız** [2, *]

[1] Kutahya Dumlupinar University, Institute of Graduate Education, Kutahya (Turkey); nuhmehmetpolat@gmail.com
[2] Kutahya Dumlupinar University, Department of Civil Engineering, Kutahya (Turkey); polat.yaliniz@dpu.edu.tr
*Correspondence: polat.yaliniz@dpu.edu.tr

Received: 04.10.24; **Accepted:** 19.02.26; **Published:** 10.03.26

Citation: Polat, N. and Yalınız, P. (2026). Effect of polypropylene fibers on strength and durability of permeable concrete road as urban drainage alternatives. Revista de la Construcción. Journal of Construction, 25(1), 171-192. https://doi.org/10.7764/RDLC.25.1.171



Highlights:

- A new drainage method with fiber-reinforced permeable concrete is proposed.
- Polypropylene fibers significantly increase concrete mechanical strength.
- FRPC pavements support urban drainage and improve road safety.
- Fibers enhance residual strength and crack resistance in permeable concrete.

Abstract: Rapid urbanization and the global climate crisis have intensified the challenges of sustainable transportation and urban drainage. Inadequate storm water infrastructure in many developing cities often results in severe water accumulation on road surfaces, increasing the risk of aquaplaning and freeze-related accidents. This study investigates fiber-reinforced permeable concrete (FRPC) as an alternative rigid pavement material capable of enhancing both drainage capacity and structural performance. Experimental mixtures incorporating polypropylene fibers at 0.5–1.0 kg/m³ were evaluated in terms of mechanical strength, durability, and permeability. The results demonstrated that the inclusion of fibers increased compressive strength by up to 77%, splitting tensile strength by 65%, and flexural strength by 40%, while abrasion resistance was significantly improved. However, permeability decreased slightly with fiber addition, and freeze–thaw resistance remained limited. Microstructural analyses confirmed that fiber bridging contributed to improved crack control and residual strength. The findings suggest that FRPC can effectively mitigate surface water accumulation and improve road safety, particularly in light-traffic areas, pedestrian and bicycle paths, and parking facilities. Overall, unlike previous studies, it explicitly addresses the simultaneous optimization of drainage capacity and mechanical performance, providing a novel integrated approach to FRPC as a sustainable pavement solution. Polypropylene fiber reinforcement provides a practical and sustainable approach to balancing permeability with mechanical durability in pavement design tailored to urban drainage needs.

Keywords: Permeable concrete, polypropylene fiber, strength, durability, drainage.

List of abbreviations:

TS: Turkish standard

EN: European norm

ACI: American Concrete Institute

ASTM: American Society for Testing and Materials

SEM: Scanning electron microscopy

EDS: Energy dispersive x-ray spectroscopy

FRPC: Fiber-reinforced permeable concrete

C-S-H: Calcium silicate hydrate

ITZ: Interfacial transition zone

CS: Compressive strength

STS: Splitting tensile strength

FS: Flexural strength

FTR: Freeze-thaw resistance

UPV: Ultrasonic pulse velocity

UW: Unit weight

BAR: Bohme abrasion resistance

$Ca(OH)_2$: Calcium hydroxide

PF: Polypropylene fiber

1. Introduction

Rapid urbanization has led to the proliferation of impervious surfaces such as asphalt pavements, parking lots, and sidewalks. These surfaces prevent rainwater from naturally seeping into the ground, leading to puddles, flooding, and safety risks in urban areas. In cold climates, the freezing of accumulated water further increases hazards such as slippery conditions and aquaplaning. These problems become even more critical in underdeveloped regions where sewage systems are inadequate for managing rainwater. Fig.1 shows examples of such a situation.

Figure 1. Cars stuck on the road after heavy rain (Evrensel, 2019; Norm Haber, 2023).

Considering the issue in terms of transport, the type of surfacing has a direct impact on the safety and comfort of driving on motorways. As there is a dependency on foreign raw materials for flexible pavements, there is an alternative to producing rigid pavements with domestic raw materials. Rigid pavements vary with concrete types with different properties and construction methods with different properties. There are many studies on the use of rigid pavements on roads. However, when it is desired to increase the water permeability of these rigid pavements, problems such as reduced strength are encountered. Therefore, if concrete roads are required to be both permeable and to have a certain strength, other additions to the mix are required. Of course, since the materials added to the concrete can only achieve a certain strength, it is not possible to use the strength achieved in all climates and on all roads. In this study, the conditions for fiber reinforced permeable concrete (FRPC) roads have been investigated and conclusions have been drawn as to where FRPC roads can be used with the strengths that can be achieved. For a better understanding of the subject, the definition of the problem, the difficulties encountered, and the proposed solution methods are shown in Table 1.

Table 1. Definition of the problem and summary of the research focus.

Problem/context	Challenge	Proposed approach
Urbanization increases impervious surfaces	Flooding, ponding, aquaplaning, freezing hazards	Develop permeable concrete pavements
Conventional permeable concrete	Reduced mechanical strength	Introduce fiber reinforcement (polypropylene)
Asphalt pavements	High dependency on imported materials	Promote rigid pavements with local raw materials
Research gap	Limited studies on combined drainage and strength performance of FRPC	Experimental study on strength, durability, and permeability

The study is also expected to contribute to sustainable development and improve the relationship between urban growth and stormwater drainage. Miguez et al. looked at the interaction between urban growth and stormwater management using a case study of the Rio de Janeiro metropolitan area (Miguez et al., 2014). With the increasing use of wheeled vehicles in many transport applications, the need to create surfaces that ensure comfort and safety has also increased. In order to meet this need, many studies have been carried out over time and different types of superstructures have been developed. These are made in three different ways: rigid (concrete), flexible (asphalt) and mixed (Tanrıverdi, 2013). Concrete pavements have become an important alternative to asphalt pavements for today's modern roads with innovations and rapid developments such as slipform, permeable concrete, fiber concrete, pre-stressed concrete, continuously reinforced concrete and the ready-mixed concrete industry due to the rapid development of concrete technology (THBB, 2003).

This study investigates the possibility of using fibers in permeable concrete for road paving and examines its applicability in urban construction. Unlike previous studies that primarily focused on either the hydraulic performance of permeable concrete or the mechanical contribution of fibers separately, this research evaluates both aspects together under the same experimental program. By analyzing the effects of polypropylene fiber addition on strength, durability, and permeability simultaneously, the study highlights the dual contribution of fiber-reinforced permeable concrete to urban drainage and transportation infrastructure.

Some water and Portland cement are applied to create a paste that forms a thin coat around aggregate particles but leaves free spaces between them and hence, pores are formed in pervious concrete. In view of its unique porous structure, it presents the characteristics of air permeability, water permeability, and low self-weight (Qin et al. 2016; Huang et al. 2010) The reason why concrete roads are preferred can be summarized as follows (Kozak, 2011):

- Long structural life
- Being economical
- It can be applied in all conditions in all seasons.
- Being environmentalist
- 100% local raw material
- Saving fuel
- Being durable
- Providing shorter stopping distance
- Lower investment cost
- Facilitates night vision

Features such as the removal of rainwater coming from the road and visibility conditions at the time of precipitation are effective on comfort and safety. The water film that will form on the road surface during rain increases the risk of aquaplaning by reducing the frictional resistance between the wheel and the surface. Precipitation waters on the pavement surface can be removed by flowing to the sides with a transverse slope, and it can be removed more quickly by constructing the pavement of the road permeable (Tanrıverdi, 2013). The reason for the decrease in vehicle cruising speed during precipitation is the uneasiness caused by the water splashing of the vehicles in front, the decrease in the visibility of the drivers of the vehicles behind and the increase in the braking distance. Permeable pavements significantly reduce vehicle splashing as they do not allow water to accumulate on the road surface. In addition, since the hollow surface and internal structure of this type of pavement absorbs a substantial part of the noise generated by the traffic, the noise disturbing the environment caused by the vehicles and their movements is less than the normal impermeable pavement (Ceylan, 1999).

The first studies on permeable pavements were made in England in 1967 under medium traffic conditions, then the situation under heavy traffic conditions was investigated. It has also been used on highways and airports in Denmark and Norway. It has been applied at the military airport in Dallas in the USA and on highways in the Netherlands. In France, Nantes was investigated on the trial road, and permeable pavements were applied in the city of Paris and on intercity roads (Ceylan, 1999). These studies are mostly in the field of porous asphalt, and serious studies on porous concrete started in the USA and Japan in the 1980s (Ghafoori, Dutta, 1995).

Permeable concrete pavement is a type of concrete with a void amount of 15-25% in general and its gaps are interconnected as much as possible. By not placing the fine part of the aggregate completely or partially, voids are created in the concrete. In order to provide a certain adherence on the wet road surface, it is necessary to prevent water accumulation on the surface. For this reason, thanks to the newly developed permeable concrete coating, the incoming rainwater enters the coating and reaches the drainage system. It has advantages and disadvantages arising from the cavity structure (Tanrıverdi, 2013).

Void ratio and permeability; it is generally accepted that the compressive strength and other mechanical properties of porous concrete are related to the void ratio. The presence of voids acts as a weakness in the cement matrix. Porous concrete is generally designed to contain between 15 and 35 percent air voids. The voids are both interconnected and large enough to allow water to pass through (McCain, Dewoolkar, 2010).

Many studies have been carried out to improve the performance of porous concrete. To give an example of these studies; talc, quartz, and lime sand have been used to improve the performance of porous concrete. The study results showed that talc, an environmentally friendly additive, is acceptable for improving the properties of porous concrete. (Azad, et al. 2019)

Permeability is related to the amount of water that passes through the pavement in free flow. Porous concrete has high permeability. The permeability of porous concrete is expressed in cm/second. The permeability of porous concrete increases exponentially as the void ratio increases (Schaefer, et al. 2006).

The mechanical and durability properties of permeable concrete and fibrous-permeable concrete used as coating materials in rigid pavements were investigated. The aim of this investigation was to reduce the risks associated with water accumulation and freezing-related accidents on road surfaces.

Reinforcing concrete with fibers is an effective way of increasing the resistance and ductility of concrete to cracking. (Kozak, 2013) Cracks in fiber concrete are prevented from growing and spreading by the bridging effect of the fibers. As steel fibers are not flexible, the bonding effect between aggregate grains is less than that of plastic fibers. This is because steel fibers are rigid and plastic fibers are flexible. In another study conducted to determine the size, type and number of fibers used in concrete, it was found that small polypropylene fibers can be used to prevent small cracks due to dynamic loading. However, if the concrete is subject to splitting and cracking under the loads to which it is subjected, it is seen that it would be more appropriate to use steel fibers or polypropylene fibers with a long structure. Polypropylene fibers used for this purpose should be used more densely (30%) in the concrete (Qian, Stroeven, 2000).

Another study of polypropylene fiber concrete using electron microscopy clearly showed the network structure formed by the polypropylene fibers in the concrete. It was also concluded that polypropylene fibers significantly reduced $Ca(OH)_2$ formation and the void ratio of the concrete. Furthermore, as a result of microscopic investigations, it was understood that the fiber ratio to be used in concrete should not exceed 0.9-1.0 kg/m³. In other words, the optimum value for the use of polypropylene fibers is 1 kg/m³. After microscopic examination, the fiber-containing concretes were subjected to mechanical tests such as compression, bending and splitting tensile tests, and strength increases of up to 20% were recorded. As a result of the microscopic experiments, it was observed that polypropylene fibers prevent capillary cracking in concrete, possible cracking, and segregation between aggregate and cement paste (Sun, Xu, 2009).

Previous studies on fiber-reinforced road concrete have reported varying results, mainly due to differences in fiber types and mixture compositions. (Ünal, 2003) reported that the abrasion resistance of polypropylene fiber concrete was lower than that of fiber-free concrete, whereas (Can, et al. 2009) reported that the abrasion resistance of polypropylene fiber concrete was higher. Moreover, little attention has been paid on the interfacial transition zone (ITZ) of pervious concrete. Thus, the crystalline phase, pore characteristic, film thickness and characteristic in the ITZ were also investigated to explore the relative mechanism. These results will provide a systematic reference for polypropylene fibers application in pervious concrete (Wu, et al. 2023).

Recent studies have investigated the mechanical and durability performance of fiber-reinforced cementitious materials under environmental loading conditions. Wu et al. (2024) examined the arresting properties of polypropylene fiber-reinforced foamed concrete subjected to wet–dry cycles and reported that fiber addition improved crack resistance and mechanical stability, although durability-related limitations remained under cyclic environmental exposure. Similarly, Sreekumara Ganapathy et al. (2025) employed regression-based modeling approaches to predict the mechanical behavior of polymer hybrid fiber-reinforced concrete and highlighted the influence of fiber combinations on strength development. However, these studies primarily focused on either durability performance or mechanical characterization, without explicitly addressing the combined optimization of permeability, mechanical performance, and durability in permeable pavement applications. In contrast, the present study evaluates polypropylene fiber-reinforced permeable concrete by simultaneously assessing drainage capacity, mechanical strength, durability, and microstructural characteristics, thereby addressing an important research gap in urban drainage pavement design.

Despite the growing body of research on pervious concrete and fiber-reinforced concrete, most existing studies have focused either on hydraulic performance or mechanical behavior independently. Limited attention has been given to the simultaneous evaluation and optimization of drainage capacity, mechanical strength, durability, and microstructural characteristics of polypropylene fiber-reinforced permeable concrete (FRPC), particularly in the context of urban pavement applications exposed to light traffic and environmental effects. Moreover, the interaction between fiber dosage, permeability reduction, and durability limitations such as freeze–thaw resistance remains insufficiently explored.

Therefore, the main objectives of this study are as follows:

(i) to quantify the effects of polypropylene fiber dosage on the mechanical strength, durability, and permeability of permeable concrete.

(ii) to relate the macro-scale mechanical and durability performance to microstructural observations obtained through SEM and EDS analyses.

(iii) to propose suitable application ranges and pavement section recommendations for fiber-reinforced permeable concrete in urban drainage systems.

The remainder of this paper is organized as follows: Section 2 describes the materials and experimental methods; Section 3 presents and discusses the experimental results; and Section 4 summarizes the main conclusions and provides recommendations for future research.

2. Experimental study

Ordinary Portland cement (CEM I 42.5 R) conforming to EN 197-1, supplied by Çimsa Cement Plant (Eskişehir, Türkiye), was used (Table 2). Super plasticizer (Master Glenium-ACE 450) was used at ratios of 1% by weight of cement. The virgin Polypropylene fibers (PF) had a specific gravity of 0.91, tensile strength and elastic modulus of 450-700 and 3000-3500 MPa respectively. Fibers had a uniform circular cross section with a diameter of 18–20 µm in diameter and 19 mm in length.

Table 2. Properties of cement used in experiments.

Chemical composition (%)		Physical properties	
CaO	62.50	Blain fineness (cm²/g)	3172
Al_2O_3	5.59	Specific gravity	3.15
Fe_2O_3	3.09	Initial setting	1 h 58 min
SiO_2	20.32	Final setting	2 h 57 min
MgO	1.74	Lechatelier soundness (mm)	2
K_2O	0.91	Compressive strength (MPa)	
Na_2O	0.34	2-day	30.8
SO_3	3.29	7-day	39.5
LOI	1.18	28-day	56.0

Two dosages (0.5 and 1 kg/m³) were investigated. Individual fibers were removed from the bundles prior to addition into the dry concrete mix. Control (with no PF) and two mixtures with 0.5 and 1 kg/m³ PF were constituted using 0.03 m³ rotating-drum mixer. Materials used in concrete mixture, were given in Table 3. As an example, PF-0.5 represents the pervious concrete series produced with 0.5 kg PF for 1 m³ concrete. Standard curing was applied to the samples. Pervious concrete pavement produced with little or no fine aggregates in the mixture. Without fine aggregates, the bonding effect of the concrete structure will have decreased.

Table 3. Material contents (kg) used in concrete production of 1 m³.

Series	Cement	Water	Admixture	Fiber	Aggregate composition			
					0-0.25	0.25-1	1-2	8-12
C	415	125	4.15	-	130	265	265	1000
PF-0.5	415	125	4.15	0.5	130	265	265	1000
PF-1	415	125	4.15	1	130	265	265	1000

Slump (S), permeability (P), unit weight (UW), ultrasonic pulse velocity (UPV), compressive strength (CS), splitting tensile strength (STS) and flexural strength (FS) Bohme abrasion resistance (BAR), freeze-thaw resistance (FTR), chemicals resistance (CR) tests and SEM observations were conducted on each series considering the standards and specimen properties summarized in Table 4.

Table 4. Experimental procedures

Test	Standard	Specimens for each series	Specimen dim., cm	Test age
S	TS EN 12350–2	3	Abrams's cone	After mixing
P	ACI 522R–06'	6	10x20	7-28
UW	TS EN 12390-7	6	15x15x15	7-28
UV	ASTM C 597	6	15x15x15	7-28
CS	TS EN 12390-3	6	15x15x15	7-28
STS	TS EN 12390-6	6	15x30	7-28
FS	TS EN 12390-5	6	5x15x60	7-28
BAR	TS 2824	6	10x10x10	7-28
FTR	ASTM C666	6	10x10x10	7-28
CR		6	10x10x10	7-28
SEM		1	Fracture surface	28

2.1. Preparation of permeable and fibrous-pervious concrete mixtures

Considering the previous studies in the experimental study, the water/cement (w/c) ratio was determined as 0.3, since it was aimed to obtain a dry-dense consistency concrete mixture. Based on previous studies, it has been observed that the strength of permeable concrete is low due to its porous structure. In addition to the selected w/c ratio, the aggregate/cement (a/c) ratio was determined as 4.0. In all concrete mixtures, the w/c ratio and a/c ratio were kept constant, and the mixtures were formed with a cement dosage of 750 kg/m³. First of all, permeable concrete specimens were poured as control specimens at the w/c ratios stated above for each test without using polypropylene fiber, and it was tried to obtain information about the concrete mixtures formed by crushing on the 7th day. Since the results obtained are suitable for the continuation of our experimental studies, serial castings have been started.

A minimum of 3 specimens were used for each test and the results were obtained by taking the averages. In addition to the above w/c and a/c ratios, polypropylene fibers were added to the concrete mixes in two different proportions to evaluate the performance of using different fiber proportions. In the mixes, polypropylene fibers were added to the concrete mixes at 0.9 kg/m³ and 1.8 kg/m³ as recommended by the manufacturer. The mixes were prepared as cubic, cylindrical and prismatic specimens considering the above-mentioned w/c, w/c and fiber ratios. Before preparing the concrete mixes and placing them in the molds, the consistency of the concrete mixes was checked by performing the slump test. The specimens removed from the molds were placed in the curing pool and fresh concrete, hardened concrete and durability tests were carried out on the 7th and 28th day. In addition, Schmidt hammer and ultrasonic pulse tests were carried out on all concrete specimens to provide information on the surface hardness and void ratio of permeable and fibrous permeable concretes.

The slump test was carried out on fresh concrete. Compressive strength, splitting tensile, bending tensile, abrasion resistance, freeze-thaw, chemical resistance, and permeability tests were conducted for each concrete group. The permeability capacity of permeable concrete was determined by the technique recommended in ACI 522R-06 (ACI Committee, 2006). The device used in this work was a transparent acrylic cylinder with open ends and diameter of 10 cm. A tick mark with a spacing of 50 mm was marked in the device front, and a 30 cm long ruler was placed on the inner wall of the device to accurately determine the liquid level drop distance. To ensure that the water penetrates only in the vertical direction in pervious concrete, sides of pervious concrete were firstly sealed with cement paste. And then the water permeable instrument was placed on the permeable stable and the sealed pervious concrete was placed on the permeable meter. Water was added to permeable meter until its surface far exceeded the first tick mark. When the liquid level dropped to the second tick mark, it starts to count as t1, and when the water level dropped to the required tick mark, the time is t2. The water permeability coefficient is calculated according to ACI 522R–06. The permeability test setup used in this study, based on the ACI 522R–06 procedure, is shown in Fig. 2.

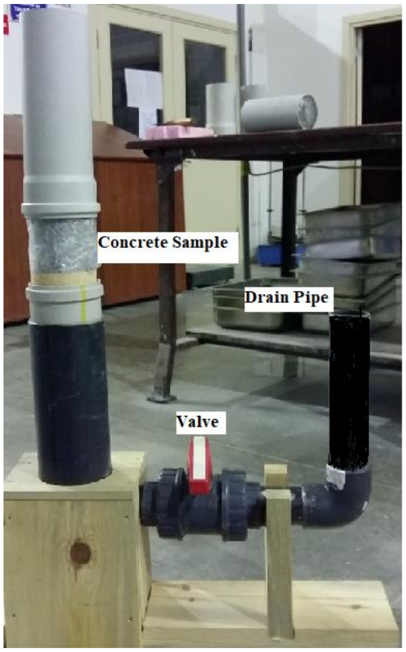


Figure 2. Falling-head permeability apparatus used in this study based on the ACI 522R–06 method.

3. Results and evaluation

3.1. Fresh concrete test results

3.1.1. Slump test results

Fig. 3 shows the slump test results of permeable concrete mixes. As the fiber increased, the slump value decreased. In Fig. 3, it was observed that the slump value decreased. The reason for this is that the fibers make it difficult for the concrete to settle, resulting in a decrease in workability and thus a decrease in consistency. Our study shows that the slump was 0 when the fiber ratio was 1.8 kg/m³. The variation of fresh concrete workability with fiber content was measured according to TS EN 12350–2, and the results were plotted against fiber dosage. A linear regression analysis was performed in Excel using the least-squares method, resulting in the equation $y = -7.5x + 23.333$ ($R^2 = 0.9643$). This equation indicates that slump decreases with increasing fiber content.

The volume incorporation rates of the polypropylene fibers used are low. In most cases it is limited to 0.1%. The fiber addition rate and the amount of air vary with the minimum workability. Fibers can be added in ready-mix plants or on site. Fibers should be mixed for at least 10 minutes after addition. Some researchers have experimented with 2% by volume. Various precautions should be taken when adding excessive proportions. If no precautions are taken, the workability of the concrete will decrease, and the amount of air will increase. The workability problem can be solved by increasing the dosage of water reducing admixtures. Air content can be controlled. The workability is reduced more with pulp fibers than with single fibers. This is because single fibers are easier and more homogeneous to disperse in the mix and the workability is better. The length of the fibers plays an important role. When the fibers are in pulp form, their length is limited to a few mm. The incorporation rate by volume is 5% of the mix. Generally, 12~50 mm is used (Acun, 2000).

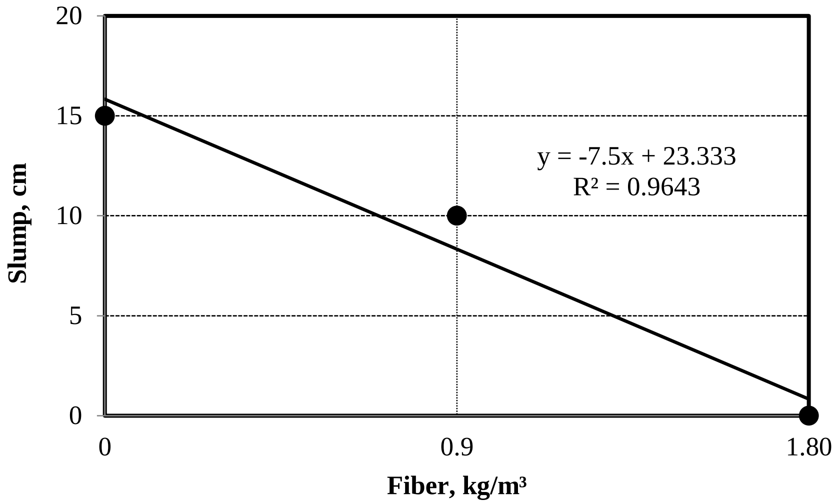


Figure 3. Slump test result of pervious concrete mixtures.

Fig.4 shows the unit weight tests of permeable concrete. When the unit weight tests were examined, it was observed that the unit weights increased up to 2.3 % with the increase in fiber. The fiber added to the mixture afterward partially filled the gaps and increased the unit weight. Unit weight values measured in accordance with TS EN 12390–7 was plotted against fiber dosage. A linear regression analysis yielded two equations: $y = 23.611x + 2129.7$ ($R^2 = 0.9906$) and $y = 16.927x + 2136.1$ ($R^2 = 0.9543$). Both regression lines indicate that the addition of fibers partially fills the voids and results in an increase in unit weight.

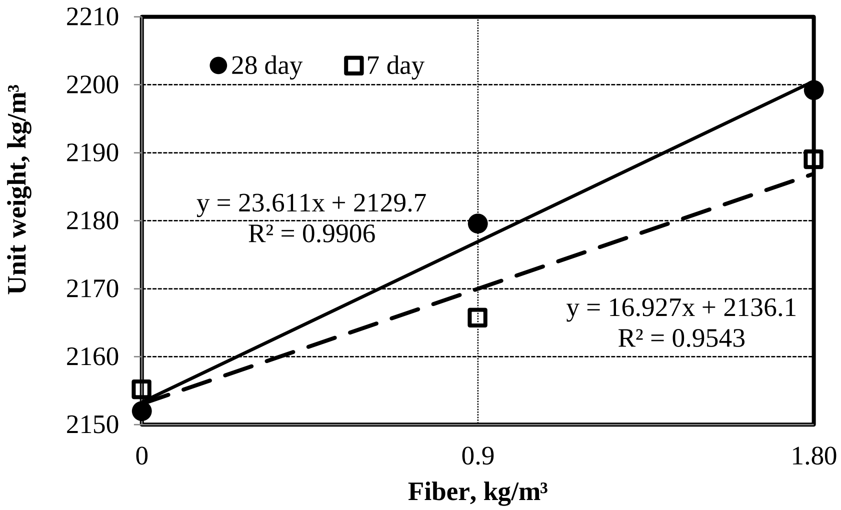


Figure 4. Unit weight of pervious concrete specimens.

From the result of this research, it was found that the use of fiber in the concrete decreases the workability of the fresh concrete Evidence of low workability was shown through the results of workability test obtained in standard slump test. It was concluded that the increasing percentage volume of fiber added into the concrete would lead the workability decreased. High volume dosage rate above 1.0% showed that the concrete was significantly stiff and difficult to compact. However, it also reduced the bleeding and segregation in the concrete mixture (Milind, 2015)

3.2. Hardened concrete test results

3.2.1. Ultrasonic pulse test results

Ultrasonic pulse test described in ASTM C 597 was applied to cube, cylinder and prismatic specimens and the results were recorded and a comparison was made between permeable concrete specimens and fibrous-permeable concrete specimens. Using this value, an idea about the void ratio of the concrete can be obtained. Ultrasonic pulse velocity values of permeable concrete specimens are shown in Fig.5. When Fig.5 is examined, decreases in values reaching 10% were observed between fiber increase and ultrasonic pulse velocity. Because the fiber reduces the workability of the concrete and partially prevents the transmission of the vibration. Ultrasonic pulse velocity tests were carried out in accordance with ASTM C597-09 (ASTM International, 2009). The measured values were plotted against fiber dosage and subjected to linear regression analysis. The obtained equations were $y = -0.1798x + 4.4271$ ($R^2 = 0.8253$) and $y = -0.1697x + 4.2353$ ($R^2 = 0.7721$). These results demonstrate that increasing fiber content reduces ultrasonic pulse velocity.

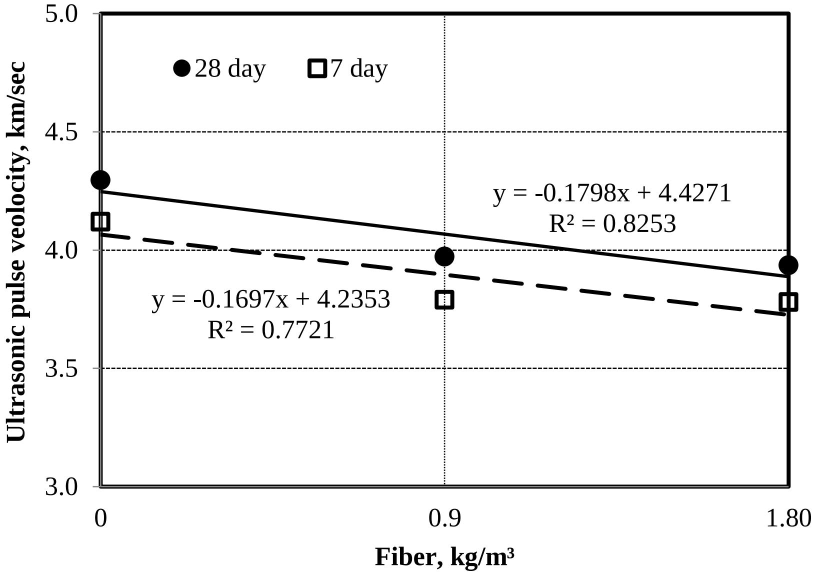


Figure 5. Ultrasonic pulse velocity of pervious concrete specimens.

3.2.2. Compressive strength test results

The concrete specimens, which were waiting in the curing pool for 7 and 28 days, were removed from the pool and dried. Firstly, the pressure values were recorded by breaking the control specimens, and then these values were compared with the polypropylene fiber specimens broken on the 7th and 28th days. Compressive strength test results are shown in Fig. 6. When the results were examined, an increase of more than 30% was observed in the strengths when the fiber ratio was 1.8kg/m³. When the curing time changed from 7 days to 28 days in compressive strength, the compressive strength increased by 12.8%. In the case of fiber use, strength increases of up to 77% were observed. In the case of using fiber, the growth of microcracks formed under an axial compression load, the control of the fibers by the bridging effect, caused an increase in strength. (Hasani, et al., 2021) concluded that modified synthetic polypropylene fiber increases concrete pavements' compressive and flexural strength and freeze-thaw resistance. In general, it is stated that the addition of fiber increases the compressive and flexural strength of concrete. The thesis study by (Kızılelma, 2021) also supports the study of Hasani et al. Compressive and flexural strength increased with the addition of fibers. In addition, the freeze-thaw resistance of fiber concrete was better than the control concrete.

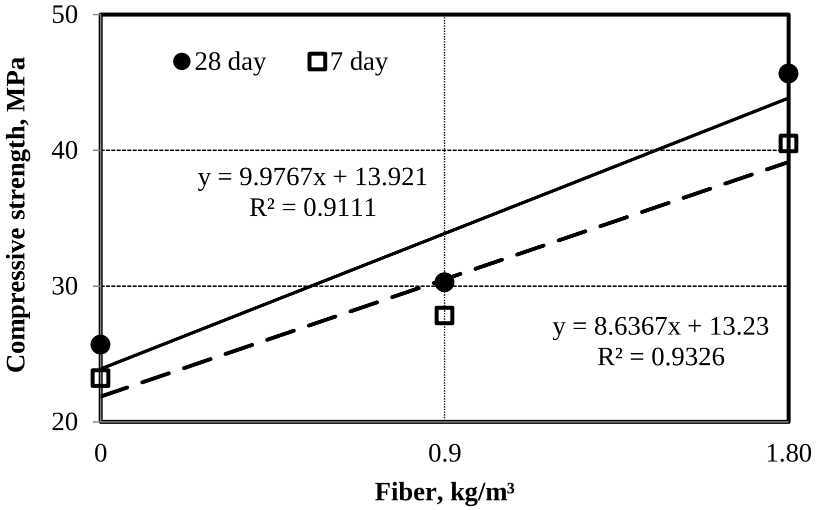


Figure 6. Compressive strength of pervious concrete specimens.

3.2.3. Test results of splitting tensile strength determination

The cylindrical specimens from the splitting tensile test were removed from the curing bath on days 7 and 28 and tested according to TS EN 12390-6 Determination of the splitting tensile strength of test specimens and subjected to undamaged tests. The values of the cylinder specimens prepared as permeable and permeable with different fiber proportions were compared. The splitting tensile strengths of the permeable concrete specimens are shown in Fig. 7. From Fig. 7 it can be seen that the tensile strength at splitting increases up to 65% as the polypropylene fiber ratio increases. This is because, in the splitting test, the axial load causes the specimen to split in a plane. Fibers perpendicular to this plane make it difficult to separate the specimen from this plane. The resulting increase in stress causes an increase in the splitting tensile strength. Bentur and Mindess (2006) reported that the addition of polypropylene fibers had no significant effect on the direct tensile splitting strength. However, the addition of macro synthetic polypropylene fibers at moderate volume changes (0.33-0.5%) showed a 10-15% increase in tensile splitting strength.

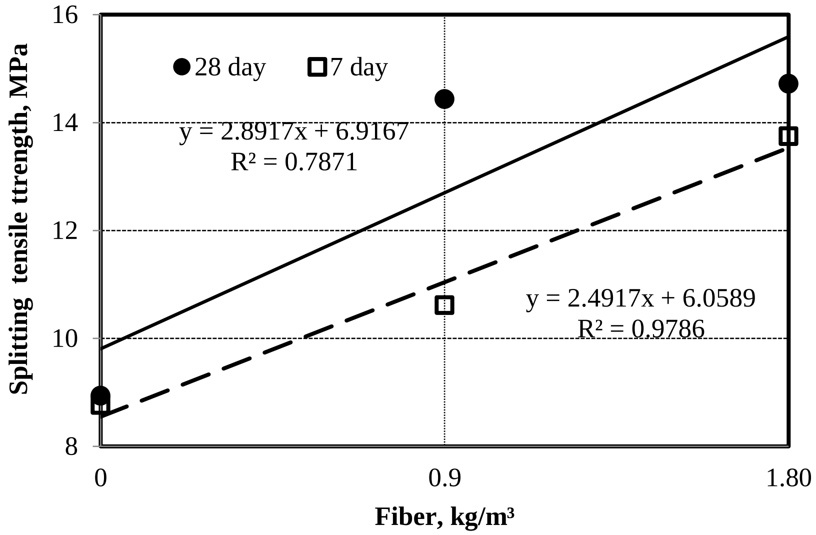


Figure 7. Splitting tensile strength of pervious concrete specimens.

3.2.4. Test results for determination of tensile strength in bending

After the tests with cube and cylinder specimens, the bending tensile test, in which polypropylene fibers can show their actual performance, was carried out as specified in the standard named TS EN 12390-5 Determination of Flexural Strength of Test Specimens. The variation of flexural strength of permeable concrete specimens with fiber content is given in Fig. 8. As the fiber content increased, a similar increase was observed in the flexural strengths at 7 and 28 days. With the fiber increase in Fig. 8, an increase of approximately 40% was observed in the bending strength values of the samples. Especially since the bending strength values of permeable concretes are low, it is not suitable to be used in road and airport concretes. In the case of fiber addition here, controlling the bending cracks with the bridging effect of the fibers caused an increase in the bending strength values. However, this increase is not enough. However, it is suitable to be used in places with light traffic and pedestrian traffic. In the splitting tensile strength test, it was found that tensile strength was significantly improved only for 0.5% of fiber dosage, and as the percentage of fiber volume dosage increased a continuous drop of strength was observed. In flexure strength, the improvement in the behavior due to the addition of the PPF is similar to that in tensile strength. Therefore, it may be concluded that the optimum value of fiber content is 0.5% for both tensile strength and flexural strength (Milind, 2015).

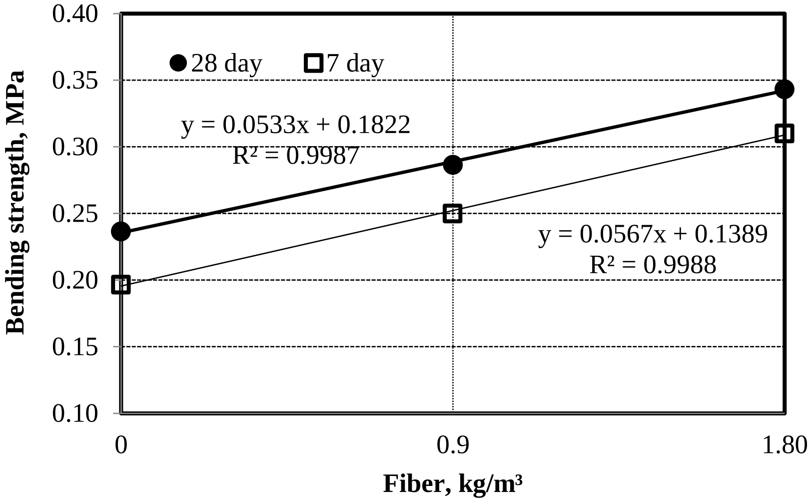


Figure 8. Bending strength of pervious concrete specimens.

3.3. Evaluation of durability properties

3.3.1 Abrasion test results

Abrasion resistance of permeable and fibrous permeable concretes at different rates; Abrasion test by friction on 71x71x71 cube specimens on Bohme abrasion device was carried out as described in TS 699. The abrasion loss was determined as the reduction in the volume of the specimen. After the height measurement of the cube specimens was taken before starting the experiment, the surface of the concrete specimen to be abraded was placed on the rotating disc and the contact side was up. The pressure piston is pressed by the weight suspended on the loading arm. After spreading 20 g of abrasive powder as standard abrasive on the friction surface, the device was started. In this case, the disc applied an abrasion force of 294 N to the specimen. The disc stopped automatically after 22 revolutions. The specimen was rotated 90° clockwise and new abrasive powder was placed on the trace. Each time the disc and the contact surface were cleaned. In this way, the second, third, and fourth faces were also eroded and a total of 88 cycles were completed. At the end of each cycle, the specimens cleaned with the brush were carefully measured and weighed. The volume of the specimen was determined according to the Archimedes experiment and the difference with the initial volume was found as the abrasion loss. After every four transformations, the cleaned specimens were carefully measured and weighed. In the research, a total of 16 cycles, i.e. 352 cycles, were applied to each specimen. Abrasion loss is calculated in terms of volume reduction using the following equation (1).

$$\Delta V = (V0-V1)/A\times 50 \qquad (1)$$

where,
ΔV: Value of the specimen surface abrasion loss, $cm^3/50\ cm^2$,
V0: The volume of the specimen before the experiment, cm^3,
V1: The volume of the specimen after the experiment, cm^3,
A: The area of the specimen's abrasion-applied surface, cm^2.

Abrasion test results are given in Fig. 9. When Fig. 9 is examined, it is seen that the abrasion loss decreases as the fiber content increases. However, the decrease in volume was less since it is permeable concrete. As the increase in the fiber ratio deteriorates the cement paste structure, the wear loss has increased. However, since the fibers hold the abrasion parts together, the wear loss in volume was less

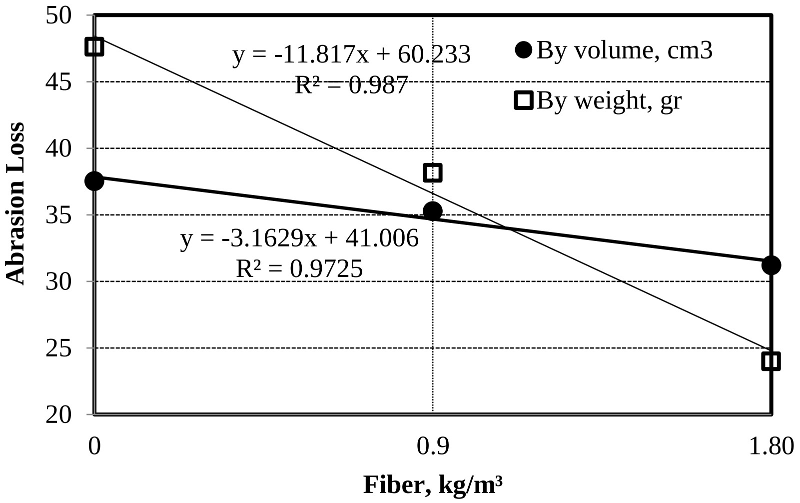


Figure 9. Abrasion test result of pervious concrete.

3.3.2 Freeze-thaw determination test results

The losses caused by freeze-thaw and de-icing solutions on the compressive strength of permeable concrete are shown in Fig. 10. When Fig. 10 is examined, it is seen that the losses increase as the fiber content increases. The losses in the cement matrix as a result of freezing and thawing, especially in pervious concrete, limit the area of attachment of the fibers due to the low amount of this matrix. In this case, the pressure increased the loss of strength.

(Hasani, et al. 2021) conducted some experimental tests to investigate the effects of steel and synthetic fibers on the performance of concrete pavements. The synthetic fiber used in this study is a modified synthetic polypropylene fiber. Flexural and compressive strength and durability tests were carried out on plain and fiber-reinforced concrete specimens. They found that the use of modified synthetic polypropylene fiber in concrete pavements increased the compressive and flexural strength, ductility, and energy absorption, and reduced the resistance of concrete to freeze-thaw cycles. Using a similar additional volume, they found that steel fiber-reinforced concrete had better flexural performance and lower compressive strength and workability than concrete reinforced with modified synthetic polypropylene fiber. They mentioned that the use of fibers improves the mechanical properties of concrete. They used a finite element program to analyze the bonded concrete pavement using the Portland Cement Association (PCA) pavement design criteria. In their analysis results, they found that concrete reinforced with modified synthetic polypropylene fiber can reduce the thickness of the bonded concrete pavement by 15%. Bilir T. found similar results in his study (Bilir, 2012).

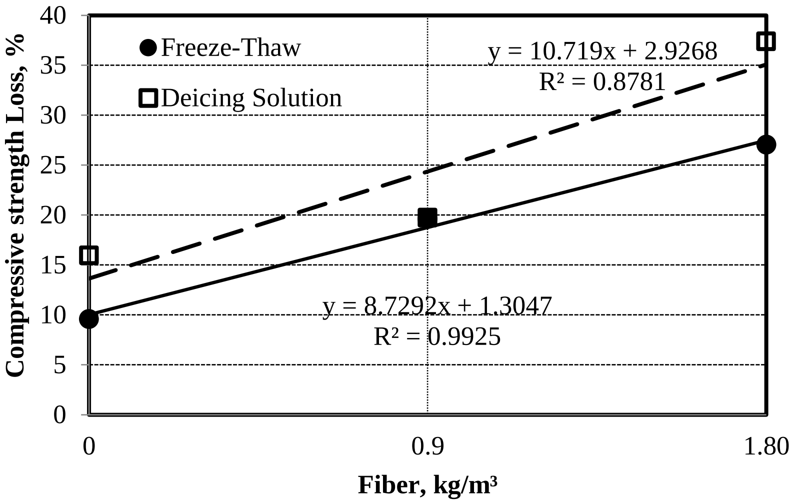


Figure 10. Effect of freeze-thaw and deicing solution on pervious concrete.

3.3.3. Permeability test results

The permeability of permeable concrete was determined using the technique recommended in ACI 522R-06 (ACI Committee, 2006). Cylindrical specimens 10 cm in diameter and 20 cm in height were prepared from permeable and fibrous permeable concrete mixes at different rates. The specimens removed from the molds were left to set for 28 days, and when the setting age was reached, they were removed from the pool and dried in the laboratory for 24 hours. The fully dried specimens were wrapped in a watertight manner. Enclosed cylindrical permeable and fibrous permeable concrete specimens were placed at one end of the U-shaped test apparatus. It was filled to a water level of 230 mm above the specimens. The lower valve was opened, and the time taken for the water level to drop to 25 mm was measured in seconds using a stopwatch. The measurement was repeated 2 times for each sample. The permeability capacity was determined by dividing the 20.5 cm by the measured time (sec). The variation of the permeability test results with fiber ratio is shown in Fig. 11. From Fig. 11 it can be seen that the permeability decreases as the number of fibers increases. As the fibers cause a partial reduction in the void structure of the permeable concrete, the permeability decreases with the reduction in the smooth voids through which the water will pass. (Mehrabi, et al., 2021) investigated the effect of fiber reinforcement on permeability and found similar results.

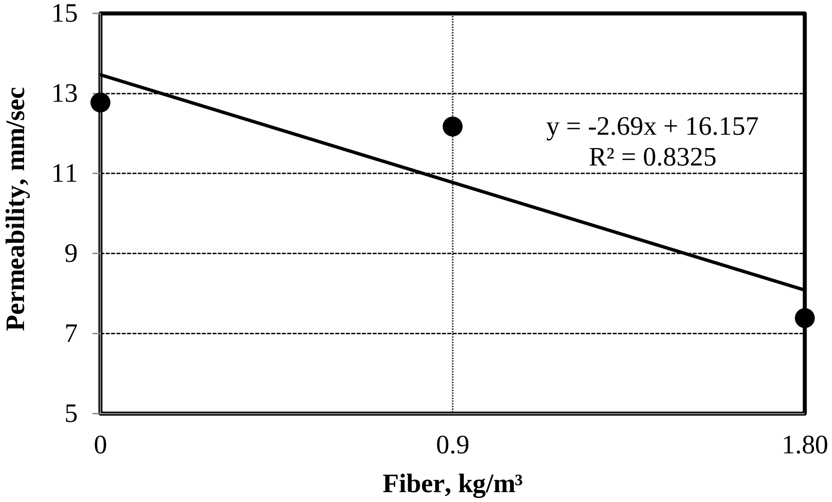


Figure 11. Permeability test results of pervious concrete.

3.4. Microstructure analysis

The microstructural analyses of the 7-day permeable concrete specimen are shown in Fig. 12. Very dense hydrated lime ($CaCO_3$) structures consisting of plate-shaped grains are seen in the 7-day permeable specimen. It can be seen that the density of hydrated lime in permeable concrete is at a high level. Aggregate voids and cracks can be seen in the 7-day permeable specimen. Limestone $CaCO_3$ was used as the aggregate. Cracks in the aggregate can be seen in the 7-day permeable specimen.

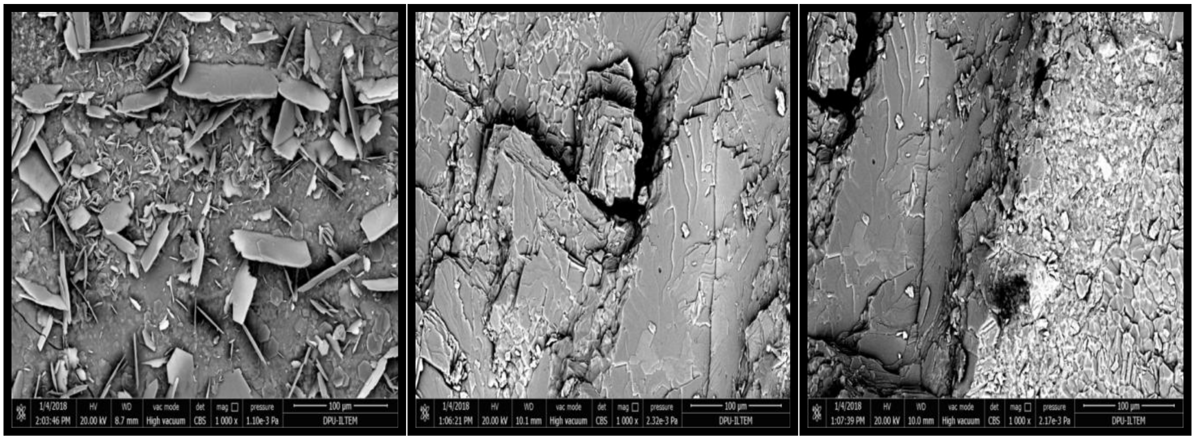


Figure 12. Microstructure analysis images.

In the 7-day permeable specimen, the aggregate cement interface and cracks formed in the cement paste were examined at 1000 and 5000 magnifications. At 5000 magnifications, a very pronounced and weak interface formation was observed where the cement paste did not completely enclose the aggregate. This is one of the most important parameters affecting the compressive strength of the concrete. It can be seen that the cement paste structure contains voids and is not very dense. The image is a backscattered electron image. Contrasts based on atomic number differences are seen in this multiphase system consisting of aggregate and hydrated cement components.

In the backscattered electron image, unhydrated cement grains appear light grey near white, calcium hydroxide ($CaOH_2$) appears light grey, calcium silicate hydrate (CSH) appears in dark shades of grey, and the voids appear black (Hussin, A. and Poole, C., 2011). The limestone aggregate ($CaCO_3$) used in the mixtures appears very dark grey due to its high atomic weight. This type of structure increases as it approaches the aggregate.

The microstructural analyses performed on a 7-day old 0.9 kg specimen of fiber-reinforced permeable concrete are shown in Fig. 13. This low-magnification SEM image (2000) shows that the fibers are homogeneously distributed, but the hydrated cement structure is quite cracked. In addition, there is a high level of $CaOH_2$ formation.

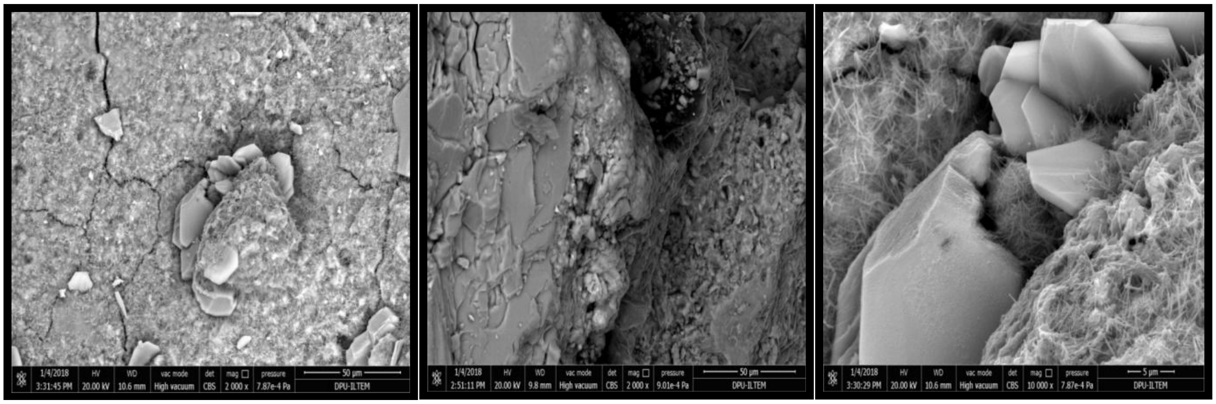
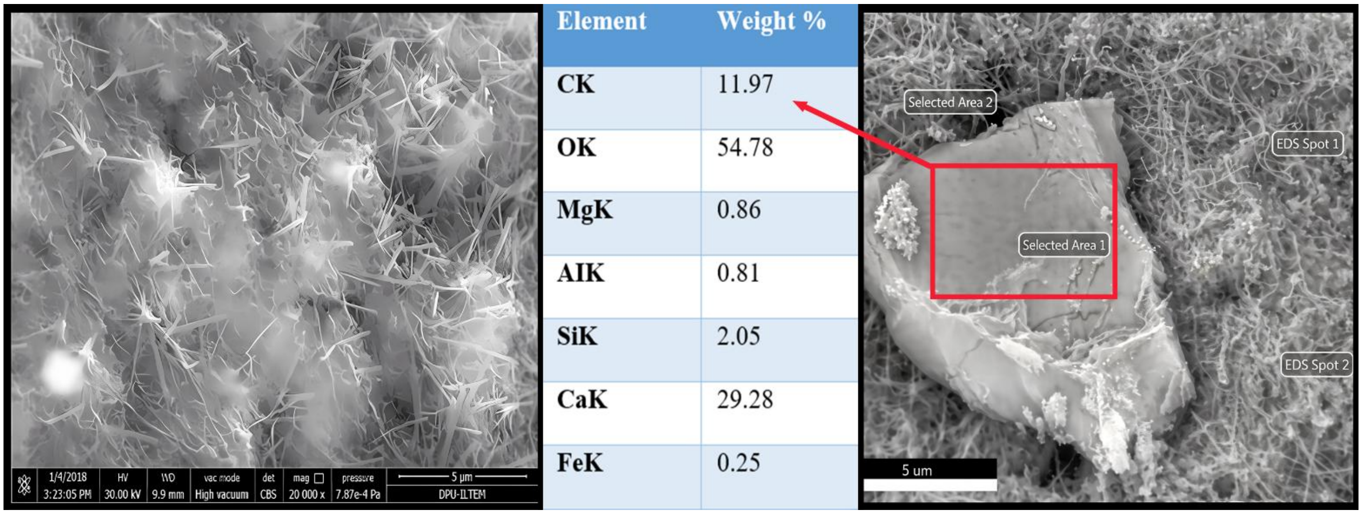


Figure 13. Microstructure analysis images (7 days 0.9 kg fiber added specimen).

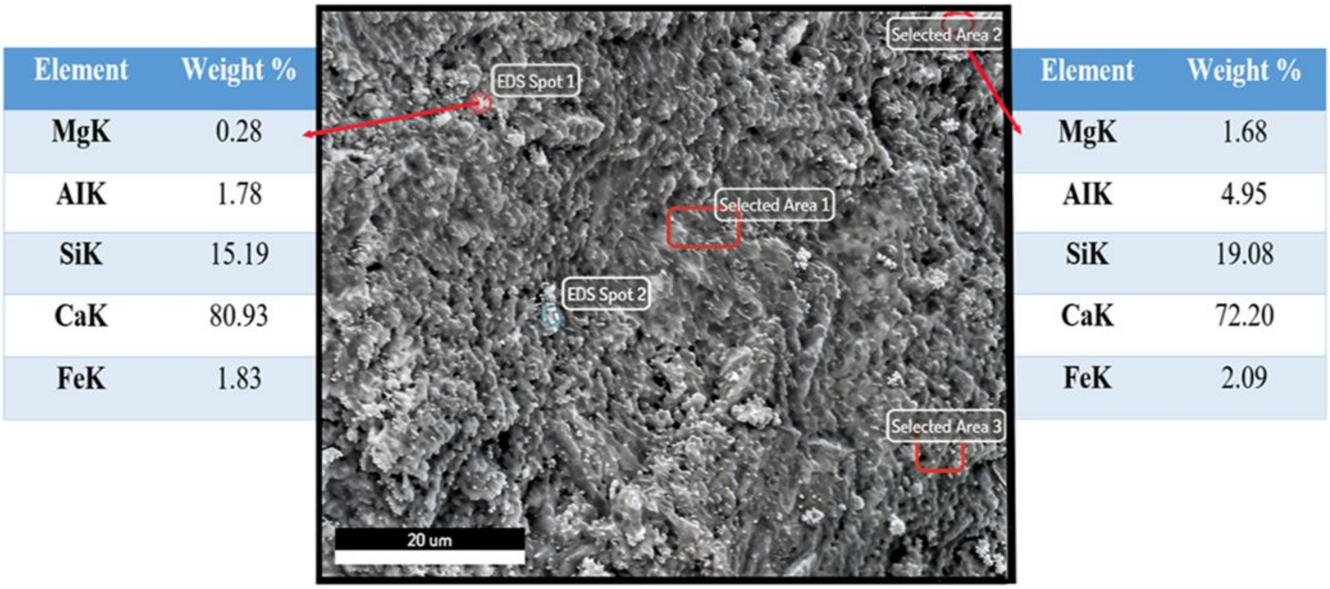
Within the hydrated cement structure of the 7-day 0.9 kg fibrous specimen, homogeneously dispersed fibers are observed. (Fig. 14.)



Element	Weight %
CK	11.97
OK	54.78
MgK	0.86
AlK	0.81
SiK	2.05
CaK	29.28
FeK	0.25

Figure 14. Microstructure analysis images.

The C-S-H structure and the off-white gray structures are probably unreacted (not hydrated) cement grains. The EDS below gives their atomic structure. (Fig. 15.)



Element	Weight %
MgK	0.28
AlK	1.78
SiK	15.19
CaK	80.93
FeK	1.83

Element	Weight %
MgK	1.68
AlK	4.95
SiK	19.08
CaK	72.20
FeK	2.09

Figure 15. SEM-EDS analysis showing selected microstructural regions and corresponding elemental composition tables.

Again, the anhydrate cement grains in EDS 1 and 2 stand out, and their Ca/Si atomic ratio is 4/1. These grains appear light grey almost white due to their atomic weight. These are the heaviest structures by atomic weight. Other structures are mostly loose and incomplete C-S-H structures with very few gaps between grains. Fig. 16 shows the fibers in the C-S-H structure. At the same time, $CaOH_2$ grains formed by the presence of a lot of water in the interstices of the C-S-H structure, and cracks in the hydrated structure can also be seen. In addition, the weak and obvious aggregate-cement paste interface and the increasing $CaOH_2$ grains as they approach the aggregate, and the porous interface structure are also seen.

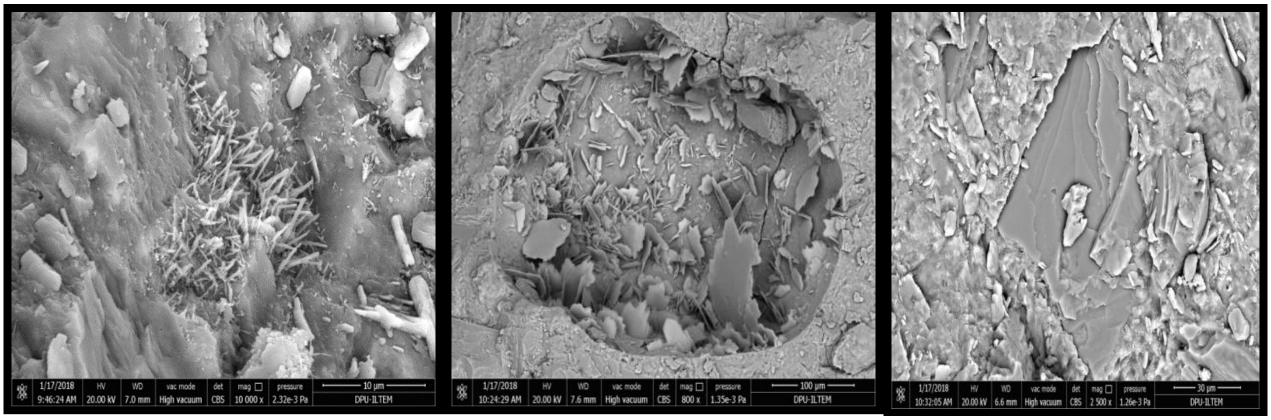


Figure 16. Microstructure analysis images.

The fact that the fibers try to hold the matrix together increases the compressive strength, but the microporous structure caused by the low slump and the fibers negatively affects the freeze-thaw strength (Fig. 17).

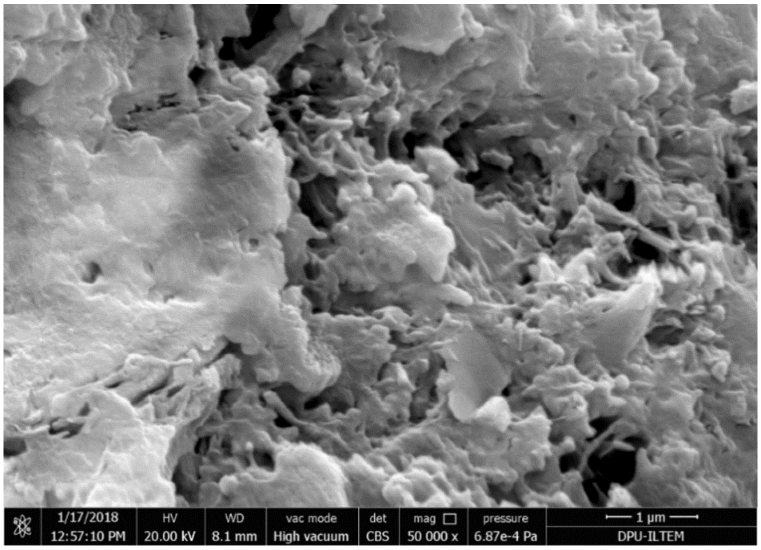


Figure 17. Microstructure analysis images.

3.5. Design of fiber permeable concrete pavements

The section detail to be used will vary for different applications. For example, if the subgrade is permeable or less permeable, it will indicate that a drainage system should be added. This situation is shown in Fig. 18 and Fig. 19. Fig. 18 shows drainage application cross sections for permeable subgrade and Fig. 19 for less permeable subgrade. If permeable concrete is used in areas with incomplete infrastructure (muddy areas), the voids may fill with mud and may not function. Therefore, geotextiles should be used in such areas. The geotextiles used should comply with the relevant standards and should not prevent water permeability.

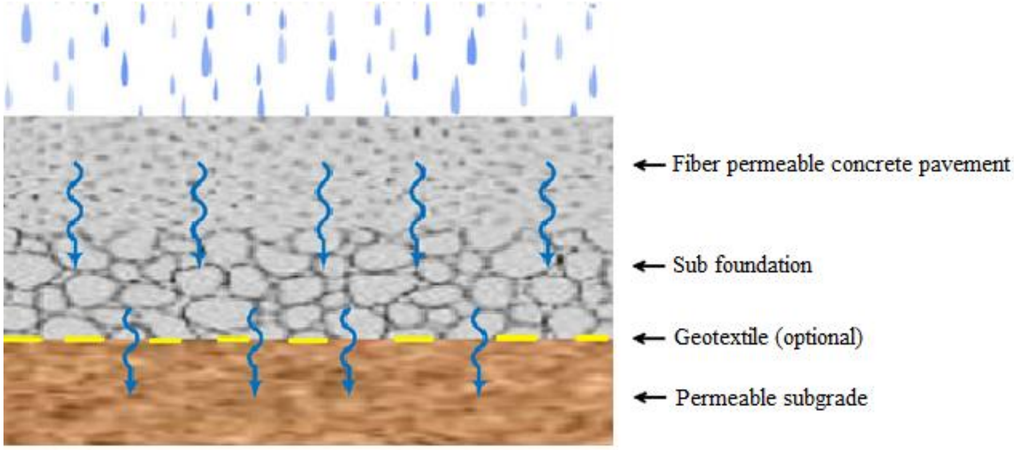


Figure 18. Fiber-reinforced permeable concrete application on permeable subgrade.

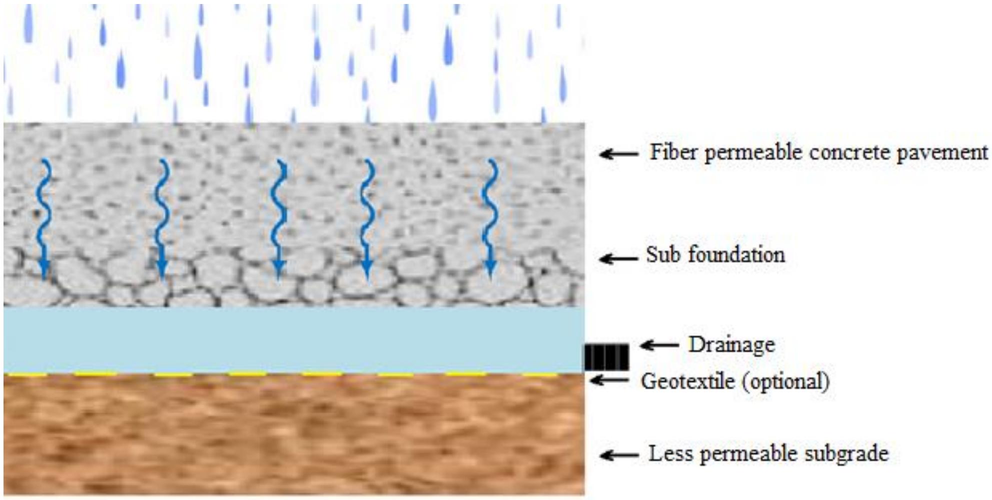


Figure 19. Application of fiber-reinforced permeable concrete on a low-permeability subgrade with a drainage system.

Furthermore, the addition of fibers to the permeable concrete provided crack control and increased the residual strength. Therefore, considering that the design strength in these areas will decrease during the service life of the urban structure, the residual strength will provide significant benefits.

4. Discussion

The results of this study reveal the critical role of polypropylene fibers (PPF) in enhancing the structural and durability performance of permeable concrete used in urban road applications. While permeable concrete inherently provides substantial drainage benefits, its mechanical weaknesses have historically limited its widespread use in transportation infrastructure. By incorporating polypropylene fibers at varying dosages, this research demonstrates how fiber reinforcement can mitigate these limitations and extend the applicability of permeable concrete.

The addition of fibers significantly improved compressive, splitting tensile, and flexural strength values, particularly at dosages of 1.0 kg/m³. This improvement can be attributed to the bridging effect of fibers, which restrained microcrack propagation and enhanced the residual strength of the concrete. Such contributions are particularly valuable in rigid pavement applications, where strength and crack control are essential. Moreover, abrasion resistance was also enhanced with the inclusion of fibers, suggesting improved long-term performance under vehicle loading and reduced surface degradation compared to fiber-free mixtures.

However, the study also identified some limitations. The inclusion of fibers reduced slump values and workability, complicating the mixing and placement process. Additionally, freeze–thaw resistance remained low regardless of fiber content, indicating that fiber-reinforced permeable concrete may not be suitable for regions with severe frost conditions. Similarly, permeability decreased with higher fiber content due to partial blockage of voids, highlighting the need for balance between mechanical performance and hydraulic conductivity in design applications. Overall, the incorporation of polypropylene fibers addresses key weaknesses of permeable concrete by providing residual strength, ductility, and crack resistance, thereby improving its viability for light-traffic roads, pedestrian paths, and parking areas. These findings underscore the potential of PPF to bridge the gap between mechanical stability and drainage functionality in sustainable urban infrastructure.

5. Conclusions

This study confirms that polypropylene fiber reinforcement plays a significant role in improving the performance of permeable concrete for urban drainage and transportation applications. The key findings can be summarized as follows:

1. Fiber addition, particularly at a dosage of 1.0 kg/m³, significantly increased compressive, tensile, and flexural strength, thereby improving crack control and residual strength. These findings are consistent with the results of Hasani et al. (2021), who reported that polypropylene fibers enhance the mechanical performance of concrete pavements through improved crack bridging and energy absorption.
2. Fiber addition increased abrasion resistance, providing better long-term surface durability under traffic loads. This observation supports the conclusions of Bilir (2012), who found that fibers can reduce surface wear in concrete pavements. However, freeze–thaw resistance did not improve, in line with the findings of Hasani et al. (2021), indicating that fiber-reinforced permeable concrete may not be suitable for cold regions.
3. While permeable concrete inherently achieves high drainage capacity, fiber reinforcement slightly reduced permeability due to partial filling of voids. Similar results were reported by Mehrabi et al. (2021), who also observed a decrease in permeability when fibers were added. Therefore, careful dosage optimization is necessary to balance mechanical performance and hydraulic functionality.

This study, polypropylene fiber-reinforced permeable concrete offers a sustainable and technically feasible alternative for urban roads, pedestrian paths, bicycle paths, and parking areas (particularly open parking lots of shopping centers and park-and-ride facilities within cities) exposed to light traffic and rainfall. Moreover, it can also be considered for use in city squares, which play a crucial role in urban transportation, as its light-colored surface provides better visibility at night, reducing the need for additional lighting. The dual contribution of this material to both drainage and mechanical performance underscores its importance for sustainable transportation and urban resilience strategies. Future studies should focus on optimizing fiber dosage, improving freeze–thaw resistance, and investigating hybrid reinforcement approaches to expand the applicability of this material under different climatic and traffic conditions.

Future research should further explore the long-term durability of polypropylene fiber-reinforced permeable concrete under various climatic conditions, including repeated freeze–thaw cycles and prolonged wet–dry exposure. Additionally, studies could investigate the optimal fiber content and its interactions with different aggregate types to enhance both permeability and mechanical performance. Exploring the use of alternative eco-friendly fibers or recycled materials could also provide sustainable options for future implementations. Overall, continued research in these areas will help to refine design guidelines and broaden the practical applications of FRPC in urban infrastructure.

Author contributions: Both authors contributed to the design and execution of the experiments, the analysis of the results, and the writing of the manuscript.

Funding: The authors received no financial support for this manuscript.

Acknowledgments: This article is produced from Nuh Mehmet Polat's Master's thesis, which was carried out under the supervision of Assistant Professor Polat Yalınız at Kütahya Dumlupınar University, Institute of Graduate Education, Department of Civil Engineering. This study was supported by the KDPU Scientific Research Projects Coordination Office under project number 2015-83.

Conflicts of interest: On behalf of all authors, the corresponding author states that there is no conflict of interest.

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