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Effect of coarse aggregate characteristics on the permeability properties of pervious concrete

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Abstract. This study analyses the effect of the geometric characteristics of coarse aggregate particles on the physical-mechanical properties and durability of hardened permeable concrete prepared by vibropressing compaction method. Four types of coarse aggregate were used to prepare the concrete mixture: gravel and crushed gravel stone of particle size fraction 4/16 and 8/16. The particle size and shape (rounded and rectangular) were considered. Four different concrete mix compositions were tested. The following properties of hardened permeable concrete were analysed in comparison: total porosity, water permeability, density, compressive strength, frost resistance, and abrasion resistance. The findings of this study showed that particle size and shape influence the physical-mechanical properties of permeable concrete. The total porosity and water permeability values were higher in the test specimens where crushed gravel stone of fraction 4/8 mm and 8/16 mm was used as coarse aggregate. The resistance of permeable concrete to volumetric freezing and thawing depends on the frost resistance of the coarse aggregate. It was also found that abrasion resistance of permeable concrete is affected by ravelling, i.e. disintegration of angular coarse aggregate particles from the concrete matrix.

Keywords: permeable concrete, physical-mechanical properties, durability

1. Introduction

Permeable concrete (PC) is a material that comprises cementitious binders, coarse aggregates, fine aggregate, water, admixtures and additives. PC is also called porous concrete, pervious concrete, no-fines concrete, gap-graded concrete, and enhanced-porosity concrete [1]. The main application of permeable concrete is in pavements as it rapidly drains and removes rainwater from the pavement surface, filters pollutants and preserves the natural hydrologic functions. It also can be used for parking lots, sidewalks, pathways, tennis courts, patios, slope stabilization, swimming pool decks, greenhouse floors, zoo areas, road shoulders, drains, noise barriers, friction courses for highway pavements, permeable bases under a standard concrete paving, and low-volume roads.

PC is relatively porous with most of the volume filled with coarse aggregate, which creates more pores in the structure, leading to higher water infiltration [2]. The infiltration is the main parameter that describes the functionality of PC [3]. The increase in the porosity of PC leads to an increase in permeability. The grading of aggregate for PC influences the permeability coefficient [4]. A higher permeability can be obtained by leaving out fine aggregate, designing single grain graded mixes or double size grain graded mixes with the gap in the grading.

The porous structure may compromise the structural strength of PC [5] because it is determined by the properties of cement paste (cement content, water to cement ratio, compaction level), coarse aggregate and the interface between the coarse aggregate and the cement paste [5-7]. The stiff consistency of PC mixture requires considerable compaction efforts to achieve the desired mechanical performance, without neglecting permeability properties, which strongly depend on the open porosity of PC [8]. Resistance of PC to freeze-thaw cycles and abrasion challenge its durability properties. The pores in PC products can provide frost resistance if water passes through the pores freely without being trapped inside the pore structure before freezing [9]. Sand, latex and air-entraining agents added to PC mixture improve the resistance of PC to freeze-thaw cycles as they preventing de-bonding between the aggregates and the cement paste. Air entrainment in a cement paste can also improve frost resistance of PC [1]. PC specimens made with smaller-size aggregates and tested by different methods produced better abrasion resistance values than the specimens made with larger-size aggregates [10]. The addition of latex can improve the abrasion resistance of PC, while the use of polypropylene fibres did not show any significant effect on abrasion.

This study aims to determine the effect of the size and shape of the local coarse aggregate particles on the physical-mechanical properties and durability of hardened permeable concrete.

2. Materials and methodology

Portland cement CEM I 42.5 R from Heidelberg Cement Group (Sweden) satisfying the requirements of standard EN 197-1 was used for the tests. The cement has the following physical and mechanical properties: compressive strength after 2 days ≥20.0 MPa, after 28 days ≥42.5≤62.5 MPa, initial setting time 180 min, volume stability 1.0 mm and specific surface area (by Blaine method) 575 m^2/kg.

Two types of coarse aggregates from the local quarries in Lithuania were used: gravel and crushed gravel stone. Particle size fractions 4/16 mm and 8/16 mm of both aggregates were tested. Gravel particles had a round shape and smooth surface. Crushed stone particles had a rectangular shape and rough surface. The granulometric properties of the coarse aggregates were determined according to the standard EN 12620 and are presented in Table 1.

Table 1. Sieve analysis data of the coarse aggregates

Sieve opening size, mm	Passing, %	
	Gravel fraction 4/16 mm	Crushed stone fraction 4/16 mm
32.0	100.0	100.0
22.0	100.0	100.0
16.0	96.6	95.5
11.0	73.9	71.7
8.0	48.4	44.0
5.6	26.0	15.7
4.0	8.2	6.8
2.0	1.6	1.8
1.0	1.0	1.0
0.5	0.8	0.7
0.125	0.6	0.6
0.063	0.5	0.5
On the sieve bottom	0.3	0.3

Gravel of particle size fraction 8/16 mm was obtained from the gravel of particle size fraction 4/16 mm by sieving with the sieves of appropriate opening sizes. Crushed gravel stone of particle size fraction 8/16 mm was prepared in the same way from crushed gravel stones of particle size fraction 4/16. The coarse aggregates used in the research were not washed and contained some dust. The gravel of particle size fraction 4/16 mm had the following physical properties: dry bulk density 1547 kg/m^3, specific gravity 2655 kg/m^3, water absorption 1.69%, particle shape index (*SI*) 5%, particle flakiness index (*FI*) 4%, resistance to fragmentation according to Los Angeles test (EN 1097-2) 25% and strength of coarse aggregate according to fragmentation index M_{fi} (LST 1476.7) 8.4 MPa. The crushed gravel stone of particle size fraction 4/16 mm had the following physical properties: dry bulk density 1451 kg/m^3, specific gravity 2667 kg/m^3, water absorption 1.58%, particle shape index (*SI*) 13%, particle flakiness index (*FI*) 11%, resistance to fragmentation according to Los Angeles test (EN 1097-2) 26% and strength of coarse aggregate according to fragmentation index M_{fi} (LST 1476.7) 9.0 MPa. The shape index of the coarse aggregates was calculated according to EN 933-4 as the ratio of the mass of the test portion to the mass of the non-cubical particles. The length (*L*) to thickness (*E*) ratio of non-cubical particles was > 3. Particle flakiness index was determined according to EN 933-3 as the percentage (by mass) of aggregate particles having an average least dimension of less than 0.6 times their average dimension.

Four different concrete mix compositions were analysed in the experimental part of the research basing on literature analysis. The water to cement ratio in all mixes was 0.34, coarse aggregate to cement ratio was 5.8 and no admixtures were added. The concrete mix composition differed by the type of coarse aggregate used. The clump shaping method was used to check if the chosen PC mix proportions were adequate [1]. A small amount of mix was extracted by hand and a clump was shaped and observed with palm open. The concrete mix proportions were satisfactory because the clump of fresh concrete preserved its shape and no cement paste bleeding was observed. And vice versa, If the clump of fresh concrete not preserved its shape the concrete mix proportions were not satisfactory. However, a small amount of cement paste segregated at the bottom of the mould in test specimens PC-3 and PC-4 while preparing the specimens and applying vibration and additional load simultaneously. It means that the content of the cement paste should be reduced when bigger-size aggregates (8/16 mm) are used. The concrete mix designs with the amounts of materials (kg per m^3) used are presented in Table 2.

Table 2. Compositions of tested mixture series

Materials	Unit	Specimen designation			
		PC-1	PC-2	PC-3	PC-4
Portland cement	kg	350	350	350	350
Water	l	119	119	119	119
Gravel fraction 4/16	kg	2030	-	-	-
Crushed gravel stone fraction 4/16	kg	-	2030	-	-
Gravel fraction 8/16	kg	-	-	2030	-
Crushed stone fraction 8/16	kg	-	-	-	2030
W/C	–	0.34	0.34	0.34	0.34

The concrete was mixed from dry materials in a rotating pan mixer Zyklos ZZ 50 HE from Pemat (Germany) under laboratory conditions. The mixing was done in two stages. First, coarse aggregates and 2/3 of the water were poured into the moistened mixer and mixed for about one minute. After the first cycle the mixture was left to stand for two minutes. Second, Portland cement and 1/3 of water were added and the mixture was mixed for about 2 minutes.

Slump test of fresh concrete was conducted according to EN 12350-2 when the mix was prepared.

The test specimens were cast in moulds in the laboratory and were compacted using a vibration table with an oscillation frequency of 50 Hz and amplitude of 0.5 mm. Concrete test specimens of 71×71×71 mm dimensions and 100×100×100 mm dimensions were cast in metal moulds. To imitate the vibropressing compaction method a load of 11.63 kg (with the size of 100×295×50 mm) was used to compact two test specimens with the size of 100×100×100 mm in each mould (Figure 1). Vibration time during the compaction of the fresh mixture was 15 ± 1 s. The test specimens with the size of 71×71×71 mm were used to determine the wear resistance of concrete, while the test specimens with the size of 100×100×100 mm were used to determine the total porosity, density, compressive strength and frost resistance of concrete. Concrete test cylinders with the diameter of 110 mm and height of 320 mm were cast in plastic moulds. These test specimens were used to determine water permeability of concrete. After the casting and compacting of concrete mixtures, all test specimens were kept in moulds in the laboratory at the temperature of 20±5ºC for approximately 20 hours. Then the test specimens cast in metal moulds were demoulded and cured in the environmental chamber for 28 days at the temperature of 20±2ºC and humidity of 90%. The test cylinders with the diameter of 110 mm and height of 320 mm were not demoulded and kept in plastic moulds in the same environmental chamber for the curing period of 28 days.

Figure 1. View of the test specimen compaction under the load of 11.63 kg (left: mould without load, right: mould with load).

The total porosity of permeable concrete specimen with the size of 100×100×100 mm was calculated from the equation (1):

$$P = \left[1 - \left(\frac{W_1 - W_2}{q_w \cdot V}\right)\right] \times 100, \% \tag{1}$$

here: P is total porosity of permeable concrete, %; W_1 is mass of the permeable concrete specimen air-dried for 24 hours, kg; W_2 is mass of the permeable concrete specimen submerged in water, kg; V is volume of the permeable concrete specimen, m^3; q_w is density of water, kg/m^3.

Water permeability of permeable concrete was defined by the permeability coefficient k, which was calculated from the equation (2):

$$k = \frac{Q \cdot L}{A \cdot h \cdot t}, mm/s \tag{2}$$

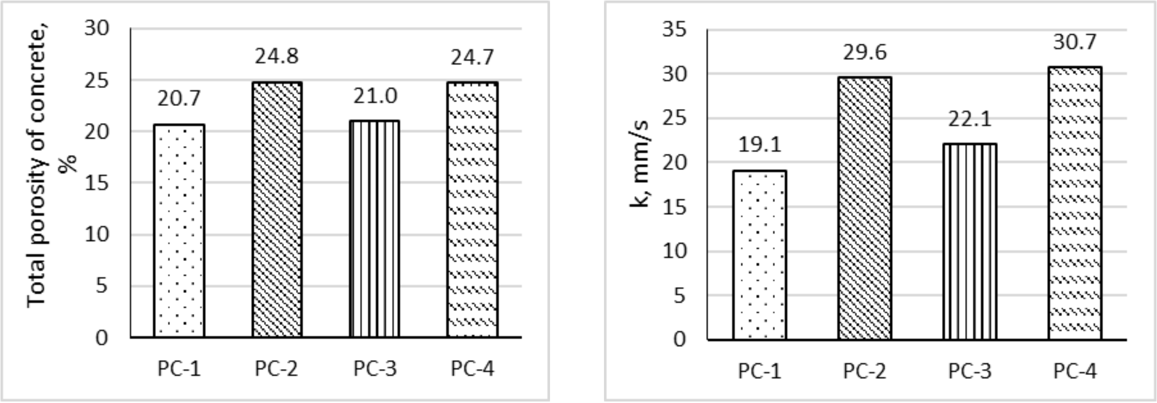
here: k is permeability coefficient, mm/s; Q is total volume of water, mm^3; L is length of a permeable concrete specimen, mm; A is cross-sectional area of a permeable concrete specimen, mm^2; h is water head, mm; t is time of water passing through a permeable concrete specimen, s.

The density of hardened concrete specimens was determined according to EN 12390-7, the compressive strength according to EN 12390-3, the wear resistance of concrete according LST 1428-15, and the frost resistance according to LST 1428-17.

3. Results and discussions

The slump test of fresh concrete was conducted after the concrete mixture preparation procedure. The slump values of the tested concrete mixtures with different particle size fractions of the coarse aggregate were about 0 mm. The tested mixtures were stiff and had low consistency because of the special composition of mix. It means that considerable compaction effort and adequate methods are required to achieve the desired mechanical performance of concrete [8]. To this end, an additional load of 11.63 kg was used during the compaction of fresh concrete.

The tests of physical and mechanical properties and durability of hardened PC were carried out after 28 days of curing. The comparison of the average values of total porosity and permeability coefficient *k* of PC specimens made with different types of coarse aggregate is presented in Figure 2. Statistical analysis of the total porosity of PC specimens calculated from the equation (1) is presented in Table 3.



a) b)

Figure 2. The results of the average values of total porosity (a) and water permeability (b) of PC (PC-1, PC-2, PC-3 and PC-4 - compositions of tested mixture series).

Fig. 2 illustrates that the total porosity (volume of pores) of PC depends on the geometrical properties of the coarse aggregate. PC specimens with gravel of particle size fraction 4/16 mm and 8/16 mm had a similar total porosity, i.e. 20.7% and 21.0% respectively, and a similar coefficient *k*, i.e. 19.1 mm/s and 22.1 mm/s respectively. The total porosity of PC increased from about 21.0% to 25.0% and coefficient *k* increased from about 20 mm/s to 30 mm/s when crushed gravel stone of particle size fraction 4/16 mm and 8/16 mm was used. As expected, a correlation between the total porosity and permeability coefficient *k* of PC was determined. PC with lower total porosity values had a lower permeability coefficient *k* and vice versa. The velocity of water flow through concrete structure increases with the increase of the porosity of PC.

Table 3. Statistical analysis of total porosity data

Description	PC-1	PC-2	PC-3	PC-4
Number of values	17	18	18	20
Min., %	16.3	20.6	16.4	21.4
Max., %	25.0	28.0	27.4	29.1
Arithmetic mean, %	20.7	24.8	21.0	24.7
Median, %	20.8	25.1	20.9	24.7
Variance, %	5.602	5.190	7.610	5.547
Standard deviation, %	2.367	2.278	2.758	2.355
Coefficient of variation	0.114	0.091	0.131	0.096

Table 3 illustrates that the total porosity of PC-1 series specimens varied in the range from 16.3% to 25.0%, while the total porosity of PC-2 series specimens varied in the range from 20.6% to 28.0%. The total porosity of PC-3 series specimens varied in the range from 16.4% to 27.4% and the total porosity of PC-4 series specimens varied in the range from 21.4% to 29.1%. Crushed gravel stone has angular and jagged edges formed during the crushing process and natural gravel has round shapes. Angularity and the jagged edges of crushed gravel stone create higher open porosity of PC-2 and PC-4 series specimens because of improper placement of coarse aggregate particles in the volume.

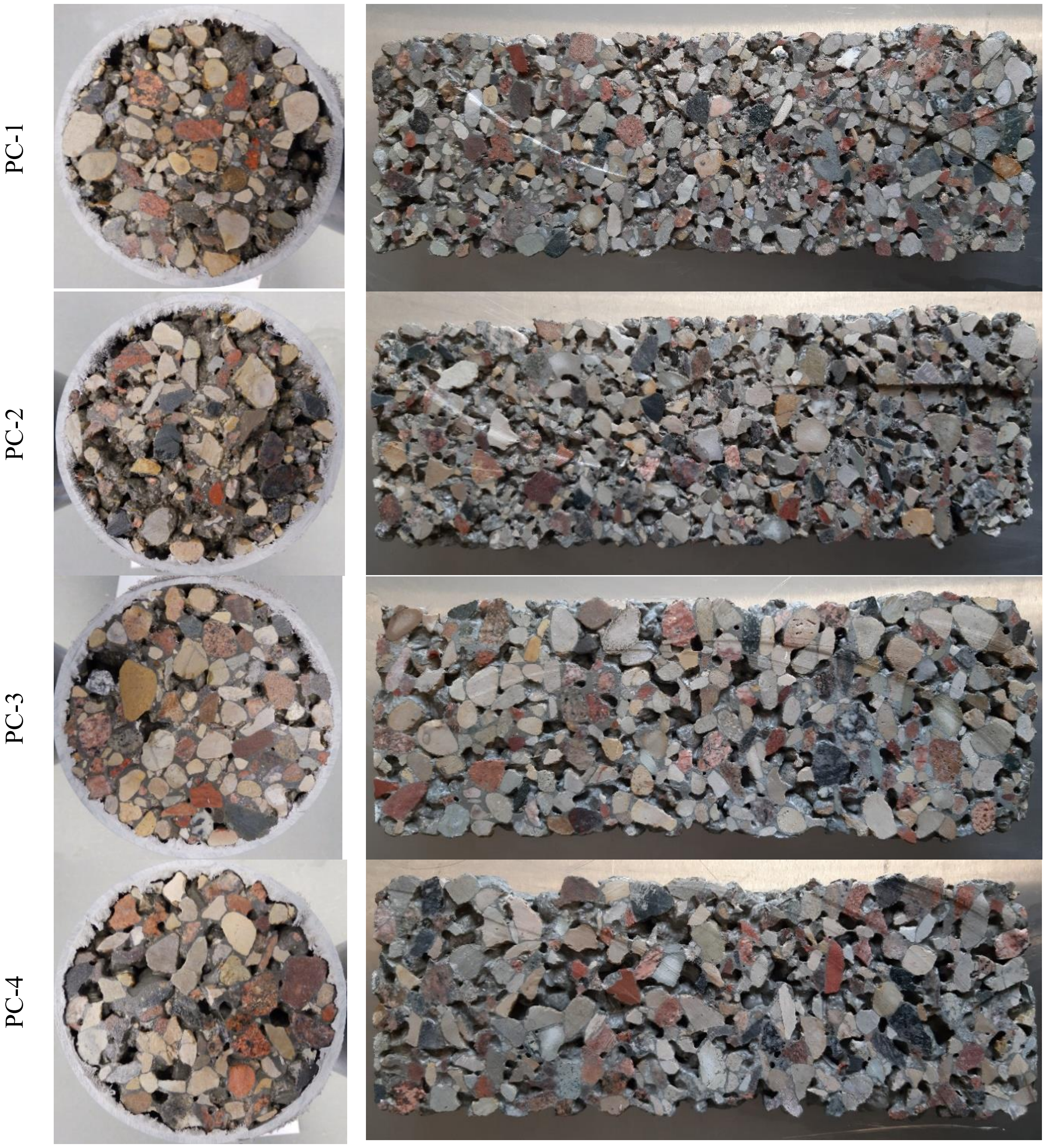
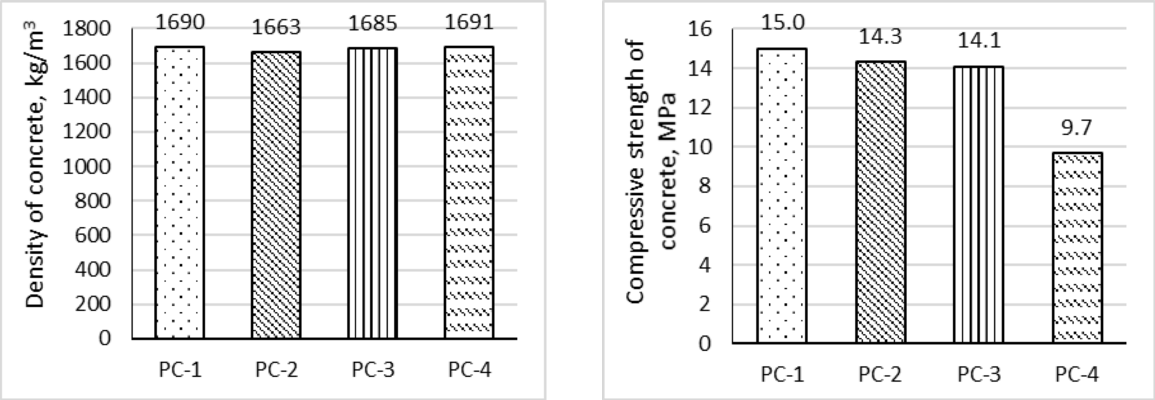


Figure 3. The view of cross and longitudinal sections of PC cylinders (left: cross section, right: longitudinal section).

Gravel of 4/16 fraction had the following geometric properties: particle shape index 5%, particle flakiness index 4%. The shape index and particle flakiness index of crushed gravel stone of 4/16 fraction were 13% and 11% respectively. The increased total porosity of PC-2 and PC-4 series specimens is seen in the pictures (Figure 3) of cross and longitudinal sections of those test specimens.

Figure 4 illustrates the comparison of the average values of PC density and compressive strength, when different types of coarse aggregate were used.



a) b)

Figure 4. Average values of PC density (a) and compressive strength (b) (PC-1, PC-2, PC-3 and PC-4 - compositions of tested mixture series).

The results given in Figure 4 show that the average values of the density of PC series specimens varied from 1663 kg/m^3 to 1691 kg/m^3, while the compressive strength varied from 9.7 MPa to 15.0 MPa. The PC test specimens with bigger-size aggregates (8/16 mm) had lower compressive strength than the test specimens when smaller-size aggregates (4/16 mm). A three-phase model of the porous concrete was adopted: aggregates, cement paste and interfacial transition zone. However, the results of compressive strength showed that not all coarse aggregate particles were properly covered with cement paste, i.e., there was no interfacial transition zone between the coarse aggregates and the cement paste in some places observed. PC made with smaller-size aggregates and angular aggregate grains (crushed gravel stone) generally requires more cement paste to produce the specified workability than PC made with round aggregate grains (gravel). The load of 11.63 kg used in vibropressing compaction process may have been too high and was the reason for a very thin layer of cement paste that bonds coarse aggregate particles. The interface between the aggregate and the paste needs to be improved to improve the strength of PC. Authors [6] noted that porous concrete fails at the binder aggregate interface because the layer of the cement paste in PC is very thin to bond coarse aggregate particles. Therefore, the compressive strength is low.

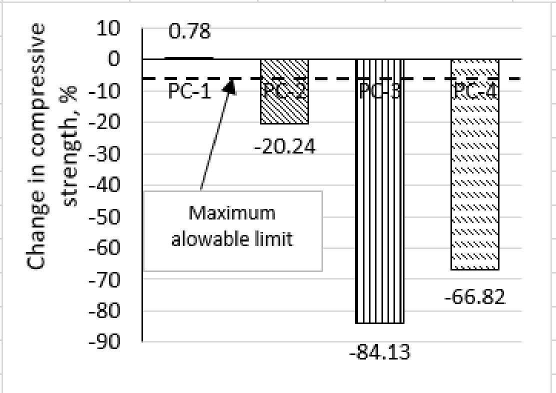


Figure 5. The results of resistance to volumetric freezing and thawing test of PC (PC-1, PC-2, PC-3 and PC-4 - compositions of tested mixture series).

Fig. 5 illustrates the results of resistance to volumetric freezing and thawing test of PC series specimens. The appearance of PC specimens before and after a different number of freeze-thaw cycles is presented in Figure 6. The first defects were observed in the PC-4 series specimens (Figure 6) after 64 freezing and thawing cycles. Later, after 108 freezing and thawing cycles, the first defects were also observed PC-1, PC-2 and PC-3 series specimens (Figure 6). The observed defects were related to the cracks in the test specimens between the hardened cement paste and the aggregate, also damaged gravel particles were observed in some places. The addition of air-entraining admixtures created entrained air bubbles in the cement paste and improved the freeze-thaw durability [1]. To avoid the damage of gravel grains used it should be replaced by crushed granite stone, which is frost resistant.

According to LST 1428-17, the change in compressive strength of PC specimens compared to control specimens must not decrease more than 5%. The results given in Figure 5 show that the compressive strength of PC-1 series specimens did not decrease more than 5% when the number of freezing and thawing cycles was 108. It means that the frost resistance mark for the test specimens of PC-1 series is F100 according to LST 1428-17. The PC-2, PC-3 and PC-3 series specimens did not pass the frost resistance test because the change in compressive strength of PC specimens compared to control specimens decreased more than 5%.

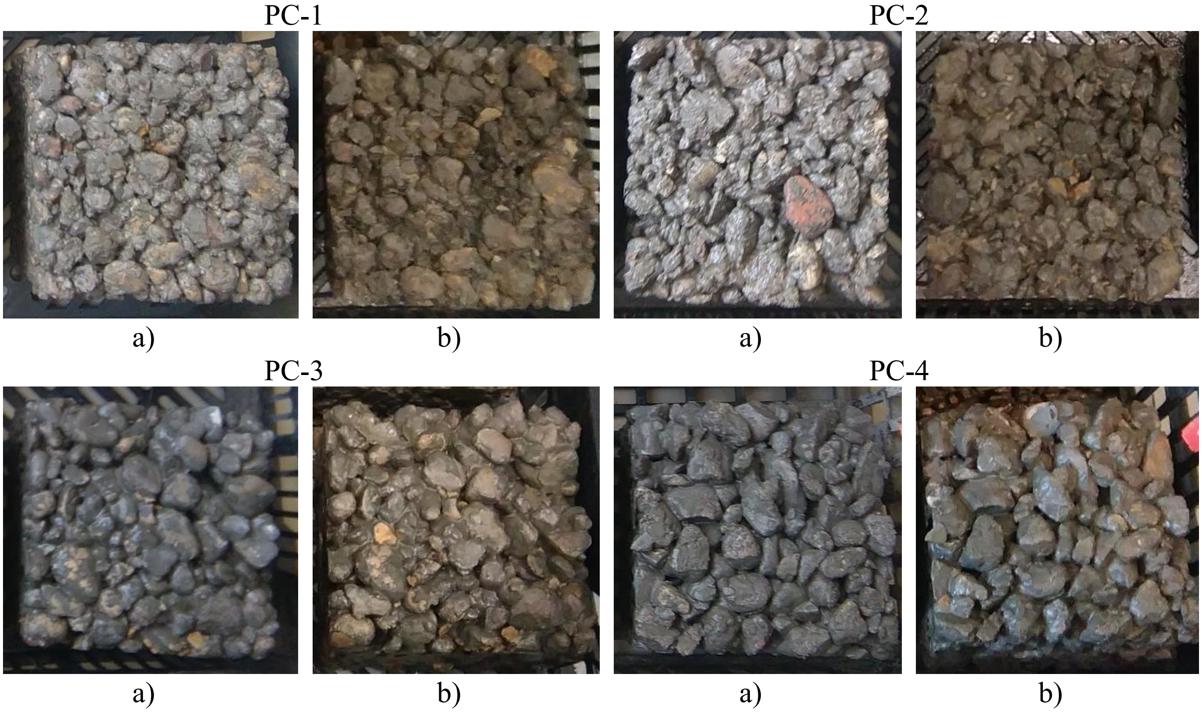


Figure 6. The view of PC series specimens before (a) and after a different number of freeze-thaw cycles (b) (PC-1, PC-2, PC-3 and PC-4 - compositions of tested mixture series).

The results of the average wear by mass of PC series specimens are given in Figure 7, while the appearance of PC series specimens before and after the wear resistance test is presented in Figure 8. According to LST 1428-15, the wear resistance of concrete is determined by the difference in the test specimen mass before and after the abrasion resistance test performed on a 600-meter abrasion road. Figure 7 shows that the specimens of PC-1 series had the lowest average wear by mass after the abrasion resistance test on 600-meter abrasion road whereas the specimens of PC-2 series had the highest values of wear by mass. It should be noted that the highest wear of PC-2 series specimens was caused by the ravelling of the angular particles of the coarse aggregate from the concrete matrix. It means, that not all angular particles of the coarse aggregate were properly covered by the cement paste and therefore ravelled from the concrete matrix during the abrasion resistance test.

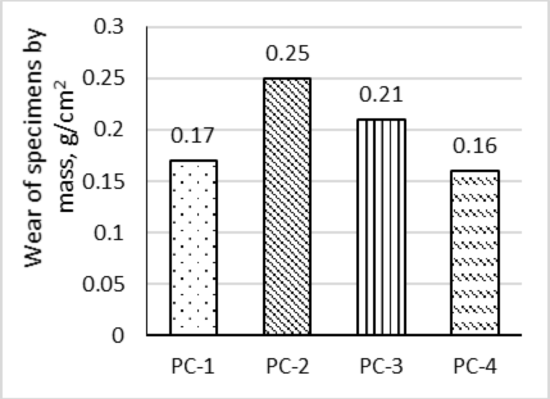


Figure 7. The results of abrasion resistance of PC (PC-1, PC-2, PC-3 and PC-4 - compositions of tested mixture series).

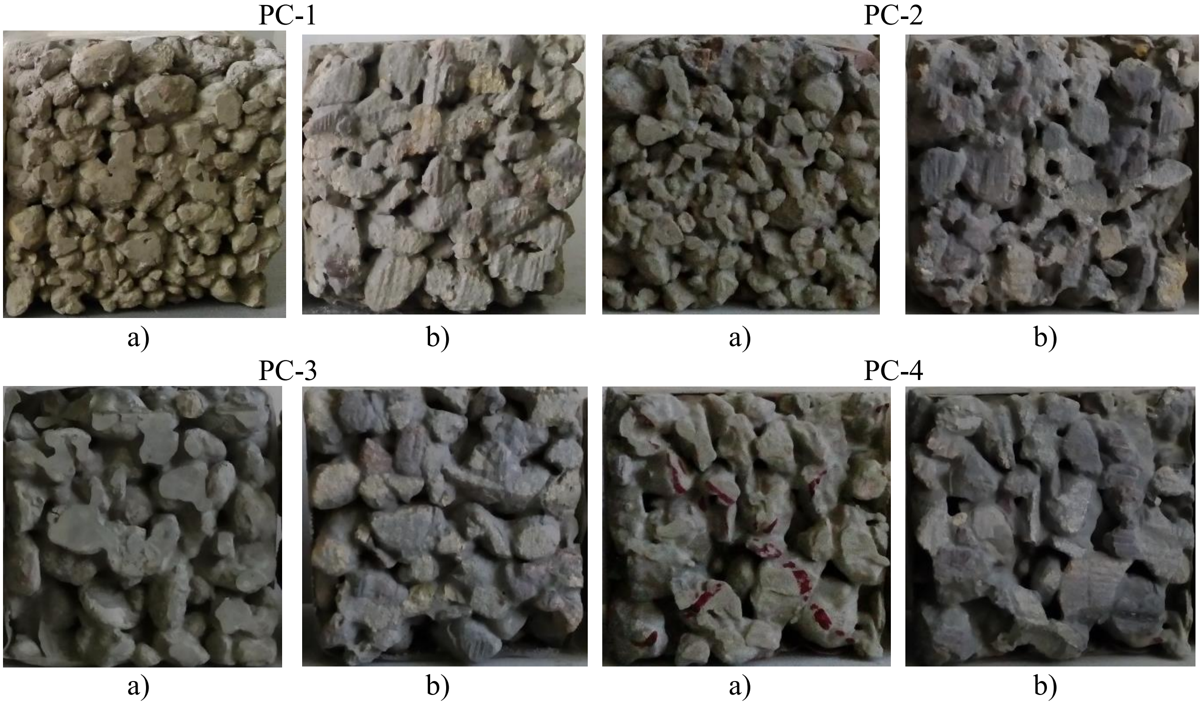


Figure 8. The view of PC specimens series before a test (a) and after a wear resistance test (b) (PC-1, PC-2, PC-3 and PC-4 - compositions of tested mixture series).

The application and final performance of permeable concrete, i.e., the rate of permeability, strength, resistance to freeze-thaw cycles, and resistance to wear should be considered while designing the permeable concrete mix. Further experiments need to be carried out to improve the properties of permeable concrete. Especially, the interface between the aggregate and the paste needs to be improved.

4. Conclusions

The type of coarse aggregates used for permeable concrete influences the permeability coefficient, compressive strength, freeze-thaw resistance and abrasion resistance. The specimens containing crushed gravel stone of fraction 4/16 mm and 8/16 mm had a higher permeability coefficient and the total porosity than the specimens where gravel of fraction 4/16 mm and 8/16 mm was used as the coarse aggregate. The total porosity of PC increased from about 21.0% to 25.0% and permeability coefficient *k* increased from about 20 mm/s to 30 mm/s when crushed gravel stone of fraction 4/16 mm and 8/16 mm was used as the coarse aggregate. Angularity and jagged edges of crushed gravel stone influenced higher open porosity of permeable concrete. Higher compressive strength (15.0 MPa) was observed in the specimens containing gravel with the particle size fraction of 4/16 mm. The test specimens of permeable concrete with bigger-sized aggregates (8/16 mm) had lower compressive strength compared to the test specimens with smaller-sized aggregate (4/16 mm). The results of compressive strength test revealed that not all coarse aggregate particles were properly covered by the cement paste, i.e., in some places there was no interfacial transition zone between the coarse aggregates and the cement paste observed. The load of 11.63 kg using in the vibropressing compaction procedure may have been too high. The permeable concrete with 4/16 fraction gravel was frost resistance after 108 freeze-thaw cycles. The lowest wear resistance of permeable concrete was determined when gravel with a particle size fraction of 4/16 mm was used. Consistency tests by slump method showed that the tested concrete mixes were stiff and had low consistency. Further studies of the properties of previous concrete should focus on improving the interface between the aggregate and the cement paste.

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