Advances in Concrete Construction, *Vol. 8, No. 1 (2019) 47-54*
DOI: https://doi.org/10.12989/acc.2019.8.1.047

Combined effect of fine aggregate and silica fume on properties of Portland cement pervious concrete

Yuanbo Zhang, Wuman Zhang* and Yingchen Zhang

Department of Civil Engineering, School of Transportation Science and Engineering, Beihang Univerisity, Beijing, 100191, China

(Received November 9, 2018, Revised April 23, 2019, Accepted April 27, 2019)

Abstract. Portland cement pervious concrete has been expected to have good water permeability, mechanical properties and abrasion resistance at the same time when Portland cement pervious concrete is applied to the actual vehicle pavement. In this study, the coarse aggregate and cement were replaced by the fine aggregate and the silica fume to improve actual road performance Portland cement pervious concrete. The Mechanical properties, the water permeability and the abrasion resistance of Portland cement pervious concrete were investigated. The results show that the compressive strength, the flexural strength and the abrasion resistance are increased when the fine aggregate and the silica fume are added to Portland cement pervious concrete separately. However, the porosity and the water permeability are decreased simultaneously. With assistance of silica fume and fine aggregate simultaneously, Portland cement pervious concrete could achieve a higher strength. The compressive strength, the flexural strength and the abrasion resistance of Portland cement pervious concrete mixed with 5% fine aggregates and 8% silica fume are increased by 93.1%, 65% and 65.2%, respectively. The porosity and the water permeability are decreased by 22.4% and 85% when Portland cement pervious concrete is mixed with 5% fine aggregate and 8% silica fume. Therefore, the replacement ratio of the fine aggregates and the silica fume should be considered comprehensively and determined on the premise of ensuring the water permeability coefficient.

Keywords: Portland cement pervious concrete; fine aggregate; silica fume; water permeability; strength; porosity

1. Introduction

The use of Portland cement pervious concrete is an effective way to solve or reduce the urban waterlogging problems (Bassuoni 2010). Portland cement pervious concrete can also lower traffic noise (Marolf 2004) and potentially reduce the heat island effect (Haselbach 2011, Kevern 2012). Usually, Portland cement pervious concrete 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 Portland cement pervious concrete (Tennis 2004, ACI 522R 2010). The strength properties are more sensitive to aggregate-to-cement ratio rather than water-to-cement ratio (Crouch 2007). The physical characteristics of aggregate play an important role in controlling the mechanical properties and durability of Portland cement pervious concrete (Kevern 2010, Jain 2011). It is generally accepted that the compressive strength of PCPC depends on the strength of cement paste, aggregate and porosity (Tennis 2004).

However, Portland cement pervious concrete should have good water permeability, mechanical properties and abrasion resistance at the same time when Portland cement pervious concrete is applied to the actual vehicle pavement (Zhang *et al*. 2018). Yang and Jiang (2002) found that smaller sized aggregate, silica fume and superplasticizer could significantly improve the strength of Portland cement pervious concrete. Yahia and Kabagire (2014) pointed out that using a small amount of fine aggregate in PCPC was beneficial to the strength and the durability. Chindaprasirt *et al.* (2009) used 3 single size aggregates to make pervious concrete with a same void ratio. The results showed that the strength of pervious concrete with large aggregate was larger than that with small aggregate. Fibers (Kevern 2014, Rangelov 2016), recycle aggregates (Yuwadee *et al*. 2016), mineral additives (Zaetang *et al.* 2017) or natural materials (Nguyen 2013, Khankhaje 2016, Ibrahim 2016) can also be used to improve the performance of Portland cement pervious concrete.

2. Research significance

Usually, the water permeability of Portland cement pervious concrete increases with the increase of the porosity. High porosity helps ensure that Portland cement pervious concrete has a sufficient water permeability. However, Chindaprasrit *et al*. (2008), Deo and Neithalath (2011) reported that strength of Portland cement pervious concrete decreased by approximately 50% for every 10% increase in the porosity. Fine aggregate and silica fume have been used to improve the strength properties of Portland cement pervious concrete. However, the addition of fine aggregate and silica fume will decrease the porosity and the water permeability coefficient. Therefore, the replacement ratio of the fine aggregates and the silica fume should be considered comprehensively and determined on the premise

∗Corresponding author, Associate Professor
E-mail: wmzhang@buaa.edu.cn

http://www.techno-press.org/?journal=acc&subpage=7
ISSN: 2287-5301 (Print), 2287-531X (Online)

Table 1 Basic physical properties of cement

Specific gravity g/cm^3)	Setting time (min)		Specific surface area (m^2/kg)	Compressive strength (MPa)		Flexural strength (MPa)	
	Initial	Final		3days	28days	3days	28days
3.15	230	300	382	20.5	-	5.6	-

of ensuring the water permeability coefficient. In this study, Portland cement pervious concrete specimens mixed with fine aggregates and silica fume were cast. The strength, the abrasion resistance, the porosity and the water permeability of Portland cement pervious concrete were measured. The results of this research are expected to help with the development of reliable quality control for Portland cement pervious concrete in the future.

3. Experiment detail

3.1 Material

Ordinary Portland cement (PO 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. River sand with fineness modulus of 2.54 and apparent density of 2610 kg/m^3 was prepared. The fine aggregates and the silica fume were used to replace coarse aggregate and cement at equal volume, respectively. Silica fume with a specific surface area of 19500 m^2/kg and 95% SiO_2 content was used. A polycarboxylate based superplasticizer (about 0.6% by weight of cement) was utilized to improve the workability.

3.2 Specimens preparation

PCPC specimens were cast according to CJJ/T135-2009 (2009). The mixing proportion of PCPC are shown in Table 2. 5%, 10% and 15% replacement of coarse aggregates by fine aggregates will improve the workability. The vibration time is controlled within 20 seconds to avoid segregation. 4% and 8% replacement of cement by silica fume will decrease the workability to a certain extent, which helps to avoid segregation. Cubes 100mm on each side were used to determine the compressive strength and the water permeability coefficient. Prisms of size 100 mm×100 mm ×400 mm were used to evaluate the flexural strength. Cubes 150 mm on each side were used to measure the surface abrasion resistance. All specimens were cured in the standard condition for 28 days.

3.3 Experiment methods

3.3.1 Permeability coefficient

The permeability coefficient was determined according to CJJ/T135-2009 (2009). The schematic diagram of the test setup is shown in Fig. 1. The values of permeability coefficient are calculated with Eq. (1).

$$K = QL/(b^2Ht) \quad (1)$$

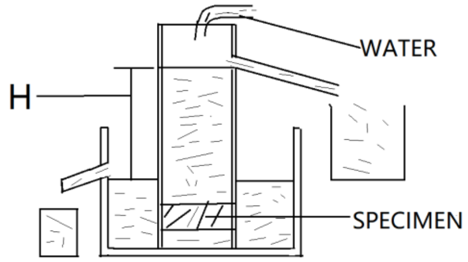


Fig. 1 The schematic diagram of the test setup

Where K is the water permeability coefficient (mm/s), b is the side length of the square section (mm), 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^3), L is the thickness of the test specimen (mm).

3.2.2 Effective porosity

The weight (W_0) was recorded after the specimens were dried at 80℃ 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 and 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. (2).

$$P = [V_s + V_w - V_{ws} - (W_s - W_0)/\rho_w]/V_s \quad (2)$$

Where P is the porosity (%), V_s is the total volume of specimen (cm^3), V_w is the volume of water (cm^3), V_{ws} is the total volume of the water and the specimen (cm^3), 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/cm^3).

3.2.3 Compressive strength and flexural strength

The compressive strength and the flexural strength were determined according to GB/T 50081-2002 (2002). Eq. (3) and Eq. (4) were used to calculate the strength.

$$f_c = \mathrm{F/A} \quad (3)$$

Where f_c is the compressive strength (MPa), A is the force surface area mm^2, F is the failure loading (KN).

$$f_f = 1.5 \times \mathrm{FL}/(\mathrm{b}h^2) \quad (4)$$

Where f_f is the flexural strength (MPa), F is destructive loading (KN), L is the span between the two supports (mm), b is the section width of specimen (mm), h is the section height of specimen (mm).

3.3.4 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

Table 2 Mixing proportion of Portland cement pervious concrete (kg/m³)

	Coarse aggregate	Cement	Water	Fine aggregate	Silica fume
A1	1565	419	133	0	0
A2	1487	419	134	78	0
A3	1408	419	135	157	0
A4	1330	419	137	235	0
B1	1565	402	133	0	17
B2	1565	385	133	0	34
B3	1526	402	133	39	17
B4	1526	385	133	39	34
B5	1487	402	134	78	17
B6	1487	385	134	78	34

Table 3 Performance of Portland cement pervious concrete mixed with fine aggregate

	Fine aggregate %	Compressive strength MPa	Flexural strength MPa	Porosity %	Permeability mm/s	Mass loss kg/m²
A1	0	19.73	2.43	21.7	1.85	8.8
A2	5	22.87	3.07	20.3	0.68	5.2
A3	10	24.72	3.47	20.7	0.34	4.2
A4	15	28.46	3.50	19.0	0.04	4.0

used to evaluate the abrasion resistance and determined by Eq. (5).

$$G_C = (m_1 - m_2)/0.0125 \quad (5)$$

Where, G_c is the wear amount per unit area (g/m²), m_1 and m_2 is the weight of specimen before and after abrasion resistance test (g), 0.0125 is the wear area (m²).

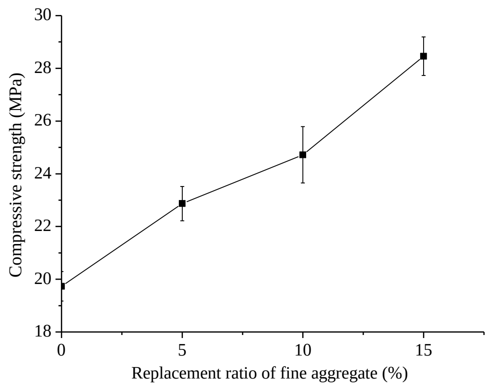
4. Result and discussions

4.1 Effect of fine aggregate on properties of Portland cement pervious concrete

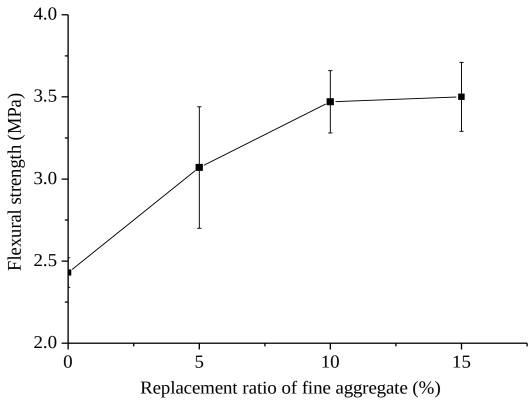
The fine aggregate is used to replace the coarse aggregate at equal volume. The replacement ratio is 0, 5%, 10% and 15%. The strength, the abrasion resistance, the porosity and the water permeability of Portland cement pervious concrete are measured. The results are shown in Table 3.

4.1.1 Strength

The effect of fine aggregate ratio on strength of Portland cement pervious concrete is shown in Fig. 2. It can be seen that the addition of fine aggregate can greatly improve the strength of Portland cement pervious concrete. The compressive strength and the flexural strength are increased by 44.0% and 44.2% when the sand ratio increases from 0 to 15%. However, the strength increases slowly after the sand ratio exceeds 10%. The enhancement of strength of Portland cement pervious concrete due to added sand particles can be explained by several mechanisms. One of them is the microcrack shield, which causes a reduction of stress in the fracture process zone. Another one is the crack bridging, which provides closing pressure in the fracture process zone. Also, the interlocking particles between the crack surfaces consume energy and thus enhance the fracture resistance (Bu *et al.* 2017, Zampini *et al.* 1995, Amparano *et al.* 2000). In addition, the usage of fine aggregate also increases the bond point between coarse aggregates, which improves the strength of Portland cement pervious concrete (Belkacem *et al.* 2014, Wu *et al.* 2009). Zaetan *et al.* (2017) found a similar result and pointed out that the increase in compressive strength was due to the filler effect of fine aggregate. The fine aggregate could improve the gradation of single size aggregates and thus alter the properties of concrete accordingly, so it improved the strength of PC. Therefore the addition of fine aggregates is a good choice for making high-strength Portland cement pervious concrete.



(a) Compressive strength

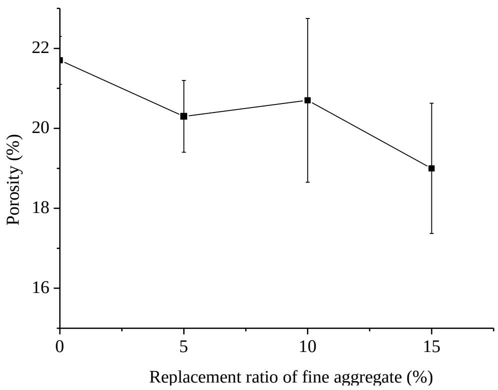


(b) Flexural strength

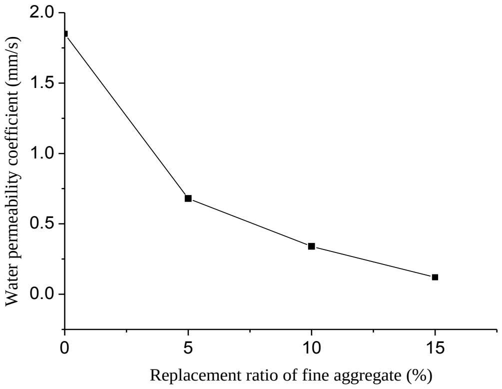
Fig. 2 Effect of fine aggregate on strength of Portland cement pervious concrete

4.1.2 Porosity and permeability coefficient

Fig. 3 presents the effect of fine aggregate on the porosity and the permeability coefficient. It is clearly that the addition of fine aggregate decreases the porosity and the permeability coefficient of Portland cement pervious concrete. The porosity is decreased by 12.4% when the sand ratio is 15%. Bu *et al* (2017) also reported that the pore size distribution curve shifted to smaller size with increasing sand content, i.e., the pores became finer with sand addition. Xu *et al*. (2018) found that fine aggregate



(a) Porosity



(b) Water permeability coefficient

Fig. 3 Effect of fine aggregate on porosity and water permeability of Portland cement pervious concrete

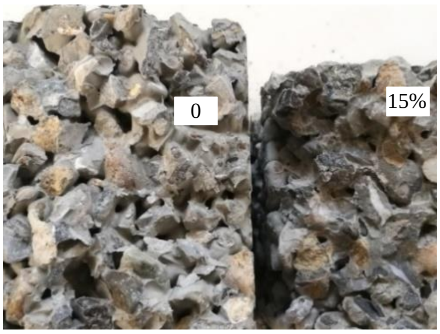


Fig. 4 The cross section of PCPC specimen with 0 and 15% fine aggregate

increased the contact area of the conjoint point among coarse aggregate to decrease the ratios of pores that larger than 7050 μm and increase the ratios of pores of 1050 μm-50 μm. They also recommended that a reasonable content of fine aggregate should be considered to improve the conjoint point.

However, the permeability coefficient is decreased by 93.5%. This results can be explained by the changes in pore structure.

The cross section of Portland cement pervious concrete specimen with 0 and 15% fine aggregate is shown in Fig. 4.

It can be observed that the pores in Portland cement pervious concrete without fine aggregate have large size and are connected to each other, which increases the porosity and permeability coefficient of Portland cement

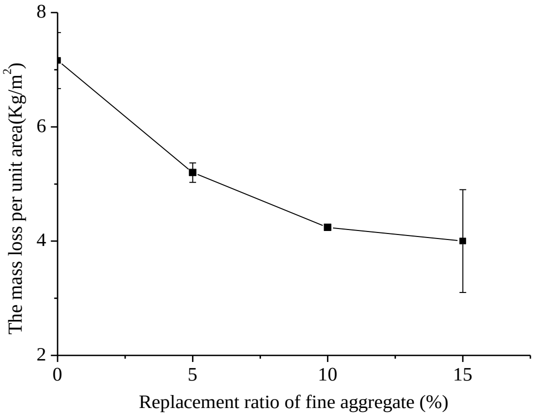


Fig. 5 Effect of fine aggregate on abrasion resistance of Portland cement pervious concrete

pervious concrete. However, the pore size is significantly reduced after the addition of 15% fine aggregate. In addition, the connectivity of the pores also has a large effect on the water permeability coefficient (Wu *et al.* 2009). Fine aggregate improves the fluidity of fresh Portland cement pervious concrete. A part of the mortar tends to accumulate on the bottom surface of the specimen during the vibrating process. The permeation path of water will be blocked after the bottom mortar layer is hardened, which significantly decreases the connectivity of pores and the water permeability coefficient. Zaetang *et al.* (2017) reported that there was a limitation for adding sand to the mixture as when the sand content was increased the permeability of PC reduced due to the increased volume paste.

4.1.3 Abrasion resistance

The effect of sand ratio on the abrasion resistance of Portland cement pervious concrete is shown in Fig. 5.

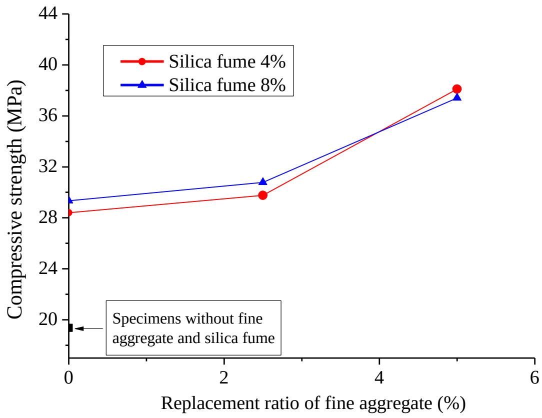
The wear amount per unit area decreases with increasing the sand ratio. Comparing to the control specimens, G_c of Portland cement pervious concrete with 15% fine aggregate is decreased by 44.1%. In other words, the addition of fine aggregates improves the surface abrasion resistance of Portland cement pervious concrete. However, the improvement effect is slowed down with the increase of the sand ratio. The addition of fine aggregates can increase the strength, which has been confirmed in Fig. 2. Usually, concrete with high strength will have high surface hardness and thus high surface abrasion resistance. Singh and Siddique (2012) also observed that depth of wear had a strong relationship with strength properties. Generally, an increase in strength and modulus of elasticity lead to an increase in abrasion resistance of concrete.

4.2 Combined effect of fine aggregate and silica fume on the performance of Portland cement pervious concrete

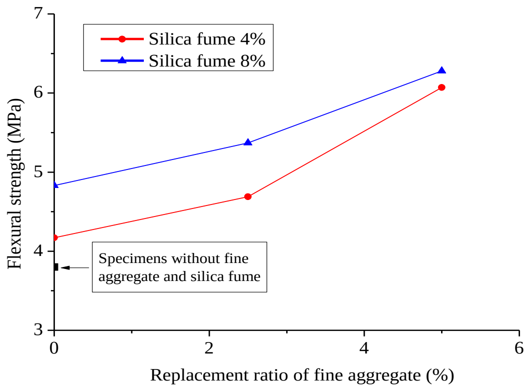
The fine aggregate and silica fume are used to replace the coarse aggregate and cement at equal volume. The replacement ratio of the fine aggregate is 0, 2.5% and 5%. The replacement ratio of the silica fume is 4% and 8%.The strength, the abrasion resistance, the porosity and the water

Table 4 Properties of Portland cement pervious concrete mixed with fine aggregate and silica fume

	Fine aggregate %	Silica fume %	Compressive strength MPa	Flexural strength MPa	Porosity %	Permeability mm/s	Mass loss kg/m^2
B1	0	4	28.4	4.17	15.67	0.33	7.6
B2	0	8	29.34	4.83	14.0	0.25	6.8
B3	2.5	4	29.77	4.69	13.67	0.16	5.6
B4	2.5	8	30.78	5.37	13.33	0.13	5.6
B5	5	4	38.40	6.07	13.0	0.13	3.6
B6	5	8	37.40	6.08	12.67	0.12	3.2



(a) Compressive strength



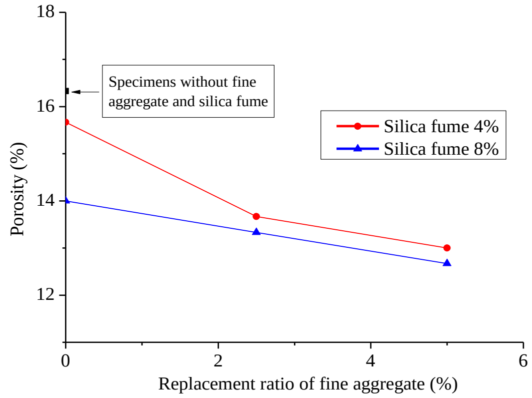
(b) Flexural strength

Fig. 6 Effect of fine aggregate and silica fume on strength of Portland cement pervious concrete

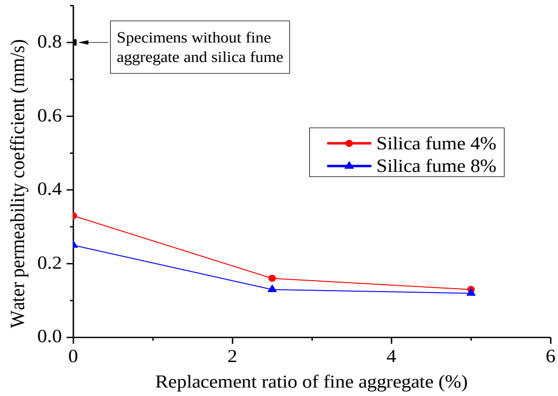
permeability of Portland cement pervious concrete are also measured. The results are shown in Table 4.

4.2.1 Strength of Portland cement pervious concrete

Fig. 6 shows the effect of the fine aggregate and the silica fume on the strength of Portland cement pervious concrete. It can be seen that both the compressive strength and the flexural strength increase with the increase of the fine aggregate and the silica fume. For Portland cement pervious concrete without the fine aggregate, 4% replacement of silica fume can significantly improve the strength of the specimens. The compressive strength and the flexural strength are increased by 46.6% and 9.7%, respectively. The flexural strength is increased by 27.1%



(a) Porosity



(b) Permeability Coefficient

Fig. 7 Effect of fine aggregates and silica fume on porosity and permeability coefficient

when the replacement of silica fume is increased to 8%.

There are two reasons for the higher strength of these silica fume Portland cement pervious concrete. The first one is the filler effect (Zaetang *et al.* 2017), silica fume can act as a filler for the spaces between cement particles because of its small particle size, which results in a reduction in the size of the individual pores and voids in the paste. Since pores are discontinuities in the cement paste matrix, reduced pore sizes require a higher stress to initiate a crack; thus, the strength is increased. The second reason for the high strength of the silica fume Portland cement pervious concrete is due to the pozzolanic nature of silica fume (Cong *et al.* 1992, Kjellsen *et al.* 1999, Mazloom *et al.* 2004, Imam *et al.* 2018, Zaetang *et al.* 2017).

Furthermore, with assistance of silica fume and fine aggregate simultaneously, Portland cement pervious concrete could achieve a higher strength. The compressive strength and the flexural strength are increased by 93.1% and 65% when Portland cement pervious concrete specimens mixed with 5% fine aggregates and 8% silica fume. This result is very important for the materials used in pavement engineering. However, the compressive is not further improved after the silica fume content is increased from 4% to 8%.

4.2.2 Porosity and permeability coefficient of pervious concrete

Fig. 7 presents the effect of fine aggregates and silica

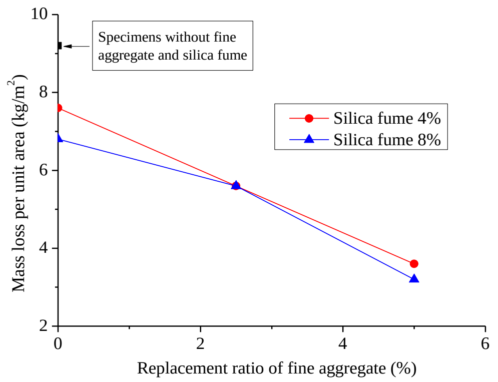


Fig. 8 Effect of fine aggregate and silica fume on abrasion resistance of pervious concrete

fume on the porosity and permeability coefficient of Portland cement pervious concrete. It is clearly that the addition of fine aggregates and silica fume decreases the porosity and water permeability coefficient of the specimens. Comparing to Portland cement pervious concrete without fine aggregates, the porosity is decreased by 4% and 14.3% when 4% and 8% silica fume are used to replace cement. The porosity is further reduced with the addition of fine aggregates. The result is consistent with the increase in strength of the specimens. The permeability coefficient of the specimens is also decreased because of the decrease in porosity, as shown in Fig. 8. The permeability coefficient are decreased by 58.8% and 65% when the replacement of silica fume is 4% and 8%. The decrease in porosity and water permeability is due really to the discontinuity and tortuosity of fine pores formed in the process of pozzolanic reaction of silica fume with calcium hydroxide in concrete (See Eq. (6)) (Torii and Kawamura 1994).

$$3Ca(OH)_2 + 2SiO_2 = 3CaO \cdot 2SiO_2 \cdot 3H_2O \tag{6}$$

The porosity and the water permeability are further decreased by 22.4% and 85% when Portland cement pervious concrete is mixed with 5% fine aggregate and 8% silica fume.

4.2.3 Abrasion resistance of pervious concrete

The effect of fine aggregate and silica fume on abrasion resistance of Portland cement pervious concrete is shown in Fig. 8.

It can be seen that the addition of silica fume improves the abrasion resistance of Portland cement pervious concrete. The mass loss per unit area is reduced by 17.4% and 26.1% when the replacement ratio of silica fume is 4% and 8%. The abrasion resistance is further improved when the fine aggregates and silica fume are simultaneously added to Portland cement pervious concrete. For Portland cement pervious concrete mixed with 5% fine aggregate, the mass loss per unit area is decreased by 60.9% and 65.2% when 4% and 8% silica fume are simultaneously used to replace cement. In addition to the improvement of the abrasion resistance caused by fine aggregates, the interface transition zone and the matrix can be dense by the hydration of silica fume, which will further increase the strength and abrasion resistance of Portland cement pervious concrete (Chung 2002, Ghafoori and Diawara 2007). The improvement of fine aggregates and silica fume to abrasion resistance of Portland cement pervious concrete is very important for the materials used in pavement engineering.

In general, the coarse aggregate and cement replaced by the fine aggregates and the silica fume can improve the strength and the abrasion resistance of Portland cement pervious concrete (Zaetang *et al.* 2017), which is beneficial to the application of Portland cement pervious concrete on the vehicle road surface. However, they usually reduce the water permeability of Portland cement pervious concrete. Therefore, the replacement ratio of the fine aggregates and the silica fume should be considered comprehensively and determined on the premise of ensuring the water permeability coefficient.

5. Conclusions

• When the fine aggregate and the silica fume are added to Portland cement pervious concrete separately, the compressive strength, the flexural strength and the abrasion resistance are increased.
However, the porosity and the water permeability are decreased simultaneously.
• With assistance of silica fume and fine aggregate simultaneously, Portland cement pervious concrete could achieve a higher strength. The compressive strength, the flexural strength and the abrasion resistance of Portland cement pervious concrete mixed with 5% fine aggregates and 8% silica fume are increased by 93.1%, 65% and 65.2%, respectively.
• The porosity and the water permeability are decreased by 22.4% and 85% when Portland cement pervious concrete is mixed with 5% fine aggregate and 8% silica fume.
• The replacement ratio of the fine aggregates and the silica fume should be considered comprehensively and determined on the premise of ensuring the water permeability coefficient.

Acknowledgments

This research was supported by the National Natural Science Foundation of China (Grant no. 51678022 and 51378042).

Conflicts of Interest

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

Reference

ACI 522R-10 (2010), Report on Pervious Concrete, ACI Committee, 522, 38.

Amparano, F.E., Xi, Y. and Roh, Y.S. (2000), "Experimental study on the effect of aggregate content on fracture behavior of concrete", *Eng. Fract. Mech*., **67**, 65-84. https://doi.org/10.1016/S0013-7944(00)00036-9.

Bassuoni, M.T. and Sonebi, M. (2010), "Pervious concrete: a sustainable drainage solution", *Concrete*, **44**, 14-16.

Belkacem, B., Madani, B., Khadra, B. and Michele, Q. (2014), "Effect of the type of sand on the fracture and mechanical properties of sand concrete", *Adv. Concrete Constr.*, **2**(1), 13-27. https://doi.org/10.12989/acc2014.2.1.013.

Bu, J., Tian, Z., Zheng, S. and Tang, Z. (2017), "Effect of sand content on strength and pore structure of cement mortar", *J. Wuhan Univ. Technol.-Mater. Sci. Ed*., **32**(2), 382-390. https://doi.org/10.1007/s11595-017-1607-9.

Chindaprasrit, P., Hatanaka, S., Chareerat, T., Mishima, N. and Yuasa, Y. (2008), "Cement paste characteristics and porous concrete properties", *Constr. Build. Mater*., **22**, 894-901. https://doi.org/10.1016/j.conbuildmat.2006.12.007.

Chindaprasrit, P., Hatanaka, S., Chareerat, T., Mishima, N. and Yuasa, Y. (2009), "Effects of binder strength and aggregate size on the compressive strength and void ratio of porous concrete", *Int. J. Miner. Metal. Mater.*, **16**(6), 714-719. https://doi.org/10.1016/S1674-4799(10)60018-0.

Chung, D.D.L. (2002), "Review improving cement-based materials by using silica fume", *J. Mater. Sci*., **37**, 673-682. https://doi.org/10.1023/A:1013889725971.

Cong, X., Gong, S., Darwin, D. and McCabe, S.L. (1992), "Role of silica fume in compressive strength of cement paste, mortar, and concrete", *ACI Mater. J*., **89**(4), 375-387.

Crouch, L.K., Pitt, J. and Hewitt, R. (2007), "Aggregate effects on pervious Portland cement concrete static modulus of elasticity", *J. Mater. Civil Eng*., **19**, 561-568. https://doi.org/10.1061/(ASCE)0899-1561(2007)19:7(561).

Deo, O. and Neithalath, N. (2011), "Compressive response of pervious concretes proportioned for desired porosities", *Constr. Build. Mater*., **25**, 4181-4189. https://doi.org/10.1016/j.conbuildmat.2011.04.055.

Ghafoori, N. and Diawara, H. (2007), "Strength and wear resistance of sand-replaced silica fume concrete", *ACI Mater. J*., **104**(2), 206-214.

Haselbach, L., Boyer, M., Kevern, J. and Schaefer, V. (2011), "Cyclic heat island impacts on traditional versus pervious concrete pavement systems", *J. Transp. Res. Board*., **2240**, 107-115. https://doi.org/10.3141/2240-14.

Ibrahim, H.A. and Razak, H.A. (2016), "Effect of palm oil clinker incorporation on properties of pervious concrete", *Constr. Build. Mater*., **115**, 70-77. https://doi.org/10.1016/j.conbuildmat.2016.03.181.

Imam, A., Kumar, V. and Srivastava, V. (2018), "Review study towards effect of silica fume on the fresh and hardened properties of concrete", *Adv. Concrete Constr.*, **6**(2), 145-157. https://doi.org/10.12989/acc.2018.6.2.145.

Jain, A.K. and Chouhan, J.S. (2011), "Effect of shape of aggregate on compressive strength and permeability properties of pervious concrete", *Int. J. Adv. Eng. Res. Stud*., **1**, 120-126.

Kevern, J.T., Biddle, D. and Cao, Q. (2014), "Effects of macrosynthetic fibres on pervious concrete properties", *J. Mater. Civil Eng*., **6**, 15-21. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001213.

Kevern, J.T., Haselbach, L. and Schaefer, V.R. (2012), "Hot weather comparative heat balances in pervious concrete and impervious concrete pavement systems", J. *Heat Isl. Inst. Int*., **7**(2), 231-237.

Kevern, J.T., Wang, K. and Schaefer, V.R. (2010), "Effect of coarse aggregate on the freeze-thaw durability of pervious concrete", *J. Mater. Civil Eng*., **22**(5), 469-475. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000049.

Khankhaje, E., Salim, M.R., Mirza, J., Hussin, M.W. and Rafieizonooz, M. (2016), "Properties of sustainable lightweight pervious concrete containing oil palm kernel shell as coarse aggregate", *Constr. Build. Mater*., **126**, 1054-1065. https://doi.org/10.1016/j.conbuildmat.2016.09.010.

Kjellsen, K.O., Wallevik, O.H. and Hallgren, M. (1999), "On the compressive strength development of high performance concrete and paste - effect of silica fume", *Mater. Struct*., **32**, 63-69. https://doi.org/10.1007/BF02480414.

Marolf, A., Neithalath, N., Sell, E., Wegner, K., Weiss, J. and Olek, J. (2004), "Influence of aggregate size and gradation on acoustic absorption of enhanced porosity concrete", *ACI Mater. J*., **101**(1), 82-91.

Mazloom, M., Ramezanianpour, A.A. and Brooks, J.J. (2004), "Effect of silica fume on mechanical properties of high-strength concrete", *Cement Concrete Compos.*, **26**, 347-357. https://doi.org/10.1016/S0958-9465(03)00017-9.

Ministry of Housing and Urban-rural Development of P.R. China (2002), Standard for Test Method of Mechanical Properties on Ordinary Concrete, GB/T 50081-2002.

Ministry of Housing and Urban-rural Development of P.R. China (2009), Technical Specification for Pervious Cement Concrete Pavement, CJJ/T135-2009.

Ministry of Transport of the P.R. China (2005), Test Methods of Cement and Concrete for Highway Engineering, JTG E30-2005.

Nguyen, D.H., Boutouil, M., Sebaibi, N., Leleyter, L. and Baraud, F. (2013), "Valorization of seashell by-products in pervious concrete pavers", *Constr. Build. Mater*., **46**, 151-160. https://doi.org/10.1016/j.conbuildmat.2013.08.017.

Rangelov, M., Nassiri, S., Haselbach, L. and Englund, K. (2016), "Using carbon fiber composites for reinforcing pervious concrete", *Constr. Build. Mater*., **126**, 875-885. https://doi.org/10.1016/j.conbuildmat.2016.06.035.

Singh, G. and Siddique, R. (2012), "Abrasion resistance and strength properties of concrete containing waste foundry sand (WFS)", *Constr. Build. Mater*., **28**(1), 421-426. https://doi.org/10.1016/j.conbuildmat.2011.08.087.

Tennis, P.D., Leming, M.L. and Akers, D.J. (2004), "National ready mixed concrete association, pervious concrete pavements", Portland Cement Association, Skokie, IL.

Torii, K. and Kawamura, M. (1994), "Pore structure and chloride ion permeability of mortars containing silica fume", *Cement Concrete Compos.*, **16**, 279-286. https://doi.org/10.1016/0958-9465(94)90040-X.

Wu, D., Liu, X., Wu, X.Q. *et al*. (2009), "Effect of forming method and sand ratio on performance of pervious concrete", *Concrete*, **5**, 100-102.

Xu, G., Shen, W., Huo, X., Yang, Z., Wang, J., Zhang, W. and Ji, X. (2018), "Investigation on the properties of porous concrete as road base material", *Constr. Build. Mater*., **158**, 141-148. https://doi.org/10.1016/j.conbuildmat.2017.09.151.

Yahia, A. and Kabagire, D. (2014), "New approach to proportion pervious concrete", *Constr. Build. Mater*., **62**, 38-46. https://doi.org/10.1016/j.conbuildmat.2014.03.025.

Yang, J. and Jiang, G. (2002), "Experimental study on properties of pervious concrete pavement materials", *Cement Concrete Res*., **33**, 381-386. https://doi.org/10.1016/S0008-8846(02)00966-3.

Yuwadee, Z., Sata, V., Wongsa, A. and Chindaprasirt, P. (2016), "Properties of pervious concrete containing recycled concrete block aggregate and recycled concrete aggregate", *Constr. Build. Mater.*, **111**, 15-21. https://doi.org/10.1016/j.conbuildmat.2016.02.060.

Zaetang, Y., Wongsa, A., Sata, V. and Chindaprasirt, P. (2017), "Influence of mineral additives on the properties of pervious concrete", *Ind. J. Eng. Mater. Sci.*, **24**(6), 507-515.

Zampini, D., Jennings, H.M. and Shah, S.P. (1995),

"Characterization of the paste aggregate interfacial zone to the fracture toughness of concrete", *J. Mater. Sci.*, **30**(12), 3149-3154. https://doi.org/10.1007/BF01209230.
Zhang, W.M., Li, H.H. and Zhang, Y.C. (2018), "Effect of porosity on frost resistance of Portland cement pervious concrete", *Adv. Concrete Constr.*, **6**(4), 363-373. https://doi.org/10.12989/acc.2018.6.4.363.

CC