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Investigation of the Effect of Compression Force on the Tensile Strength and Infiltration Rate of Pervious Concrete Blocks

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Abstract: Pervious concrete is widely used as a paving material. Pervious pavement is generally constructed by pouring fresh pervious concrete and compacting. However, it has some difficulties such as finishing and curing. In addition, the road has to be closed, until the pervious concrete gains enough strength. Pervious concrete block is a new material that can overcome these difficulties. In this study, the effect of compression force on the strength and infiltration rate of pervious concrete blocks has been investigated. The compaction process was different from traditional methods in this study, and was applied according to predesignated compression forces on fresh pervious concrete mixtures sensitively. Within the scope of the study, 36 different mixtures were produced by applying four different compression forces (25, 50, 75, and 100 kN) in three different sample thicknesses (60, 80, and 100 mm) with three different aggregate sizes (2–4, 4–8, and 8–16 mm). As a result, it was found that while the increase in the compression force increases the splitting tensile strength of pervious concrete blocks with 2–4 and 4–8 mm aggregate, it causes a decrease in the strength due to the aggregate crushing phenomenon in mixtures with 8–16 mm aggregate, 6 cm thick samples. In this study, it was seen that the expectation that the increase in compaction would always cause an increase in strength is not valid, contrary to the literature. The infiltration rate decreased as the compression force increased, as expected. It was determined that the new infiltration rate measurement method has been found effective. Considering the strength requirement in the TS 2824 EN 1338 standard, pervious concrete blocks produced with 4–8 mm aggregate, compressed with 75 kN force and having 80 mm thickness have been determined as the optimum block type.

Keywords: pervious concrete; pervious concrete block; compaction; infiltration rate

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1. Introduction

Pervious concrete is a building material that generally contains 15% to 25% voids in the hardened state. Although it has many area of use, it is mainly used as pavement material [1]. Pervious pavements have been developed to reduce the runoff rate and the volume of rainwater accumulated in urban areas [2]. In addition to floods, pervious pavements can be used to reduce traffic noise. In a study, pervious concrete pavement materials were compared to the porous asphalt, Portland cement concrete, and dense-graded asphalt pavement materials, and it was found that the pervious concrete pavement was superior to the other pavement types in terms of noise absorption [3]. Pervious concrete pavement can also reduce the urban heat island effect [4].

Pervious concrete has become a promising road paving material, due to the increasing impermeable surface density, in parallel with urbanization. In many parts of the world, attempts are being made to increase the usage areas of pervious pavements. For example, in China, an initiative called sponge city was launched in 2012 [5]. In China, pervious concrete pavement has been offered as an alternative to traditional concrete and has been planned or constructed in selected cities in 2015 and 2016. Pervious concrete was also chosen as a surface layer in highway and tunnel pavements, in addition to urban pavement applications for the development of the sponge city [6]. In the future, it is also expected that some transportation agencies might adapt the use of full depth permeable pavement in highway shoulders to manage rainwater flow in more efficient and cost-effective methods, as part of the sustainable transportation system [7].

Although pervious concrete pavements are highly interesting, and multifunctional, there are some disadvantages. The biggest disadvantage of pervious concrete is its insufficient strength. Compared to conventional concrete, the strength is quite low. Pervious concrete generally made with a single sized aggregate bonded by Portland cement is used at limited levels as a paving material, due to its insufficient structural strength [8]. For this reason, there is a need to make pervious concrete strong, durable, and practical for use as a road paving material.

Many studies have been conducted to increase the mechanical strength of pervious concrete. Increasing the binder area and increasing the strength of the cement paste are two different methods of increasing the strength of pervious concrete [9]. Some researchers have been able to obtain high-strength pervious concrete. In the study [10], pervious concrete mixtures that can be used as road paving material on high volume roads were developed. In addition, pervious concrete block studies have also been carried out by some researchers. In the study [11], pervious concrete blocks with dimensions of 198 × 98 × 80 mm were produced and tested. In the study, it was stated that at 28% void ratio, 4.5 MPa flexural strength, and 0.8 cm/s permeability value, and at 25% void ratio, 5 MPa flexural strength and 0.3 cm/s permeability value were obtained. In another study [12], it was also aimed to develop porous concrete block pavement applicable to motorway with heavy traffic. As a result of the study, (980 × 980 × 150 mm) concrete block was found suitable for motorway pavements. The effects of aggregate gradation and percentage of fines on the mechanical, functional and structural performance of pervious interlocking paver blocks were also evaluated in a study. In order to produce pervious interlocking paver blocks, hydraulic pressing was applied with a pressure of up to 10 MPa after placing the fresh mortar in the mold. An infiltration test was also performed on the pervious interlocking paver block road pavement section. In the study, it was found that the mechanical strength improved with the increase in the percentage of fines. It was also stated that pervious interlocking paver block could be an effective road paving material for low-volume roads, urban heat island and pavements with drainage problems [13]. Pervious concrete block produced by alkaline activation was also studied by some researchers. In a study, the use of the accelerated carbonation curing method was investigated to increase the performance of non-structural precast alkali-activated fly ash pervious concrete paving blocks. The blocks in the study were produced with dimensions of 200 × 100 × 60 mm and were subjected to a 3-stage curing process. The results showed that accelerated carbonation curing significantly improved the performance of the blocks. In the relevant study, a vibrating hammer was used for compaction [14].

However, the applications of high-strength pervious concrete road paving blocks have not become widespread enough, yet. Therefore, more studies are needed to examine the parameters that affect the quality and properties of pervious concrete. Strength of pervious concrete is negatively correlated with its porosity and permeability. It was found that, regardless of pervious concrete type and aggregate size, the compressive strength decreases and the permeability increases with the increase in total void ratio in a laboratory study [15]. Compressive strength and hydraulic conductivity are competitive parameters [16]. There is a negative correlation between mechanical strength and permeability, and therefore mechanical strength decreases with increasing permeability [17].

Compaction is an important factor affecting the strength, porosity and permeability properties of pervious concrete. Increasing the compaction of the sample is one of the effective methods to increase the strength of pervious concrete. Torres et al. [18] conducted porosity, mechanical strength and permeability tests on pervious concretes placed in three different compaction levels. As a result, maximum porosity and permeability values were obtained at the lowest compaction level and minimum porosity and permeability values were obtained at the highest compaction level. It was stated that the applied compaction energy decreases the porosity and causes the cement paste between the aggregates to establish more bridging. In the study, it was observed that the compressive and splitting tensile strength values increased with the increase in compaction energy, contrary to permeability and porosity values. Bonicelli et al. [19] also evaluated the effects of four different compaction energies. As a result, with the increase in compaction energy, there was an increase in strength, and a decrease in the void volume and drainability. In addition, it was reported that drainability has a negative correlation with all mechanical properties. In addition, in the study conducted by Adresi et al. [20], the VeBe test was used to analyze the effect of various compaction energy levels on the strength and permeability properties of pervious concrete. As a result, it was found that the compaction energy level significantly affected the mechanical and permeability properties, and increasing the compaction time from 13 to 82 s caused the unconfined compressive strength to increase from 1.851 to 10.38 MPa, while the permeability decreased from approximately 0.4 cm/s to almost 0.03 cm/s. In another study conducted by Yang and Jiang [9], samples were produced by applying molding pressure on pervious concrete mixtures. As a result, pervious concrete with high strength and permeability was obtained. The change in the molding pressure applied in the study significantly changed the strength and permeability. When 2 MPa molding pressure was applied, compressive strength was obtained as 57.2 MPa and permeability as 1.7 mm/s; when 1 MPa molding pressure was applied 26.7 MPa compressive strength and 20 mm/s permeability value were determined, respectively. As in pervious concrete with natural aggregates, it has been found that in pervious concrete with recycled aggregates, the strength increases and the permeability decreases with the increase in compaction. In the study conducted by Wei et. al. [21], vibration molding and layered insertion-tamping methods were used as molding methods. As a result, it was found that extending the vibration time increased the compressive strength and decreased the permeability of pervious recycled aggregate concrete. It was also stated that the layered insertion-tamping method provided a higher strength than the vibration molding method.

In summary, compaction energy affects porosity and permeability and, generally, with the increase in compaction energy, strength increases, and permeability and porosity decrease. However, since many factors affect the mechanical strength and permeability properties of pervious concrete, it is not correct to generalize this to all pervious concrete. All these studies have shown that it is very important to determine the optimum levels of parameters that strongly affect the strength and permeability of pervious concrete.

The Aim of This Study

Pervious concrete is a relatively new material in pavement applications in comparison with conventional concrete pavements. More studies are needed to determine the properties of pervious concrete that will provide better performance. This study contributes to the investigation of the effect of different compression forces on the strength and permeability properties of pervious concrete blocks produced with different aggregate sizes and different sample thicknesses. In addition, determining the ideal compression forces according to different sample thicknesses and aggregate sizes, to obtain pervious concrete blocks having high strength and high permeability that can be used in road applications, are among the aims of this study.

2. Materials and Methods

In the study, three different crushed stone aggregates in sizes 2–4, 4–8, and 8–16 mm were used. Specific mass values of aggregates are 2.63 kg/dm^3, 2.67 kg/dm^3, and 2.69 kg/dm^3, respectively. The granulometry curves of the aggregates are given in Figure 1.

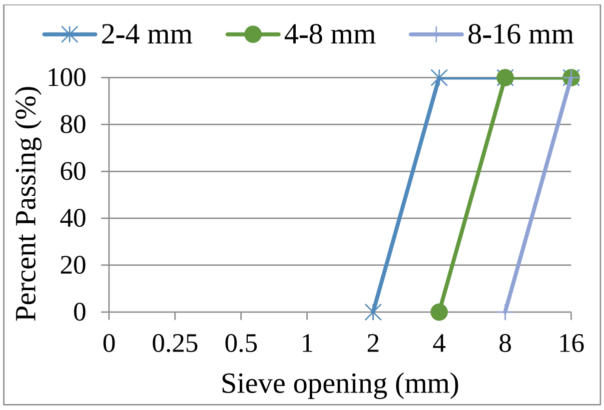


Figure 1. Aggregate granulometry.

CEM I 42.5 R Portland cement was used in the study. BASF MRoc MS 610 brand silica fume was used as a mineral admixture in the study. The physical and chemical properties of Portland cement and silica fume are given in Table 1.

Table 1. Physical and chemical properties of silica fume and cement.

Parameters	Silica Fume	Cement
SiO_2 (%)	91.97	-
Cl (%)	0.06	0.0224
Fe_2O_3 (%)	1.32	-
Al_2O_3 (%)	0.62	-
Na_2O (%)	0.49	0.16
K_2O (%)	1.49	0.86
MgO (%)	1.25	-
CaO (%)	0.31	-
SO_3 (%)	0.35	3.11
H_2O (%)	0.22	-
Loss on Ignition (%)	1.33	2.44
Activity Index (%)	131.5	-
Specific Surface (cm^2/gr)	-	3423
Insoluble residue (%)	-	0.31
Specific Gravity (gr/cm^3)		3.17

In the study, BASF MasterGlenium 51 brand superplasticizer admixture was used to reduce the water/binder ratio and increase workability. The properties of the superplasticizer admixture are obtained from a local supplier as density: 1.084 g/cm^3, pH: 6, solid matter: %35.64, chlorine content: %0.0527 and alkaline content: %1.19 [22].

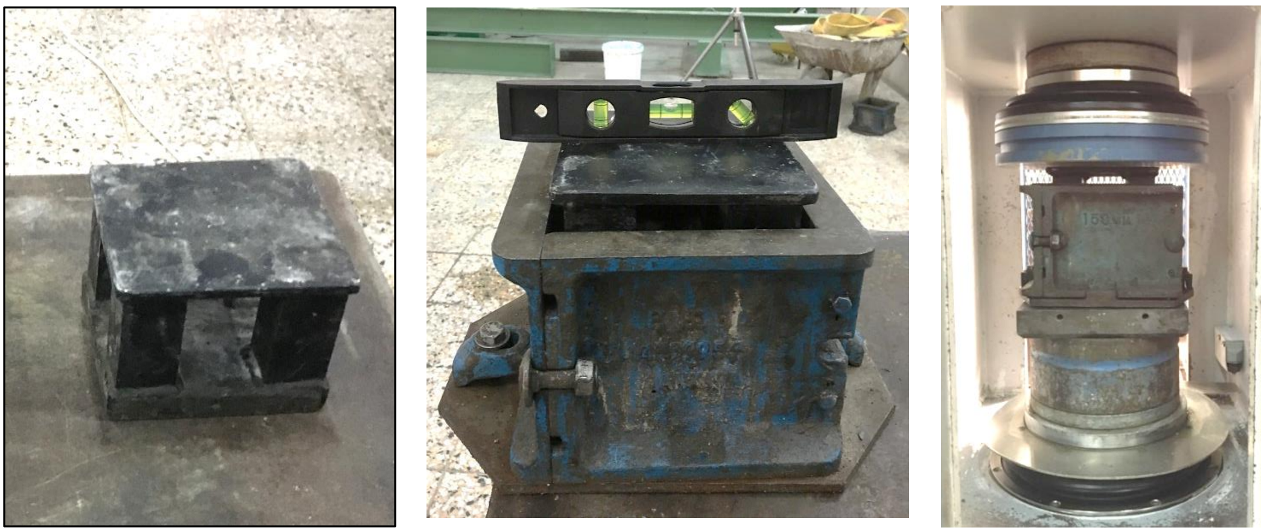
Aggregate/binder ratio is an important parameter that affects the properties of pervious concrete. Considering the mechanical strength and permeability values in previous studies [10,22], the aggregate/binder ratio was determined as 2.5 in this study. Within the scope of the study, 36 different mixtures were produced by applying 25, 50, 75, and 100 kN compression forces in a 15 × 15 cm surface area with 6, 8, and 10 cm thicknesses, with 3 different aggregate sizes. The mixture names are called (F, M, C)-X-Y; the letters F, M and C represent the 2–4 mm, 4–8 mm, and 8–16 mm aggregate sizes, respectively. X represents the compression force and the letter Y represents the thickness of the block. For example, F 25-6 represents the pervious concrete made with 2–4 mm aggregate size, pressed under 25 kN force, and thickness of the sample is 6 cm. Mixture ratios are seen in Table 2.

Table 2. Mixture Ratios of pervious concrete (PC).

Components (kg/m^3)	PC Made with 2–4 mm Aggregate (F Series)	PC Made with 4–8 mm Aggregate (M Series)	PC Made with 8–16 mm Aggregate (C Series)
Cement	400	400	400
Superplasticizer	8	8	8
Silica fume	80	80	80
Water	88	78	72
Aggregate	1440	1415	1400

All components of the pervious concrete, the aggregate, silica fume, cement and some amounts of water, were placed in the tilting concrete mixer and mixed for a time which was enough for the wetting of the mixture components. Then, the remaining amount of water and the super plasticizer admixture were added to the mixture together and the pervious concrete was mixed in the tilting concrete mixer until a homogeneous mixture having a metallic shine was formed. The mixture was poured into the pan, mixed by hand with a trowel, molds were filled up to the relevant height, and the surface was leveled with a wooden mallet.

Vibration, dropping, rodding, blowing with a standard Proctor/Marshall hammer and gyratory compactor could be considered as most adopted pervious concrete laboratory compaction methods [19]. These compaction methods can be described as traditional laboratory compaction methods. The Proctor hammer, especially, has been commonly used in pervious concrete studies. But it is difficult to apply uniform compaction with traditional methods sensitively. So, in this study, the compaction process was different from traditional methods, and was applied according to predesignated compression forces on fresh pervious concrete mixtures with a novel method, sensitively. In the compaction process, a specially produced steel apparatus was used that can enter into the 150 mm cube sample mold. After the fresh concrete was placed in the cube sample mold, the steel apparatus was placed and kept in the press machine, up to the relevant compression force. The compression force applied to the pervious concrete sample is not a dynamic force. This force is a load applied by the universal testing machine with a uniform load increase up to the required 25–100 kN. The steel compaction apparatus, leveling application, and compaction application are shown in Figures 2 and 3.



(**a**) (**b**) (**c**)

Figure 2. (**a**) Steel compaction apparatus, (**b**) leveling application, and (**c**) compaction application in the press machine.

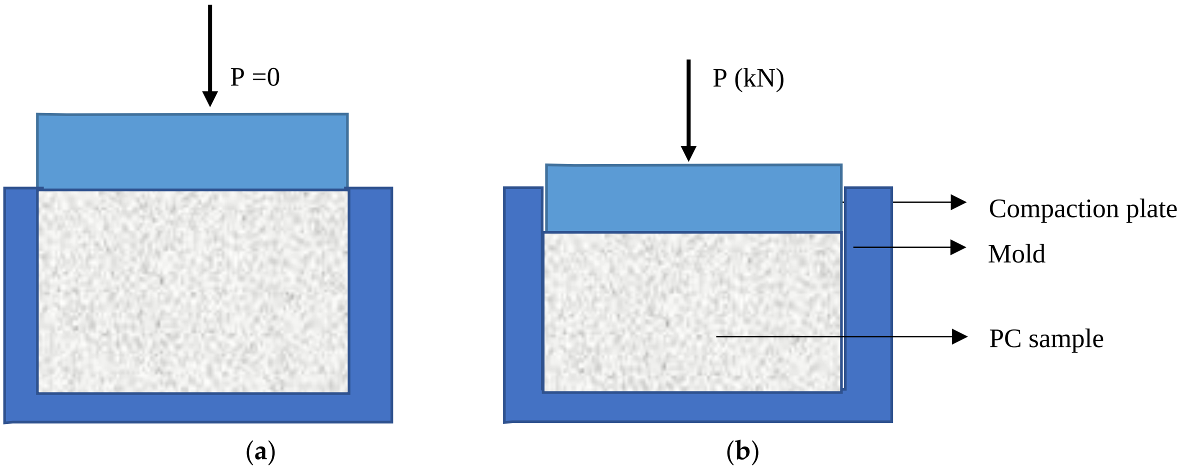


Figure 3. Compaction application of the sample: (**a**) before compaction, (**b**) after compaction.

Samples were removed from the molds after 48 h, and stayed in the curing pool until the day of the test. In each series, four samples were used in splitting tensile strength tests and two samples were used in infiltration rate tests. After the infiltration rate tests, the same samples were used in the density tests.

Various strength and durability properties for concrete pavement blocks have been determined by standards and regulations. The TS 2824 EN 1338 [23] standard deals with properties and test methods of cement-bonded unreinforced concrete blocks, and does not involve pervious blocks. Since one of the aims of this paper was to obtain pervious concrete blocks having high strength and high permeability that can be used in road applications, it was decided to use the related standard in terms of the splitting tensile strength test method and targeted strength. According to the standard, the characteristic splitting tensile strength of concrete blocks should not be less than 3.6 MPa. In addition, a special infiltration rate test was developed in this study. Splitting tensile strength was calculated using the Equations (1) and (2) below. The splitting tensile strength test and infiltration rate test are given in Figure 4. The schematic drawing of the infiltration rate test is given in Figure 5.

$$S = l \times t \tag{1}$$

where S, l, and t are the fracture area (mm^2), length of the fracture section (mm), and thickness of the concrete block at the fracture plane (mm), respectively.

$$T = 0.637 \times k \times P/S \tag{2}$$

where T, P, and k are the strength (MPa), the ultimate load (N), and correction coefficient for the block thickness, respectively.

Within the scope of this study, a new test method was developed to measure the infiltration rate on samples, equivalent to those carried out for the strength measurements. A plexi pipe with an inner diameter of 64 mm was adhered to the surface of the block as an infiltration ring by using hot silicone, so that no leakage would occur. Samples were saturated before the experiment. Due to the fact that the infiltration rate changes as the aggregate size changes, different amounts of water were put into the water reservoir, according to the aggregate size. A total of 120, 240, and 360 g of water were put into the water reservoir, according to the mixtures made with 2–4, 4–8 and 8–16 mm aggregate, respectively. In order to accurately measure the moment when the water contacts the sample surface and the moment it disappears from the sample surface, a video recording was taken in each experiment. The infiltration rate was calculated by using Equation (3) in the ASTM C 1701 [24] standard. Photos of demolded samples and tested samples are shown in Figure 6.

$$I = \frac{K \times M}{\left(D^2 \times t\right)} \tag{3}$$

where I is the infiltration rate (mm/h), M is the mass of infiltrated water (kg), D is the inner diameter of the infiltration ring (mm), t is the time passed for the percolation of the measured amount of water (s), and K is a coefficient of 4,583,666,000 in the SI unit. This coefficient, whose unit is (mm^3s)/(kg h), provides the infiltration rate in (mm/h).

(**a**) (**b**)

Figure 4. (**a**) Splitting tensile strength, (**b**) infiltration rate test.

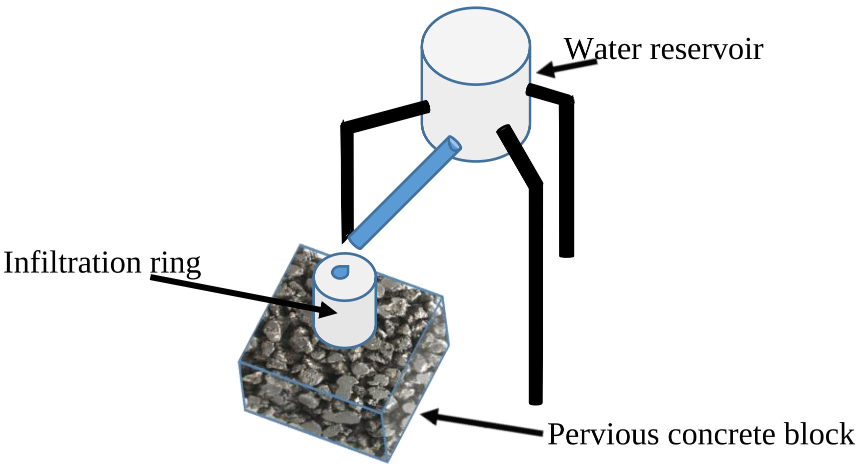


Figure 5. Schematic drawing of the infiltration rate test.

The density values of the samples were also measured in the study. In order to determine the density values, the dimensions of the samples were measured precisely with calipers and then dried in the oven until they reached a constant mass. Densities of samples were determined using the equation below.

$$d = \frac{M}{15 \times 15 \times L} \tag{4}$$

The notations in the equation are, respectively, d: density (gr/cm^3), M: oven-dried sample mass (gr), L: arithmetic mean of block thickness measured from 12 different points (cm).

(**a**) (**b**)

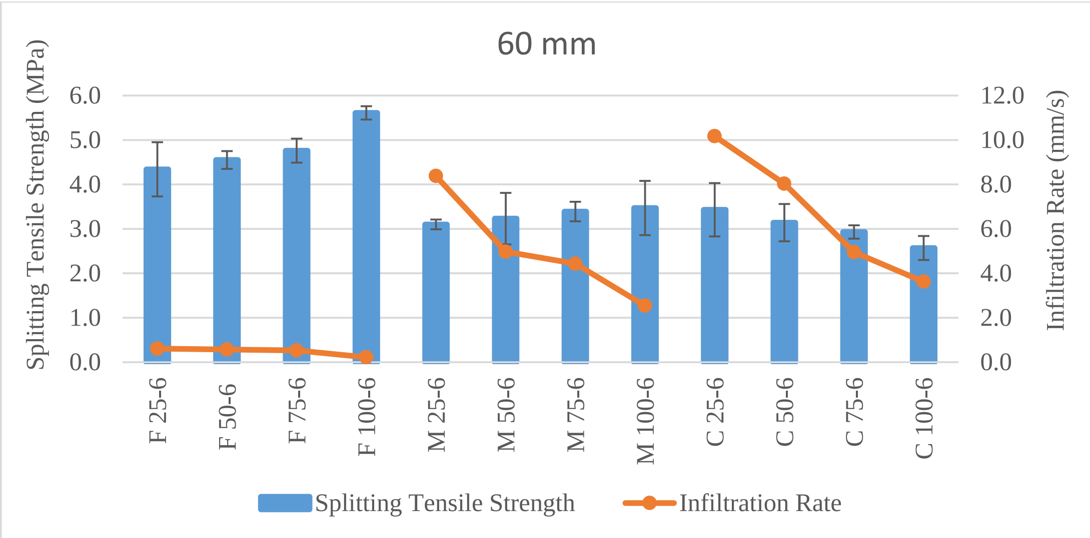
Figure 6. (**a**) Demolded samples, (**b**) tested samples.

3. Results and Discussions

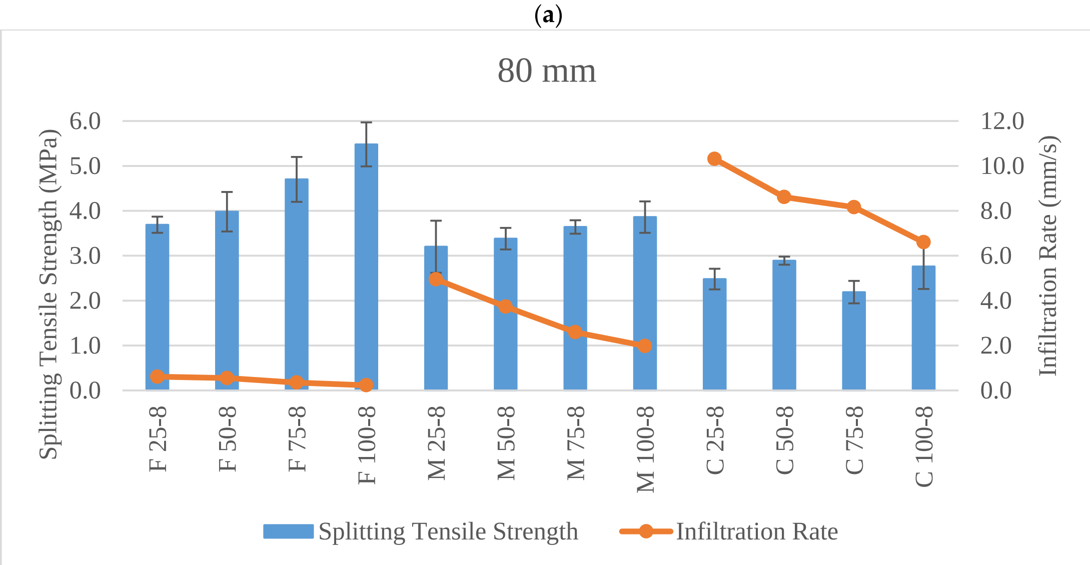
Splitting tensile strength tests were carried out when the blocks were 28 days old. Density, splitting tensile strength and infiltration rate values are given in Table 3. Splitting tensile strength and infiltration rate changes, according to the mixture types, are shown in Figure 7.

Table 3. Test results.

Mixtures	Density (gr/cm^3)	Splitting Tensile Strength (MPa)	Infiltration Rate (mm/s)
F 25-6	2.02	4.34	0.61
F 50-6	2.04	4.55	0.57
F 75-6	2.07	4.76	0.53
F 100-6	2.12	5.61	0.22
F 25-8	1.95	3.69	0.61
F 50-8	1.97	3.98	0.55
F 75-8	2.03	4.70	0.35
F 100-8	2.11	5.48	0.23
F 25-10	1.95	3.62	0.71
F 50-10	1.98	3.63	0.59
F 75-10	1.99	3.88	0.54
F 100-10	2.05	4.02	0.29
M 25-6	1.90	3.10	8.38
M 50-6	1.94	3.23	4.97
M 75-6	1.99	3.39	4.43
M 100-6	2.02	3.47	2.54
M 25-8	1.93	3.20	4.95
M 50-8	1.97	3.38	3.73
M 75-8	2.01	3.64	2.59
M 100-8	2.05	3.86	1.98
M 25-10	1.93	3.26	2.78
M 50-10	1.95	3.44	1.97
M 75-10	2.02	3.69	1.79
M 100-10	2.11	3.94	1.25
C 25-6	1.94	3.43	10.17
C 50-6	1.97	3.14	8.03
C 75-6	1.99	2.93	4.95
C 100-6	2.05	2.57	3.62
C 25-8	1.93	2.48	10.31
C 50-8	1.94	2.89	8.61
C 75-8	1.97	2.19	8.16
C 100-8	2.02	2.76	6.60
C 25-10	1.87	2.30	12.45
C 50-10	1.93	2.31	10.26
C 75-10	1.95	2.35	10.17
C 100-10	2.01	2.38	6.85



(**a**)



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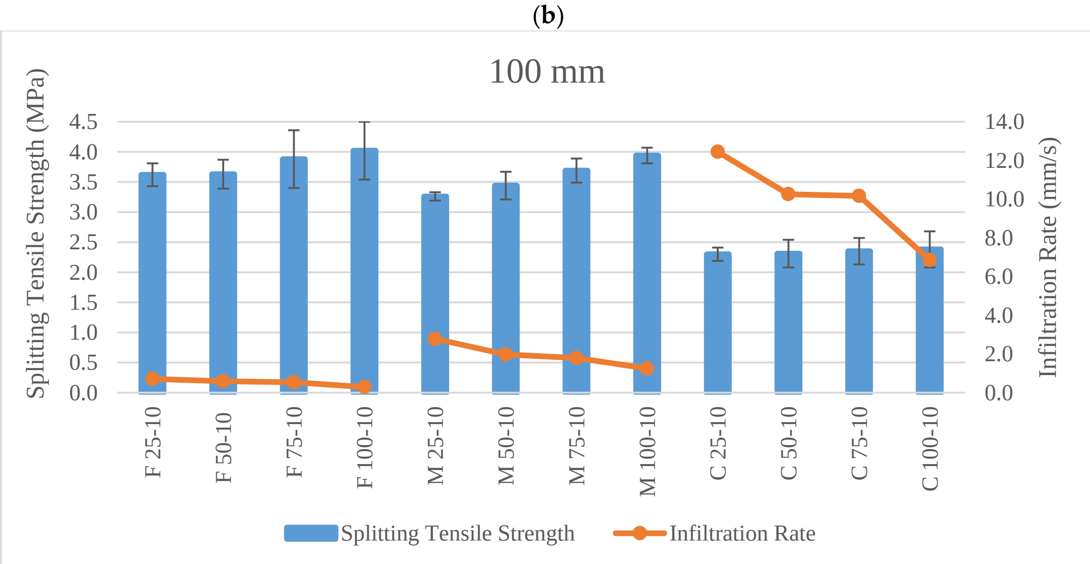

(**c**)

Figure 7. Changes in splitting tensile strength and infiltration rate values of pervious bock samples with (**a**) 60 mm thickness, (**b**) 80 mm thickness and (**c**) 100 mm thickness.

When the variation in the splitting tensile strength was examined, it was observed that the strength increased as the compression force increased in all F and M series of pervious concrete block samples and in the C series of samples with a thickness of 10 cm. When the splitting tensile strength increase rates were examined, with the increase in compression force, the increase in the maximum strength of samples produced with F series aggregates of 6 cm thickness was 29%, the increase in the maximum strength of samples produced with F series aggregates of 8 cm thickness was 49%, and the increase in the maximum strength of samples produced with F series aggregates of 10 cm thickness was 11%. Increases in the maximum strength of samples produced with M series aggregates were found to be 12%, 21%, and 21% in 6 cm, 8 cm and 10 cm thickness samples, respectively. No clear relationship was found between the increasing rate of strength and thickness in samples produced with F series aggregates. It can be said that the compression force is more effective as the thickness increases in samples produced with M series aggregates. However, as the compression force increased, the strength decreased in 6 cm thick samples with 8–16 mm sized aggregate. The maximum strength decrease in samples produced with C series aggregates of 6 cm thickness was 25%. In 8 cm thick samples with 8–16 mm sized aggregate, the strength increased with the compression force, while the strength started to decrease after 50 kN. It is thought that these situations are due to the crushing tendency of coarse aggregates with increasing compaction energy, with the decrease in sample thickness. Figure 8 shows the crushed aggregate image after the compaction process.

Figure 8. Crushed coarse aggregates after compaction.

In M series mixtures, as the sample thickness increased, the strength increased at the same compression force. Density values may give an idea of how to explain this situation. Figure 9 shows the change in density and splitting tensile strength of M series. When Figure 9 is examined, it is seen that almost all density values increase at the same compression force with the increase in thickness. As a result, in the M series samples, as the sample thickness increased, the aggregates compacted better, the strength increased, and the infiltration rate decreased. Figure 10 shows the change in density and infiltration rate of M series.

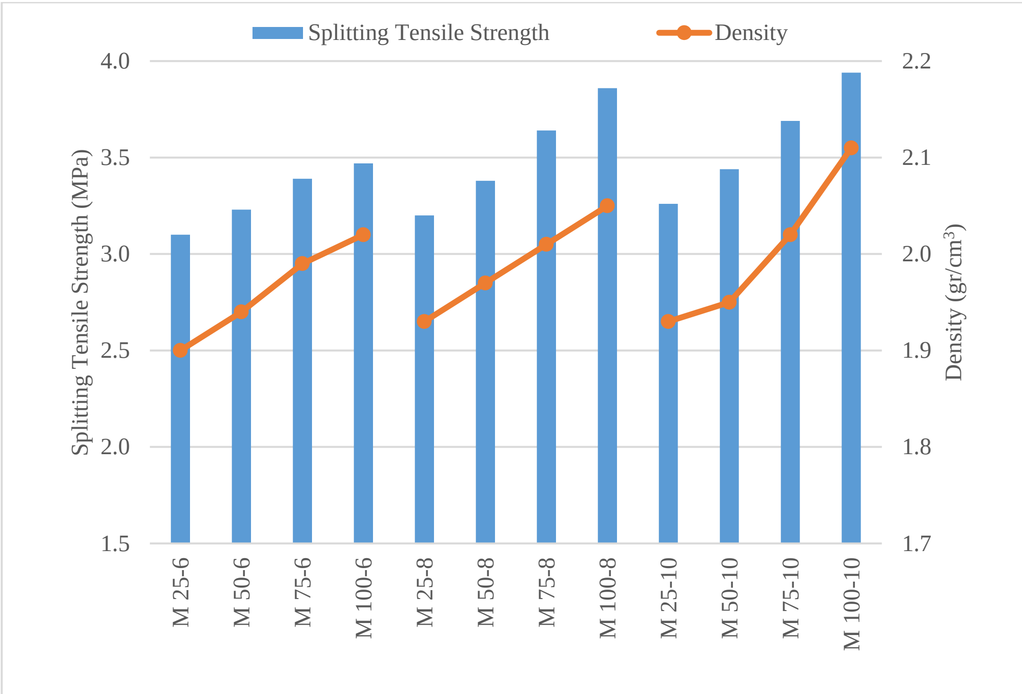

Figure 9. Density and splitting tensile strength in M series samples.

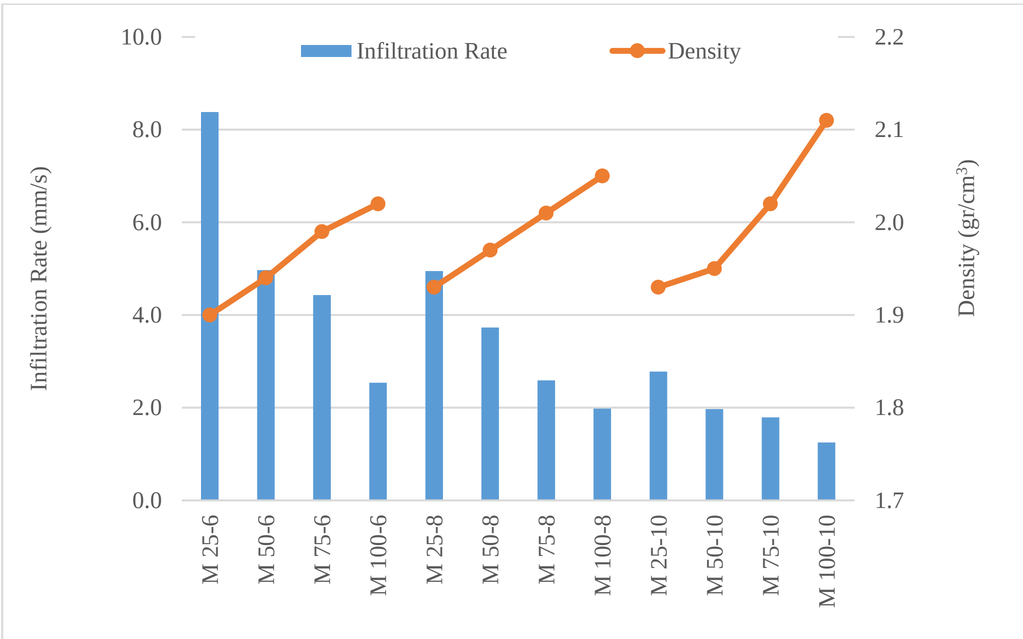

Figure 10. Density and infiltration rate changes in M series samples.

When the infiltration rate changes in all the series of mixtures were examined, it was observed that the infiltration rate decreases as the compression force increases, in all mixtures. Increasing sample thickness led to an increase in the infiltration rate at the same compression force level in the C series mixtures. However, this finding was not clearly observed in samples produced with F and M series aggregates. In fact, it was observed that the infiltration rate decreases as the thickness increases in M series samples at the same compression forces. This situation is thought to be related to the compaction characteristics in the aggregates, because the density increased as the thickness increased in samples produced with M series aggregates at the same compression forces. In addition, it was experimentally observed that increasing aggregate size was a factor that increased the infiltration rate. Regardless of the aggregate size differences, the ratio of the highest infiltration rate to the lowest one in 60 mm thick samples was found to be 46.22, and this ratio was 44.83 in 80 mm thick samples and 42.93 in 100 mm thick samples. For the samples with the same aggregate size and thickness, the related ratio did not exceed 3.3. Exceeding the optimum compression force can cause a dramatic drop in the infiltration rate.

In this study, compaction, which is very important for pervious concretes, was applied by using a press machine precisely, and, differently from the literature, four levels of pervious concrete blocks produced in 6, 8, 10 cm thicknesses, and the changes in splitting tensile strength and infiltration rate were investigated. Durability properties and field studies of pervious concrete blocks have planned for testing in future studies.

4. Conclusions

The effects of compression force (25–100 kN), sample thickness and aggregate sizes (2–4 mm, 4–8 mm and 8–16 mm) have been investigated on the strength and permeability properties of pervious concrete blocks in this study. Based on the results, the following conclusions can be drawn.

1. It has been found that compression is quite an influential parameter for the strength and infiltration rate of pervious concrete blocks. In the F and M series samples, it has been found that, among mixtures that have same thickness and aggregate size, as the compression force increases, the splitting tensile strength increases and the infiltration rate decreases. When the splitting tensile strength increase rates of the samples having the same sample thickness were examined, it was found that with the increase in the compression force, the increase in the splitting tensile strength of the samples reached up to 49%.
2. It has been observed that the expectation that strength will always increase with the increase in the compression force is not valid. In mixtures with 8–16 mm aggregates and 60 mm thickness, aggregates were crushed with the increase in compression force, which led to a decrease in the strength.
3. Pervious blocks produced with 4–8 mm aggregate, compressed with 75 kN force and having 80 mm thickness have been determined as the optimum block type.
4. The M 75-8 sample has enough splitting tensile strength, according to the TS 2824 EN 1338 (2005) standard, and has the highest permeability.
5. An effective new test method was developed to measure the infiltration rate on samples equivalent to those that strength measurements were carried out.

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