

Effect of porosity on frost resistance of Portland cement pervious concrete

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Abstract. Portland cement pervious concrete (PCPC) is an effective pavement material to solve or reduce the urban waterlogging problems. The Mechanical properties, the permeability, the abrasion resistance and the frost resistance of PCPC without fine aggregate were investigated. The increase of porosity was achieved by fixing the dosage of coarse aggregate and reducing the amount of cement paste. The results show that the compressive strength and the flexural strength of PCPC decrease with the increase of porosity. The permeability coefficient and the wear loss of PCPC increase with the increase of the porosity. The compressive strength and the flexural strength of PCPC subjected to 25 freeze-thaw cycles are reduced by 13.7%-17.8% and 10.6%-18.3%, respectively. For PCPC subjected to the same freeze-thaw cycles, the mass loss firstly increases and then decreases with the increase of the porosity. The relative dynamic modulus elasticity decreases with the increase of freeze-thaw cycles. And the lower the PCPC porosity is, the more obvious the dynamic modulus elasticity decreases.

Keywords: Portland cement pervious concrete (PCPC); porosity; physical properties; freeze-thaw cycles

1. Introduction

The use of Portland cement pervious concrete (PCPC) is an effective way to solve or reduce the urban waterlogging problems (Bassuoni 2010). PCPC can also lower traffic noise (Marolf 2004) and potentially reduce the heat island effect (Haselbach 2011, Kevern 2012). Usually, PCPC is prepared with little to no fine aggregate. The coarse aggregates only wrapped in a thin layer of cement paste, which will lead to lower mechanical properties of PCPC (Tennis 2004, ACI 522R 2010). It is generally accepted that the compressive strength of PCPC depends on the strength of cement paste, aggregate and porosity (Tennis 2004). And the strength properties are more sensitive to aggregate-to-cement ratio rather than water-to-cement ratio (Crouch 2007). Yang and Jiang (2002) found that smaller sized aggregate, silica fume, and superplasticizer could significantly improve the strength of PCPC. Yahia and Kabagire (2014) pointed out that using a small amount of fine aggregate in PCPC was beneficial to the strength and the durability. Fibers (Kevern 2014, Rangelov 2016), recycle aggregates (Yuwadee *et al.* 2016) or natural materials (Nguyen 2013, Khankhaje 2016, Ibrahim 2016) can also be used to improve the performance of PCPC.

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In addition to acceptable mechanical properties, PCPC used in cold area should also have better frost resistance. Some experimental studies indicated that the addition of polypropylene fibers (Yang 2011, Kevern 2014), silica fume (Yang 2011) or sand (Kevern 2008) could improve the freeze-thaw durability of PCPC. Gesoglu *et al.* (2014) reported that 10% and 20% tire chips-crumb rubber used to replace natural aggregates could obviously improve the frost resistance of PCPC. Wu *et al.* (2016) found that there was a strong relationship between the strength and the frost resistance of PCPC. Olek and Weiss (2003) observed that the rapid freeze-thaw frequency also caused serious damage to PCPC. Lund *et al.* (2017) reported that PCPC under fully saturated conditions had poor frost resistance. The physical characteristics of aggregate play an important role in controlling the mechanical properties and durability of PCPC (Kevern 2010, Jain 2011). Poor quality aggregate will lead to higher probability of freeze-thaw damage in PCPC (Chandrappa 2016).

2. Research significance

The void content in PCPC typically ranges from 15% to 35% of the total volume. Therefore, porosity is a very important parameter and affects the permeability, mechanical properties and durability of PCPC (ACI 2010). Usually, the permeability of PCPC increase with the increase of the porosity. However, Chindaprasrit *et al.* (2008), Deo and Neithalath (2011) reported that strength of PCPC decreased by approximately 50% for every 10% increase in the porosity. It is not clear whether the frost resistance of PCPC with higher porosity is the same as that of the traditional concrete. In this study, PCPC specimens with different porosity were cast and subjected to freeze-thaw cycles in water. The target porosity is 14%, 17%, 20% and 23% of the total volume, respectively. The results of this research are expected to help with the development of reliable quality control for PCPC in the future.

3. Experiment detail

3.1 Material

Ordinary Portland cement (P·O 42.5) produced by Tangshan Fushun cement Co., Ltd. was used and the basic physical properties of cement are shown in Table 1. The particle size range of coarse aggregate was 5-10 mm. A polycarboxylate based superplasticizer (about 0.6% by weight of cement) was utilized to improve the workability.

3.2 Specimens preparation

PCPC specimens without fine aggregate were cast according to CJJ/T135-2009 (2009). The

Table 1 Basic physical properties of cement

Setting Time		Bending Strength(MPa)		Compressive Strength(MPa)		Fineness
Initial	Final	3d	28d	3d	28d	Sieving Residue
235min	5h	5.8	—	20.6	—	4.42%

Table 2 Mixing proportion of pervious concrete

	Water to cement ratio												
	0.25				0.30			0.35			0.40		
Cement (kg/m ³)	488	416	344	469	400	331	452	385	319	253	436	372	307
Aggregate (kg/m ³)	1553				1553			1553			1553		
Water (kg/m ³)	122	105	86	141	120	99	158	135	112	89	174	149	123
CW/A [*] (%)	39.3	33.6	27.7	39.3	33.5	27.7	39.3	33.5	27.7	22.0	39.3	33.6	27.7
Target Porosity (%)	14	17	20	14	17	20	14	17	20	23	14	17	20

*CW/A = (Cement+Water)/Aggregate

mixing proportion of PCPC are shown in Table 2. The target porosity was 14%, 17%, 20% and 23% of the total volume. Cubes 100mm on each side were used to determine the compressive strength. Cubes 150 mm on each side were used to measure the surface wear resistance. Prisms with a size of 100 mm × 100 mm × 400 mm were used to evaluate the flexural strength and the frost resistance. All specimens were cured in the standard condition for 28 days.

3.3 Test methods

3.3.1 Effective porosity of PCPC

The weight (W_0) was recorded after the specimens were dried at 80°C for 24 hours. And the dimensions were measured to determine the total volume (V_s) of specimen. Then the specimen was completely immersed into water (V_w in volume) for 24 hours. The total volume (V_{ws}) of the water and the specimen was recorded. The container remained sealed during the immersion process of the specimen. The specimen was moved out from water and the free water flowed out from the void. The weight (W_s) was recorded after the surfaces of the specimen were wiped with a saturated surface-dry rag. The porosity of the PCPC specimen was calculated with Eq. (1).

$$P = [V_s + V_w - V_{ws} - (W_s - W_0)/\rho_w]/V_s \quad (1)$$

Where P is the porosity (%), V_s is the total volume of specimen (cm³), V_w is the volume of water (cm³), V_{ws} is the total volume of the water and the specimen (cm³), W_s is the weight of the specimen under saturated surface-dry condition (g), W_0 is the weight of the specimen under dry condition (g), ρ_w is the density of water (g/cm³).

3.3.2 Permeability coefficient of PCPC

The permeability coefficient was determined according to CJJ/T135-2009 (2009). The values of permeability coefficient were calculated with Eq. (2).

$$K = Qd/AtH \quad (2)$$

Where K is the coefficient of permeability (mm/s), A is cross-sectional area of the specimen (mm²), t is the lasting time of the experiment (s), H is the difference of water head (mm), Q is the seepage quantity at the time t (mm), d is the thickness of the test specimen (mm).

3.3.2 Abrasion resistance

The abrasion resistance was measured according to JTG E30-2005 (2005). The load of pressure

head was 200 N. The rotation speed of horizontal pallet was 17.5 ± 0.5 r/min and the transmission ratio between the spindle and the horizontal pallet was 35:1. The wear loss per unit area was used to evaluate the abrasion resistance and determined by Eq. (3).

$$G = (m_0 - m_1)/A \quad (3)$$

Where G is the wear loss per unit area (kg/m^2), m_0 , m_1 is the weight of specimen with and without the abrasion test (kg), respectively. A is the abrasion area (0.0125 m^2).

3.3.2 Freeze-thaw cycles

The freeze-thaw cycles test was performed in the freeze-thaw apparatus according to GB-T50082-2009 (2009). In a single freeze-thaw cycle, the temperature of the specimens cools from 5°C to -18°C and then warms to 5°C within 2.0-4.0 hours. The weight and the dynamic modulus elasticity of all specimens were recorded at a regular interval. These results can be used to calculate the mass loss and the relative dynamic modulus elasticity.

4. Results and discussions

4.1 Measured porosity

Fig. 1 shows the relationship between the target porosity and the measured porosity. It can be found that the measured porosities are very close to the target porosities when the water to cement ratio is 0.25. The gray area in Fig. 1 represents the area where the data points may be distributed. The narrower the gray area, the more concentrated the data is. However, the measured porosities are lower than the target porosities of PCPC specimens when the water to cement ratio is 0.30, 0.35 and 0.40. And the deviation between the measured porosity and the target porosity increases with the increase of water to cement ratio. This result can be attributed to the high fluidity of cement paste with high water to cement ratio. In the casting process, the separation trend of

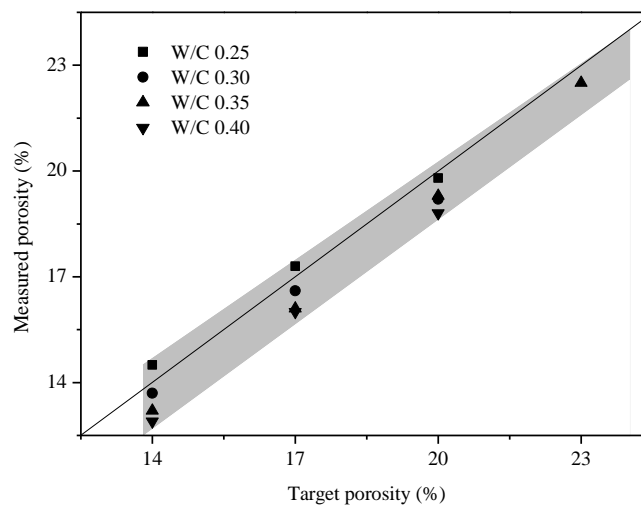


Fig. 1 Relationship between target porosity and measured porosity

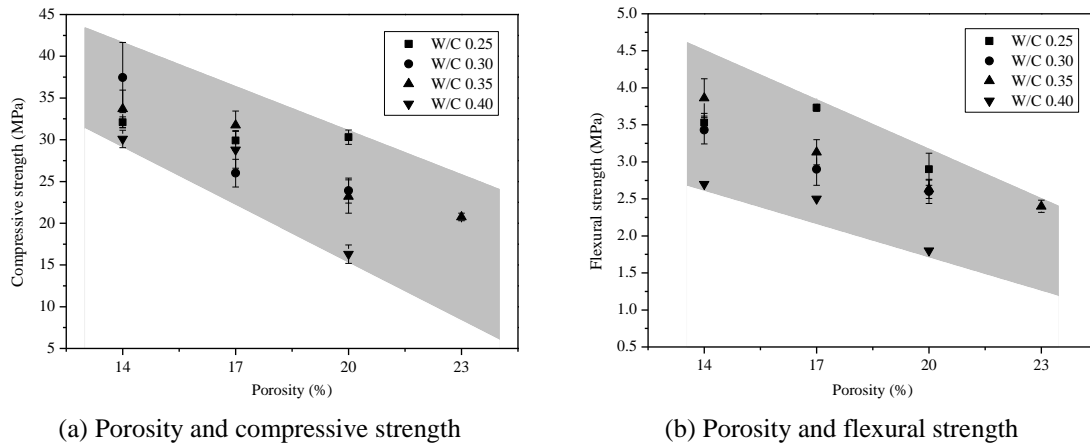


Fig. 2 Relationship between porosity and flexural strength

cement paste from aggregate surface increases with the increase of the water to cement ratio when the total weight of coarse aggregate, cement and water is a constant value. The separated cement paste is easier to accumulate at the bottom of the specimen and block some voids. Cosic *et al.* (2014) reported the similar results that the effective porosity was 50-75% of the total porosity.

4.2 Mechanical properties of PCPC

The relationship between the porosity and the mechanical properties of PCPC is shown in Fig. 2. Due to no fine aggregate in PCPC, the fresh cement paste wrapped the surface of coarse aggregate. The hardened cement paste bonded the coarse aggregate together. Therefore, the strength of PCPC will depend on the strength of hardened cement paste (Tennis 2004, ACI 522R 2010). There is a linear relationship between the strength of hardened cement paste and the water to cement ratio. Namely that is an optimum water to cement ratio for the specimen with the same porosity and coarse aggregate content. For the compressive strength, the optimum water cement ratio is 0.3 and 0.35 when the porosity is 14% and 17%, respectively. It can be found that the compressive strength and the flexural strength of PCPC with 0.30, 0.35 and 0.40 W/C decrease with the increase of porosity. For PCPC with a same water to cement ratio, the increase of porosity is achieved by reducing the amount of cement paste, which decreases the thickness of cement paste. Torres *et al.* (2015) found that the strength properties of PCPC decreased with the decrease in paste thickness. Therefore, the mechanical properties of PCPC decrease with the increase of porosity. This foundation is in agreement with the results reported by Chindaprasrit *et al.* (2008), Deo and Neithalath (2011). The vibration time was about 1 minute in the casting process of PCPC with 0.25 W/C, which may affect the mechanical properties of the specimens. Therefore, the strength of PCPC with 0.25 W/C does not meet the above rule.

4.3 Permeability of PCPC

Fig. 3 shows the relationship between the porosity and the permeability coefficient of PCPC. It is clear that the permeability coefficients of PCPC increase with the increase of the specimen porosity. Torres *et al.* (2015) also reported that the porosity and the permeability increased with

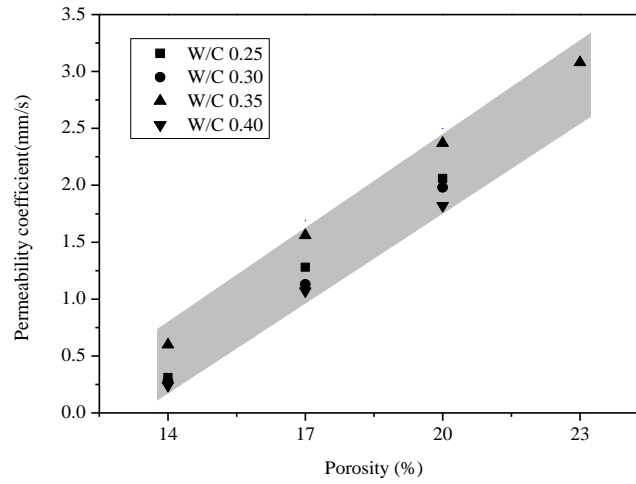


Fig. 3 Relationship between porosity and permeability coefficient

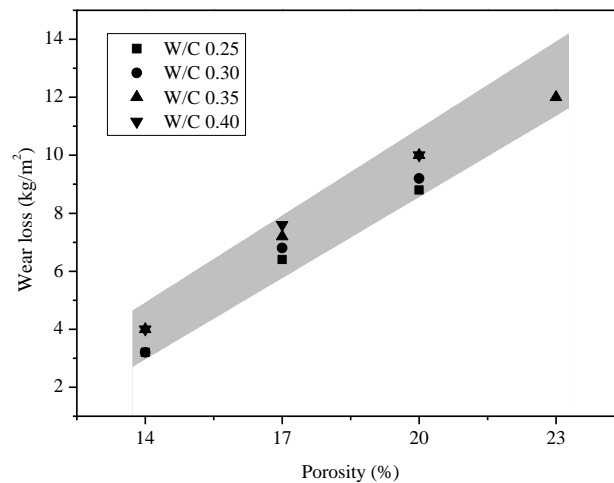


Fig. 4 Relationship between porosity and abrasion resistance

the decrease of cement paste thickness. In addition, most pores in the specimen are connected to each other because no fine aggregate is used in PCPC. The number or the volume of the connected pores will increase with the increase of porosity when the total weight of coarse aggregate is a constant value. For the specimen with a same porosity, the permeability coefficients of 0.35 W/C PCPC are greater than that of 0.25, 0.30 and 0.40 W/C PCPC. That is to say, there is an optimum water to cement ratio for the permeability coefficient of PCPC with the same porosity. This result can be explained that higher and lower water to cement ratio may reduce the connectivity of the pores.

4.4 Abrasion resistance of PCPC

The relationship between the porosity and the abrasion resistance of PCPC is given in Fig. 4. It

can be seen that the wear loss increase with the increase of the porosity. There are two reasons can be used to explain this result. Firstly, the abrasion resistance of PCPC is determined by the strength of hardened cement paste wrapped on the surface of coarse aggregates. Because the coarse aggregate strength is greater than that of hardened cement paste. Secondly, for PCPC with the same water to cement ratio, the increase of porosity is achieved by fixing the dosage of coarse aggregates and reducing the amount of cement paste, which decreases the thickness of cement paste and reduces the bonding strength. Gordana *et al.* (2015) also reported that the surface abrasion of PCPC from constant traffic caused the pavement to deteriorate more quickly than conventional concrete.

It is known from Table 2 that the cement and water to aggregate ratio also has a same value when the porosity is equal. Therefore, the thickness of the cement paste coated on the aggregate surface is equal when the amount of aggregate is fixed. The strength of hardened cement paste depends on the water to cement ratio and decreases with the increase of the water to cement ratio. For PCPC with the same porosity, the wear loss is increasing with the increase of the water to cement ratio, especially for the specimens with 17% porosity.

4.5 Frost resistance of PCPC

Frost resistance is a very important parameter for PCPC used in the cold areas. Fig. 5 shows the strength loss of 0.35 W/C PCPC subjected to 25 freeze-thaw cycles in water. It can be found that both the compressive strength and the flexural strength of the specimens decrease after 25 freeze-thaw cycles, which is in agreement with the damage law of ordinary concrete under freeze-thaw and can be explained by the classical freeze-thaw mechanism (Wu *et al.* 2016). In addition, more water will penetrate into PCPC and increase the contact area between PCPC and water because of the high porosity of PCPC. The area of PCPC subjected to freeze-thaw cycles will be much greater than that of ordinary concrete. Not only the water in the cement paste pore and the interface zone, but also the water in a large number of macro-pores in PCPC subjected to freeze-thaw cycles will cause expansive force. The coarse aggregates are only bonded by the hardened cement paste

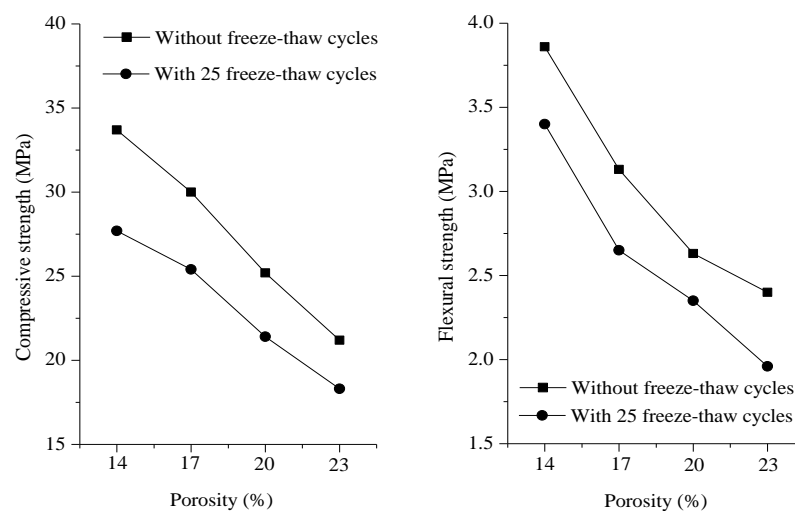


Fig. 5 Strength loss of 0.35W/C PCPC subjected to 25 freeze-thaw cycles

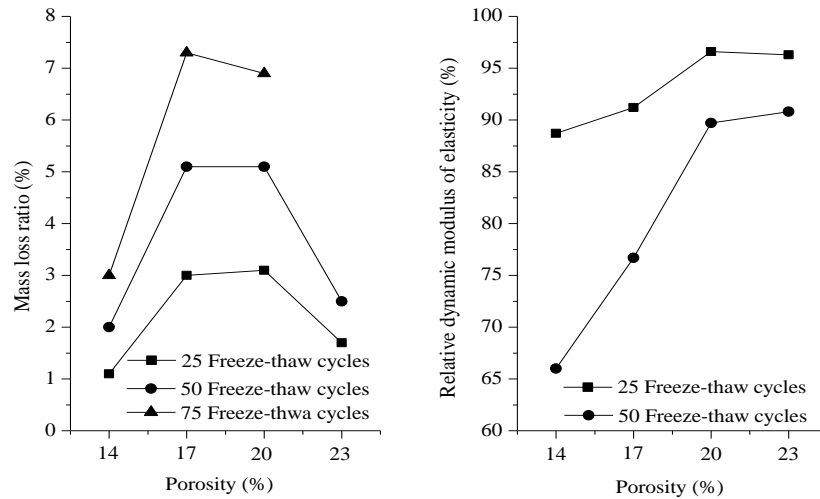


Fig. 6 Mass loss and relative dynamic modulus elasticity of 0.35 W/C PCPC subjected to freeze-thaw cycles

because there is no fine aggregate in PCPC, so PCPC is more easily damaged by the freeze-thaw cycles. The compressive strength and the flexural strength of PCPC subjected to 25 freeze-thaw cycles are reduced by 13.7%-17.8% and 10.6%-18.3%, respectively.

The mass loss and the relative dynamic modulus elasticity of the specimens are shown in Fig. 6. Surface scaling is the loss of paste and mortar from the surface of concrete by the cyclic freeze-thaw. In extreme cases, the loss of paste can result in loosening of coarse aggregate and gradual reduction in strength of concrete structures (Cho 2007). For all PCPC specimens, the mass loss increases with the increase of freeze-thaw cycles (Olek 2003). For PCPC subjected to the same freeze-thaw cycles, the mass loss firstly increases and then decreases with the increase of the porosity. The results can be explained that the area of PCPC contacted with water is greater when PCPC has a higher porosity. Under this condition, more hardened cement paste will be damaged by freeze-thaw cycles and the mass loss will increase. However, the cement paste layer around the coarse aggregates will be further reduced with the further increase of the porosity. The hardened cement paste stripped off during the freeze-thaw process will be reduced, which causes that the mass loss rate of the specimens with 23% porosity is lower than that of the specimens with 17% and 20% porosity. However, the specimens with 23% porosity had been broken during the 50-75 freeze-thaw cycles.

The relative dynamic modulus elasticity decreases with the increase of freeze-thaw cycles. And the lower the PCPC porosity is, the more obvious the dynamic modulus elasticity decreases. After 50 freeze-thaw cycles, the relative dynamic modulus elasticity of PCPC with the porosity of 14% and 23% decreased by 34.0% and 9.2%, respectively. The dynamic modulus elasticity of all specimens also cannot be measured after 75 freeze-thaw cycles. And the specimens without external loading fractured during the testing of the dynamic modulus elasticity, as shown in Fig. 7. That is to say, the bond strength of hardened cement paste has been severely reduced after 75 freeze-thaw cycles in water.

Comparing to the conventional concrete, PCPC has low mechanical properties (Tennis 2004, ACI 522R 2010) and poor frost resistance (Lund 2017), but it is indeed an effective pavement material to solve the urban waterlogging problem. Therefore, it is urgent to improve the



Fig. 7 PCPC specimen subjected to 75 freeze-thaw cycles

performances of PCPC so that it can be applied to a wider range of pavement, such as heavy traffic pavements. In addition, it should also be considered how to solve the problem of the pore blockage after a long term use.

5. Conclusions

- The compressive strength and the flexural strength of PCPC subjected to 25 freeze-thaw cycles are reduced by 13.7%-17.8% and 10.6%-18.3%, respectively.
- The mass loss increases with the increase of freeze-thaw cycles. For PCPC subjected to the same freeze-thaw cycles, the mass loss firstly increases and then decreases with the increase of the porosity.
- The relative dynamic modulus elasticity decreases with the increase of freeze-thaw cycles. And the lower the PCPC porosity is, the more obvious the dynamic modulus elasticity decreases.
- The specimens without other external loading fractured during the testing of the dynamic modulus elasticity, which indicated that the bond strength of hardened cement paste had been severely reduced after 75 freeze-thaw cycles in water.

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Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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