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Influence of binder, aggregate and compaction techniques on the properties of single-sized pervious concrete

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Abstract. In this paper, 18 single-sized pervious concrete mixtures were tested. The mixtures were prepared by altering: the amount and type of binder, type of aggregate, and the method of compaction. Concrete was compacted in layers in one of five different consolidation techniques: with standard tamping rod, wooden lath, concrete cylinder, or vibration of 12 and 40 s. Tests carried out on the specimens were: slump, density, porosity, coefficients of permeability, compressive strength and splitting strength. The relationships between porosity-density and porosity-strength were established. Two mixtures were selected for the preparation of test slabs on different subgrades and their permeability was tested according to ASTM C 1701-09 Standard. By comparing laboratory and field tests of permeability, it was concluded that the subgrade affects the test results. Measurements on the test slabs were repeated after 1 and 2 years of installation.

Keywords: pervious concrete; permeability; method of compaction; mechanical properties; test slabs

1. Introduction

At a time when environmental protection is becoming more and more important, the interest for pervious concrete is growing again. Pervious concrete was used for the first time in 1852 for the construction of two houses in the United Kingdom as no-fines concrete (Ghafoori and Dutta 1995). In the last half-century, it has been especially used in the USA and Japan, where it was developed as an environmentally friendly material (Bhutta *et al.* 2012, Ćosić *et al.* 2015). The basic characteristic of pervious concrete is high porosity and permeability. Porosity is achieved by the fact that there is little or no fine aggregate in the composition of concrete. Between 15% and 25% voids are achieved in the hardened concrete (Tennis *et al.* 2004) and high porosity reduces the strength of pervious concrete compared to standard concrete mixtures (Ibrahim *et al.* 2014, Mahboub *et al.* 2009, Mahalingam and Mahalingam 2016). Usually, their compressive strength is within the range of 3.5 to 28 MPa (Tennis *et al.* 2004), but some studies show that strength exceeding 50 MPa can be achieved without affecting permeability (Zhong and Wille 2015). Pervious concrete of lower strength can be used for lighter traffic loads such as footpaths, bicycle paths and parking places, swimming pool decks, tennis courts (Lian and Zhuge 2010, Kabagire and Yahia 2016). Due to a high void ratio, the main purpose of pervious concrete is to enable water from the concrete surface to penetrate into the lower layers and allow a more rational dimensioning or complete elimination of the stormwater drainage system. Its advantages include the reduction of traffic noise and urban heat islands (Fu *et al.* 2014). Wuman *et al.* (2018) investigated the effect of porosity on frost resistance of pervious concrete. They found that the compressive strength and the flexural strength of the pervious concrete decrease after 25 freeze-thaw cycles. Because of the high porosity of pervious concrete, more water will penetrate into concrete and so increase the freezing area between concrete and water.

Pervious concrete is a mixture of cement, coarse aggregate and water. Sometimes fibers (Rehder *et al.* 2014, Kevern *et al.* 2015, Dong and Gao 2011, Shoenberger and Tom 1992) can be added to achieve certain strength and durability, and poor abrasion resistance or low split tensile strength can be enhanced by adding latex (Wu *et al.* 2011, Wu *et al.* 2016, Huang *et al.* 2010). Since the recommended water and binder ratio is between 0.25 and 0.35 (Tennis *et al.* 2004, Schaefer *et al.* 2006) the effect of other parameters-binder, aggregate, and the method of compaction on the properties of pervious concrete is observed.

Binder-The recommended amount of cement ranges from 270 to 415 kg/m^3 of concrete (Tennis *et al.* 2004). The increase in the amount of cement reduces the amount of voids and permeability of concrete (Sonebi and Bassuoni 2013). For the production of pervious concrete, it is possible to replace part of the cement with supplementary cementitious materials such as fly ash (Sata *et al.* 2016) and silica fume. According to Sonebi *et al.* (2016) and Andrew and Bradley (2010), it is recommended to restrict the amount of fly ash up to 10% and silica fume up to 5%,

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while according to Ravi Teja and Sai Ranga Rao (2017) the optimal proportion of fly ash is 30%. Tho-in *et al.* (2012) created geopolymer pervious concrete with alkali-activated lignite high-calcium fly ash binder. Fu *et al.* (2014) tested the effect of silica fume and alkali-activated slag on the properties of pervious concrete. The addition of alkali-activated slag had better mechanical properties compared to the control mixture, while 20 and 30% of the silica fume addition had poorer properties. Toghroli *et al.* (2018) studied the waste materials as the partial cement replacement in pervious concrete. The properties of pervious concrete have depended on the waste materials' type.

Aggregate-may affect by origin and grain size distribution. The aggregate used for pervious concrete is usually a single-sized coarse aggregate or grading between 9.5 and 19 mm. Also, pervious concrete has been made with larger fractions, of 25 and 37.5 mm (Sonebi *et al.* 2016, ACI 522R-10, Report on Pervious Concrete 2010). According to Yang *et al.* (2008), by increasing the aggregate size, the connecting points between the aggregate are reduced, contact forces between the coarse aggregate weaken, reducing the strength of pervious concrete, but at the same time the content of effective voids and the permeability of pervious concrete increase. The authors suggest that the suitable maximum grain size of aggregates for pervious concrete pervious road base material is 26.5 mm. Larger grain ensures better permeability of concrete (Andrew and Bradley 2010, ACI 522R-10, Report on Pervious Concrete 2010). Adding little sand amounts reduces permeability, but increases strength. This is following the principle of packing density in the aggregate sample. The packing density of each aggregate fraction in the sample is almost the same and does not depend on the grain size (Krstulović 2000). By mixing the fractions, the packing density of aggregate increases and is the largest in gap-graded curves with the largest difference between the nominal sizes of the smallest and the largest fraction. The greater aggregate packing densities in concrete require less cement paste to fill the remaining voids.

The method of consolidation technique of pervious concrete can greatly affect its final characteristics. This is concrete of poor workability and is most often no-slump concrete. The compaction method has the biggest effect on strength and permeability (Ćosić *et al.* 2015, Croush *et al.* 2007). Rizvi *et al.* (2009) experimented with different methods of placing pervious concrete into cylinders to find the installation method that best simulates installation on the field. They used a standard rod and a Proctor hammer weighing 2.5 kg. The samples were compacted with the rod in three layers, with 25, 15, and 5 strokes, and with the Proctor hammer in 2 layers with 10 and 20 strokes. Although none of the samples had the same air content as the samples taken from the field, the content of the pores, however, was in the range characteristic of pervious concrete. Zhuge (2008) used two methods of consolidation technique: a hammer and a vibrating table. Compaction with hammer resulted in higher density concrete, but of weaker permeability. Vibration proved to be a more suitable method for limestone and dolomite concrete. To achieve maximum cohesion between the aggregate particles, Lian and Zhuge (2010) combined the standard rod with a static compactor in the consequent vibrating procedure. Such a compaction method should increase the strength of the concrete. In Putman and Neptune (2011) rods left holes in the compacted concrete, which greater degree of variability in the obtained results while consolidation using the standard Proctor hammer resulted in concrete with values of density and porosity closest to field samples. However, as one series of samples is compacted with 5 strokes and the remaining samples with 10 strokes, it cannot be concluded which way of installation is better. Mahboub *et al.* (2009) assessed two different ways of compacting pervious concrete: rod and pneumatic. The results showed that pneumatic compression results in compressive strength, permeability, and porosity of the concrete corresponding to pavement core, while the results of rod compacting are different from the concrete installed on the field. According to Chindaprasirt *et al.* (2008) pervious concretes having appropriate void ratios are produced with adequate paste content and flow and sufficient compaction with top surface vibration of 10 s with vibrating energy of 90 kNm/m^2. Yang *et al.* (2008) compacted pervious concrete in cylinder-shaped molds of 150 mm in diameter and 150 mm in height, vibrating on a vibrating table with a 5 kg load on the top of the cylinder, and the vibration process lasted 40 seconds for each sample. Kavern *et al.* (2009) used the gyratory compaction test method and observed the initial workability of pervious concrete and the resistance of the tested mixture to further compaction. In Shu *et al.* (2011) comparative field and laboratory tests were conducted that the field cores showed lower abrasion resistance, lower strength and higher porosity and permeability than the rodded specimens. Dong *et al.* (2013) used a standard rod to compact the specimens for their research where the Cantabro, loaded wheel and surface abrasion tests were evaluated and compared.

Time-due to the influence of rainfall that contains dissolved solids, dust and similar substances, the permeability decreases over time. The permeability of concrete may also decrease due to covering concrete with sand in coastal areas. In Haselbach *et al.* (2006) the authors tested the permeability of concrete after covering it with fine sand and then simulating runoff. In Deo *et al.* (2010) the reduction of permeability due to clogging was tested by experimental tests and model testing and the term “clogging potential” was defined.

The experiment of this paper involved two stages: laboratory and field tests. Laboratory tests aimed to determine how the compaction method and binder materials affect the characteristics of single-grain pervious concrete. Field tests aimed to determine how much the laboratory results differ from the field tests, and how the permeability of the built-in concrete decreases over the time, because according to Sonebi *et al.* (2016) “... there is a need for more studies focusing on the correlating results obtained from laboratory to field data, concerning compaction, porosity, permeability, curing, quality of joints, and durability of PCPC.”.

2. Part I - Laboratory tests

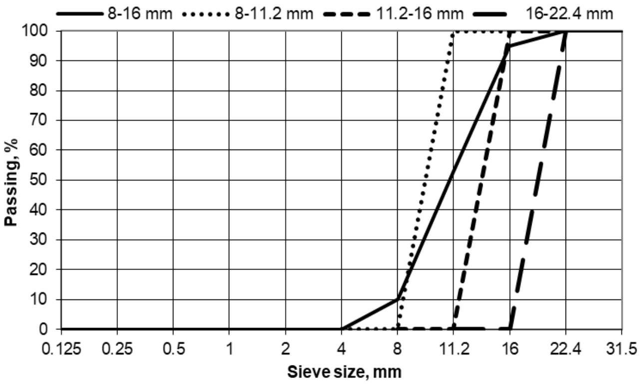


Fig. 1 Grain-size distribution curves of aggregate fractions

2.1 Materials and preparations of specimens

To test the influence of the compacted method and composition on the characteristics of pervious concrete, a total of 18 pervious concrete mixtures were made. Cement CEM II/B-S 42.5 N, silica fume, fly ash and crushed limestone and natural aggregate were used. The fraction of the aggregate was 8-16 mm, and for some mixtures, the fraction was separated at 8-11.2 mm, 11.2-16 mm without oversized and undersized grain, Fig. 1.

A fraction of 16 to 22.4 mm was prepared for one mixture. All concrete mixtures were pure single-grain, except for a mixture of two-grade fractions of 8-11.2 mm and 16-22.4 mm with 2:3 by weight. No chemical additives were added to the mixtures. Two mixtures had a total amount of binder of 450 kg, two mixtures of 400 kg, 12 mixtures had a total amount of binder of 350 kg, and two mixtures of 250 kg of cement per m^3 of concrete. The initial value of the water/binder ratio was 0.35, but the amount of water was corrected during mixing so that a stable ball could be formed in hand without crumbling or loses its void structure as the paste flows into the spaces between the aggregates (Tennis *et al.* 2004), Fig. 2(a). The real values of w/b-ratio are shown in Table 1. The dry components were mixed for 1 minute in a pan mixer and then water was added and the mixing continued for the next 5 minutes.

The measured consistency of fresh concrete according to HRN EN 12350-2. Testing fresh concrete - slump test for all samples is between 0 and 1 cm, Fig. 2(b).

The samples were compacted in 5 different ways in cubes of 15 cm in size and cylinders of 10 cm in diameter and 20 cm in height. Each sample was cast into the mold in 3 equal layers by compaction or vibration. The compacting was done in one of the ways mentioned above: each layer with 25 strokes with a tamping rod or wooden lath (30×10×5 cm) and hammer or compacting with a concrete cylinder weighing 1.5 kg. Samples compacted by vibration were placed on Vebe vibrating table. On 3 series of samples, the first 2 layers were vibrated for 5 seconds and the third for 30 seconds. 4 series of samples were vibrated for about 3.75 s per layer so that the total vibration time was less than 12 s. In the combination of 5+5+30 seconds, the total vibrating time of samples is based on test results (Yang *et al.* 2008). During vibration, the samples in the mold were pressed with a wooden lath.

(a) ball of mixture P5

(b) the slump of mixture P5

Fig. 2 Testing of concrete in a fresh state

The composition and compacting method of each mixture is given in Table 1.

After casting the samples are kept in the mold for 24 hours, after that they are put in water at 20±2°C until the test day, in accordance with the HRN EN 12390-2. Testing hardened concrete - Part 2: Making and curing specimens for strength tests.

2.2 Testing in the hardened state

The properties of the hardened pervious concrete specimens were carried out on 28 days aged samples as follows:

-density and porosity were tested on cube specimens of 15 cm edge length. Porosity was determined by the expression

$$P = 1 - \left(\frac{\frac{M_1 - M_2}{\rho v}}{V} \right) \cdot 100\ (\%) \tag{1}$$

where M_1 is sample weight air-dried for 24 h, M_2 is the pervious concrete sample submerged underwater weight, ρ_v is the density of water and V is the pervious concrete sample volume.

- permeability

Huang *et al.* (1999) and Huang *et al.* (2010), defined the relationship between hydraulic gradient (i) and discharge velocity (v) in the form

$$v = K' i^m \tag{2}$$

Table 1 Composition of the mixtures, quantity for 1 m^3 and method of compactions

Mixture	Cement	*w/b*	Silica fume	Fly ash	Aggregate			
					8-16 mm	8-11.2 mm	11.2-16 mm	16-22.4 mm
	kg/m^3		kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3
P1	315	0.35	35		1473.1			
P2	280	0.35	70		1463.5			
P3	245	0.35	105		1453.8			
P4	350	0.35	50		1377.3			
P5	315	0.35		35	1472.2			
P6	280	0.35		70	1461.7			
P7	245	0.35		105	1451.1			
P8	350	0.35		50	1375.9			
B1	350	0.34				1486.32*		
B2	350	0.27					1486.32*	
B3	400	0.26					1396.19*	
B4	250	0.32				666.63*		999.94*
B5	350	0.28						
B6	350	0.28				1486.2		
B7	350	0.29			1486.2			
B8	250	0.35			1666.6			
B9	350	0.33				1486.2		
B10	350	0.32					1486.2	

Method of compactions:

(grey)	Intensive compacting of a sample by concrete cylinder weighing 1.5 kg
	Vibration, in 3 layers < 12 s
(yellow)	Compacting by wooden lath and hammer, 25 impacts, in 3 layers
(blue)	Rodding by metal rod in 3 layers, 25 impacts per layer
(green)	Vibration for 40 s (the first layer 5 s + the second layer 5 s + the third layer 30 s)

* Natural aggregate

where *K'* is a pseudo coefficient of permeability and can be used to compare hydraulic conductivity of different materials and m is a shape parameter. The authors derived this expression (2) because of high porosity and the interconnected air voids path in pervious concrete, Darcy's law for laminar flow is no applicable.

In this research, permeability by falling head method (FH) and constant head (CH) was tested on cylindrical specimens in accordance with Sandoval *et al.* (2017).

Permeability coefficient FH (mm/s) was determined according to the expression

$$FH = \frac{a}{A} \cdot \frac{L}{t} \cdot log\frac{H_g}{H_d} \quad (3)$$

where L is the length of the specimen, t is the time required for the water to pass from level H_g to H_d through the pipe, H_g is the initial height of the water, H_d is the final height of the water, a is the area of the cylindrical pipe and A is the area of the specimen

Permeability coefficient CH (mm/s) was defined by the expression

$$CH = \frac{V \cdot L}{H_{const} \cdot A \cdot \Delta t} \quad (4)$$

where V is collected volume of water, L is the length of the specimen, H_{const} is constant for all tests being equal to 320 mm, A is the area of the specimen, Δt is the time required to get V volume that has drained, which is in this test 30 s. This test follows the principle of Darcy's Law (ASTM D2434-68 Standard Test Method for Permeability of Granular Soils (Constant Head), 2006) and therefore, it is recommended by the Report on Pervious Concrete ACI 522R-10, 2010.

-compressive strength was determined on 3 cube-shaped specimens of 15 cm with a constant loading rate of 0.50MPa/s in according to HRN EN 12390-3. Testing hardened concrete - Part 3: Compressive strength of test.

-tensile strength by splitting was tested on cylindrically shaped samples by loading them with a constant rate in the range of 0.04 to 0.06 MPa/s according to HRN EN 12390-6. Testing hardened concrete-Part 6: Tensile splitting strength of test specimens.

2.3 Results and discussion

The results obtained by the tests are shown in Figs 3, 6, and 8 and Table 2.

According to Fig. 3, the density values range from 1714.38 to 2069.63 kg/m^3 and porosity from 18 to 36.4%, which is more than the usual 15 to 25% (Tennis *et al.* 2004). As can be seen in the diagram, concrete of higher porosity has a lower density. The least pervious samples are the ones with added silica fume. Samples B1, B2, B9, and B10 have the same amount of cement, are equally placed, have the

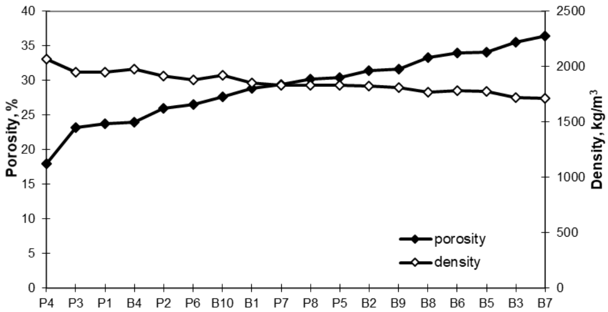


Fig. 3 Porosity and density of pervious concrete specimens

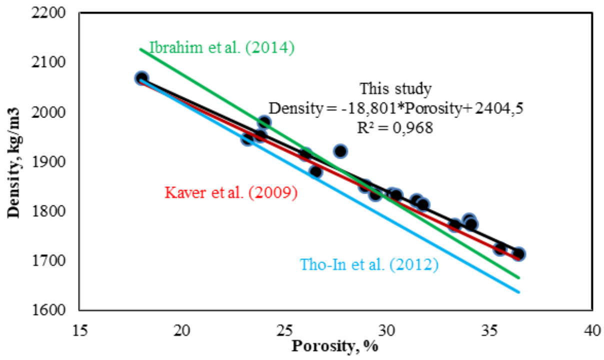


Fig. 4 Relation between porosity and density of pervious concrete

Table 2 Measured values of permeability by the method of the falling head (FH) and constant head (CH). The colors correspond to the compacting method as shown in Table 1

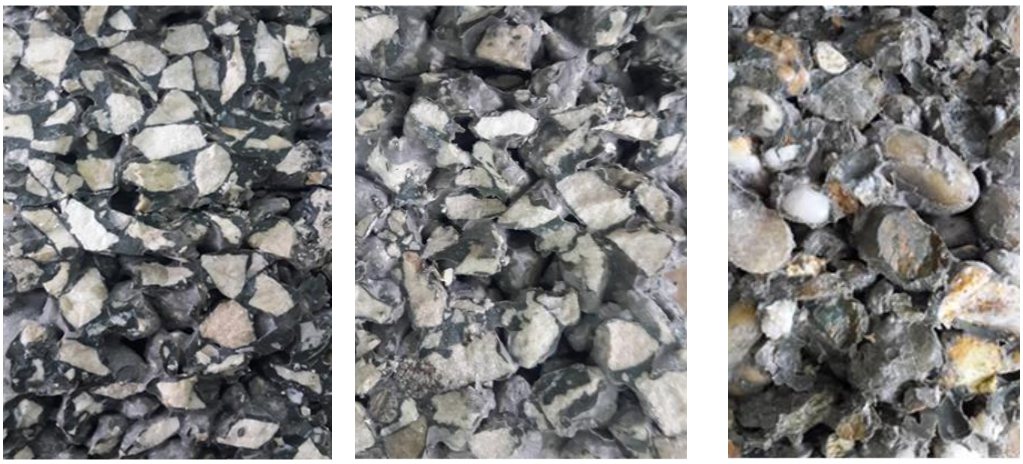
Mixure	FH-Falling head	CH-Constant head
B6	29.00	23.54
B8	28.70	24.12
B7	27.72	22.20
B5	23.79	20.14
P8	22.75	12.05
B4	21.60	16.24
P5	21.21	13.49
P6	18.24	10.74
P7	16.72	10.46
B2	14.45	11.85
B10	12.65	10.86
B3	10.95	8.87
P3	9.39	2.28
B1	8.37	7.26
B9	8.13	6.96
P1	7.32	4.34
P2	4.43	2.75
P4	0.00	0.00

same amount of aggregates, but the aggregates in B1 and B2 are natural and in B9 and B10 are crushed aggregates. B1 and B9 have smaller grain than B2 and B10. The lowest porosity has B10, then B1, and then B2 and B9. In the combination of mixtures with natural aggregate (B1 and B2), smaller grain resulted in lower porosity, while in the mixture with crushed aggregate (B9 and B10) it was vice versa. The result obtained for the crushed aggregate is following Joshaghani *et al.* (2015) where it is concluded that "The void ratio of specimens is slightly higher for larger size aggregates due to higher surface area of the aggregates". B3 has a higher porosity than B2 even though it is made of more cement.

The relationship between porosity and density can be shown by linear connection, Fig. 4. The obtained linear connection is practically identical to that obtained by Kaver *et al.* (2009). For lower porosity values, almost the same density is obtained as in this test Tho-in *et al.* (2012) and Kevern *et al.* (2009), while the porosity of about 30% is similar to the value in this test Ibrahim *et al.* (2014) and Kevern *et al.* (2009).

The results of the permeability test by both methods gave almost the same trend of concrete. Coefficients obtained by the FH method are slightly higher than CH.

According to the constant head method, the best permeability was that of mixture B8, compacted by vibration in 40 seconds, with the smallest amount of cement, followed by mixtures B6 and B7 with slightly more cement and placed by a wooden lath and hammer. In the case of the falling head



(a) B6 (b) B8 (c) B4

Fig. 5 Cross-section of mixtures B6, B8, and B4

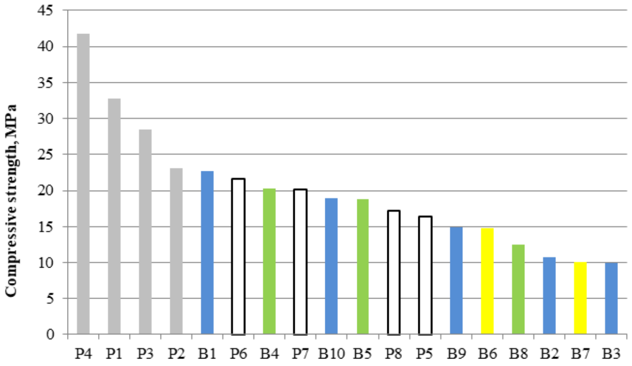


Fig. 6 Compressive strength

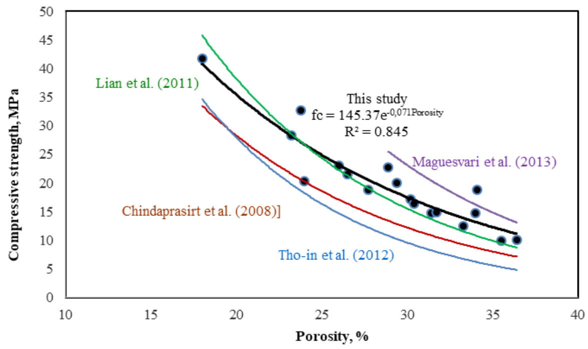


Fig. 7 Relationship between porosity and compressive strength of pervious concrete

method, the order was B6 (Fig. 5(a)), B8 (Fig. 5(b)), and B7. All three mixtures have similar permeability. These are, according to results, followed by concrete with the addition of fly ash compacted with the vibration of up to 12 s, and concrete without additives compacted with the rod and finally, the worst permeability was in the mixtures with the addition of silica fume that was placed by compacting with the concrete cylinder. Longer vibrations favorably affect the permeability of concrete. Concrete with fly ash has much better permeability compared to concrete with silica fume. Mixtures B4 and B8 are placed in the same way and have the same amount of cement. Unlike B8 with crushed aggregate, B4 has a natural aggregate with the discontinuity of 11.2 to 16 mm, Fig. 5(c).

Discontinuity increased the packing density of aggregate in the mixture, thereby reducing the permeability of concrete. This is also confirmed by Fig. 3 because the mixture B4 has higher density and lower porosity than B8. In the combination of B1, B2, B9, and B10, larger-grain concrete has better permeability.

The correlation between the permeability coefficients CH and FH can be fitted in a linear line as shown in the following equation

$$CH = 0{,}8024 \cdot FH - 0{,}5875 \tag{5}$$

with R^2 of 0.95. Sandoval *et al.* (2017) established correlation $CH=1.518{\cdot}FH^{2.95}$ with R^2 of 0.97, but all samples were produced with the same amount of aggregates, cement, and water/cement ratio (*w/c*).

Fig. 6 shows the results of compressive strength. The column colors correspond to the compaction method as shown in Table 1.

Compressive strength is the highest in concrete with silica fume, and the addition of fly ash has a positive effect on the strength of the concrete. For the silica fume mixtures, better strength is achieved on samples with a smaller amount of silica, and in the mixture of fly ash is the reverse. Of the mixtures without additives, the best are B1, B4, B10, and B5. Mixture B1 made from natural aggregates, of fraction 8-11.2 mm, and placed by compacting with a steel rod, has the highest compressive strength, while mixture B3, of 11.2-16 mm fraction and the same compacting method and aggregate type as mixture B1, has the lowest compressive strength. Mixture B3 contains 50 kg/m^3 of cement more than mixture B1. Mixture B2 has higher compressive strength than B3 by 0.8 MPa. Both mixtures are compacted by the same method, have the same amount, type and fraction of aggregates, but mixture B2 contains 50 kg/m^3 of cement less.

The results of the strength of B2 and B3 confirm the study Yang *et al.* (2008), where it was concluded that reducing the cement content in the mixture increases compressive strength. According to Yang *et al.* (2008) and Maguesvari and Narasimha (2013) in single-grain mixtures, samples of smaller nominal fractions have higher compressive strength, which in this study is confirmed only for mixtures with natural aggregate. In mixtures with crushed aggregates B6 and B7, B9 and B10 samples with higher nominal fraction size have higher strength. Mixtures B10 and B5 have the same composition of solid components but are differently placed. Their strength varies by less than 0.1 MPa, but mixture B5 is pervious and has much better permeability. In this case, vibration had a positive effect. Mixture B4 was compacted in the same way. With the smallest amount of cement and good permeability, its strength is 20.3 MPa. The discontinuity of the aggregate composition and the impact of vibration during the installation of B4 contributed to this result, because mixture B8, containing the same amount of cement and aggregate, has a much lower strength. In the combination of mixtures B1 and B2, the smaller nominal size of the aggregate yielded greater strength and in the combination of B9 and B10, it was vice versa, which is in accordance with their porosity. As stated in the introduction, pervious concrete can develop compressive strengths in the range of 3.5 to 28 MPa (Tennis *et al.* 2004) and the obtained results are in the range of 9.87 to 41.83 MPa.

According to Chindaprasirt *et al.* (2008) and Chindaprasirt *et al.* (2009) the relation between strength and porosity can be shown as follows

$$f_c = f_{c0} e^{-bV} \tag{6}$$

where f_c -compressive strength in MPa, f_{c0}-compressive strength for zero void concrete, V is porosity in % and b is experimental constant. Fig. 7 shows the equation obtained in this test, as well as the test results of other authors Tho-in *et al.* (2012), Chindaprasirt *et al.* (2008), Maguesvari and Narasimha (2013) and Lian *et al.* (2011).

The obtained results are closest to the expression obtained by Lian *et al.* (2011), while for greater porosity the result of this test lies between the expressions Maguesvari and Narasimha (2013) and Lian *et al.* (2011).

The results obtained by the splitting of the samples are shown in Fig. 8.

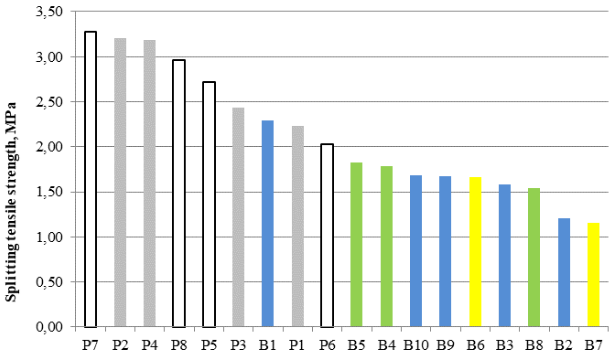


Fig. 8 Splitting tensile strength

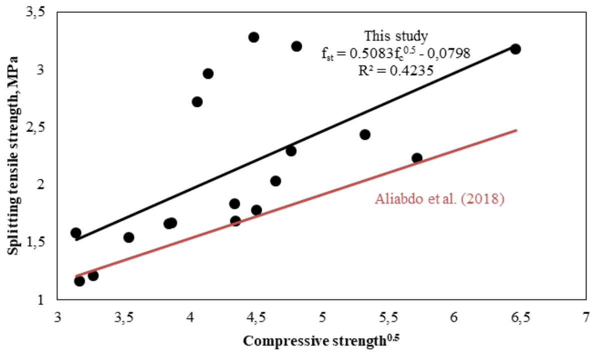


Fig. 9 Correlation between splitting tensile strength (f_t) and the square root of compressive strength $(f_c)^{0.5}$

Concrete with supplementary cementitious materials has better tensile strength values by splitting method. The best mixture is P7, followed by P2 and P4. Of concrete without additives, the best is B1, followed by B5 and B4. If it is taken into account that the mixtures with the addition of silica fume and B1 do not have high permeability, vibration favorably affects the tensile strength obtained by the splitting of the samples.

Fig. 9 shows the relationship between the square root of compressive strength and splitting tensile strength, according to Aliabdo *et al.* (2018), where authors obtained a similar coefficient of correlation R^2=0.4469.

3. Part II - Field tests

3.1 Preparations of specimens

Concrete tested in the laboratory should also be tested on the field. According to Table 2, mixtures B6, B7 and B8 have the best permeability. For this test, mixtures B6 and B7 were selected because they can be compacted on the field in the same way as in the laboratory. According to the composition for these mixtures, test slabs of dimensions 80×80×15 cm were installed (Brnas and Juradin 2016). The possibility of using selected mixtures for a pervious concrete pavement to be used for the parking area of passenger cars with a small axle load by recommendations of the Guide for the Design and Construction of Concrete Parking Lots, ACI 330-08 by the American Concrete Association (ACI), is also being considered. The target

Fig. 10 Three types of subgrades: soil, clean drainage stone (the crushed aggregate 8-16 mm) and grass

Fig. 11 Installation of test slabs

flexural strength is 3.5 MPa, which is sufficient for more than adequate for most low-volume pavement applications. Following Guide for the Design and Construction of Concrete Parking Lots, the selected plate thickness was 15 cm. The slabs were built on three types of subgrades: soil, clean drainage stone (the crushed aggregate 8-16 mm) and grass, Fig. 10.

The placed was done by compacting with a wooden lath and hammer in 3 layers, Fig. 11. When casting each layer, the concrete was uniformly distributed and compacted within the formwork. The slabs were installed in the field, next to the parking lot of the faculty. This was a parking area where there was no danger of the freezing and thawing cycles, so additional tests were not be performed. The slabs were about 100 m away from the road and were not directly exposed to traffic.

Mixtures B6 and B7 were tested for tensile strength on 28-day samples of dimensions 120×120×450 mm according to HRN EN 12390-5. Testing hardened concrete - Part 5: Flexural strength of test specimens. The values for mixture B6-3.4 MPa and B7-4.3 MPa were obtained. According to Tennis *et al.* (2004), the bending strength of pervious concrete ranges from 1 to 3.8 MPa, both mixtures meet this criterion but only mixture B7 meets the required flexural strength of 3.5 MPa (ACI 330-08). However, for using selected mixtures for pervious concrete pavement, the compressive strength of this mixture (Fig. 6) should be increased.

3.2 Testing on test slabs

The first measurement of the infiltration rate on test slabs according to ASTM C 1701 Standard Test Method for Infiltration Rate of In-Place Pervious Concrete was made as soon as the slabs reached the required strength and the measurements were repeated after one and two years concerning the first test. The surface was swept before each measurement. The permeameter (steel ring) to the pavement was secured with sealant, Fig. 12. According to this standard, a pre-wetting test should be made, followed by an actual test within 2 minutes of prewetting. The infiltration rate is determined according to the expression

Fig. 12 The measurement of the infiltration rate on test slabs according to ASTM C 1701 Standard

Table 3 Measurement results in laboratory and field on pervious concrete B6 and B7

Test slab	Measured permeability values, mm/s		
	FH-Falling head	CH-Constant head	ASTM C 1701
B6-Soil	29.00	23.54	26.3
B7-Grass			15.8
B7-Gravel	27.72	22.20	15.5
B7-Soil			3.8

$$I = \frac{\mathrm{K \cdot M}}{\mathrm{D}^2 t} \tag{7}$$

where I is infiltration rate, M is mass of infiltrated water, D is the inner diameter of infiltration ring (30.48 cm -12 in.), t is the time required for a measured amount of water to infiltrate the pavement and K is constant of 4583666000 (Anderson *et al.* 2013).

The results obtained after the installation of the test slabs are presented in Table 3, with the results of the laboratory measurements on cylinder samples B6 and B7.

According to Netinger Grubeša *et al.* (2018), the measured permeability values according to ASTM C 1701-09 are always lower than in laboratory tests. In this study, the values for the B6 mixture are in the range of laboratory tests, while for B7 mixture they are lower and different: the results for grass and gravel subgrade are almost the same, but the soil subgrade significantly deviates. The possible cause of the low infiltration rate of the B7 mixture on soil subgrade is the impermeable subgrade (clay or rocks) underneath the slab because the slab was installed on the rock-filled ground. Since the composition and installation of mixtures is the same for laboratory and field tests, the permeability of the built-in concrete also depends on the permeability of the subgrade on which it is placed.

Fig. 13 shows measured permeability values on test slabs over two years. It is evident that the permeability of concrete significantly decreases over time.

The largest decrease in permeability occurs one year after installation, which means that at the latest during this period, it is necessary to start cleaning the pervious concrete in accordance with the recommendation Drake and Bradford (2013), while the authors Gunderson (2008) and Henderson and Tighe (2012) recommend cleaning 2 to 4 times a year, depending on the area and weather conditions (Kia *et al.* 2017). According to Hein *et al.* (2013), the most efficient way to clean pervious concrete is the so-called VPWV method (Vacuum/Pressure Wash/Vacuum).

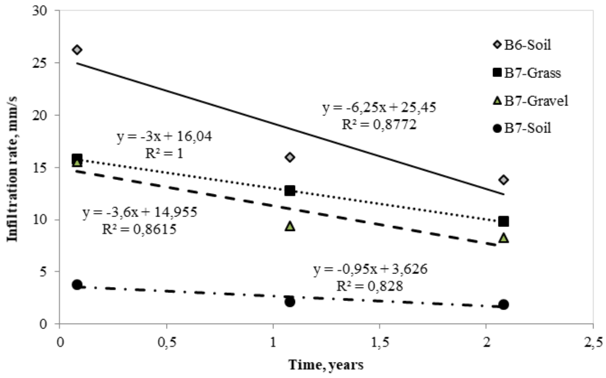


Fig. 13 A trend of a decreasing infiltration rate over time for test slabs

4. Conclusions

In this paper, the properties of single-sized pervious concrete with the various amount and type of binder, type of aggregate, and the method of compaction were tested. For testing purposes, test slabs were made on the field, equally compacted as the laboratory specimens. Based on the results obtained, it can be concluded that:

- Supplementary cementitious materials such as fly ash and silica fume reduce concrete porosity but increase strength. Fly ash has an overall better effect on pervious concrete.
- In single-sized mixtures with natural aggregate, smaller grain yields lower porosity and greater strength while in mixtures with crushed aggregate it is reversed.
- Vibration favorably affects the permeability and strength of concrete, longer vibration gives better permeability and shorter vibration gives better strength. Excessive concrete compaction can adversely affect permeability.
- The gap-graded aggregate curves increase the packing density of aggregate, so the concrete with a smaller amount of cement has good strength. Increasing the strength can be achieved by increasing the gap between the nominal sizes of the smallest and the largest fraction, with the expected reduction in permeability.
- The established relationship between porosity-density and porosity-compressive strength is in accordance with the so far proposed terms.
- This study presents a liner equation to correlate the permeability results obtained by the method of the

falling head (FH) and constant head (CH).

• The test slab made with a fraction of 8-11.2 mm has better permeability and strength than the standard 8-16 mm slab. Since the fraction is used in the asphalt industry, the application of such concrete should not be a problem.

• The permeability of the built-in concrete, apart from the composition, depends on the compaction method, the subgrade on which it is placed, as well as the time elapsed after installation. It is necessary to establish a relation between the laboratory and field measurement methods and to consider the impact of the permeability of the subgrade on which pervious concrete is installed.

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