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Properties of pervious concrete containing high-calcium fly ash

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Abstract. This paper presents the properties of pervious concrete containing high-calcium fly ash. The water to binder ratios of 0.19, 0.22, and 0.25, designed void ratios of 15, 20, and 25%, and fly ash replacements of 10, 20, and 30% were used. The results showed that the use of fly ash as partial replacement of Portland cement enhanced the mixing of paste resulting in a uniform mix and reduced amount of superplasticizer used in the mixture. The compressive strength and flexural strength of pervious concrete were slightly reduced with an increase in fly ash replacement level, while the abrasion resistance increased due mainly to the pozzolanic and filler effects. The compressive strength and flexural strengths at 28 days were still higher than 85% of the control concrete. The aggregate size also had a significant effect on the strength of pervious concrete. The compressive strength and flexural strength of pervious concrete with large aggregate were higher than that with small aggregate.

Keywords: cement paste; pervious concrete; void ratio; fly ash; compressive strength; flexural strength

1. Introduction

Pervious concrete is a concrete with high porosity and continuous void (ACI 522R, 2010). The difference between pervious concrete and normal concrete is pervious concrete mixture contains little or no-fine aggregate (Sumanasooriya and Neithalath 2011, Tennis *et al*. 2004, Zaetang *et al*. 2013). In addition, pervious concrete has very low workability similar to a roller-compacted concrete with required compaction energy (Aamer Rafique Bhutta *et al*. 2012). Generally, the compressive strength of pervious concrete is between 2.8-28.0 MPa depending on the void ratio (ACI 522R 2010, Chindaprasirt *et al*. 2011, Lian *et al*. 2011). To obtain good quality and high strength pervious concrete, the flow of cement paste, void ratio, and the energy of compaction need to be controlled. In England and the US, pervious concrete has been used for over 30 years (Golroo and Tighe 2011, Shu *et al.* 2011). It has been studied and researched extensively in the US, Japan, and other countries (Aamer Rafique Bhutta *et al*. 2012, Yang and Jiang 2003). Pervious

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Table 1 Characteristics of ordinary Portland cement and fly ash

Properties	Cement	Fly ash
SiO_2 (%)	20.81	37.62
Al_2O_3 (%)	4.97	20.45
Fe_2O_3 (%)	3.51	12.37
CaO (%)	66.80	19.48
MgO (%)	0.78	2.79
SO_3 (%)	2.34	2.11
K_2O (%)	0.40	2.48
Na_2O (%)	0.01	1.97
Loss on ignition (%)	0.13	1.40
Specific gravity	3.14	2.27
Specific surface area (cm^2/g)	3300	2700

concrete has been used in the paving of roads and parking lots in order to efficiently solve the problem of storm water runoff and ground water (Golroo and Tighe 2011, Putman and Neptune 2011, Haselbach *et al*. 2006, Leming *et al*. 2007), and the drainage of retaining walls which help reduce the pressure of water. It can be used for paving the river, sewage and water treatment filters to reduce the pollution in water. In addition, it can be used for foundation of grass planting in the lawn or deck in order to reduce heat reflection, and also used for sound absorption. For these reasons, it can be said that pervious concrete is an environmentally friendly material.

Fly ash is a by-product obtained from coal burning process to produce electricity in a power generating plant. Generally, fly ash enhances concrete workability, segregation resistance, later age strength, and durability (Rukzon and Chindaprasirt 2008, Siddique and Khatib 2010, Ramanathan *et al*. 2013, Vimonsatit *et al.* 2015, Sunil *et al.* 2015). Furthermore, the electrical resistivity and capillarity of self-compacting concrete at the later age is improved with incorporation of fly ash (Silva and De Brito 2013). The high calcium fly ash contains high CaO and thus possesses the self cementing property. Moreover, the use of fly ash as a replacement of cement is another way to reduce the amount of cement, energy use and CO_2 emission (Siddique 2004, Limbachiya *et al*. 2012).

The purpose of this study is to investigate the use of high-calcium fly ash in pervious concrete. The first part dealt with property and workability of paste containing high-calcium fly ash and the second part dealt with void, compressive strength, flexural strength, water permeability, and abrasion of concrete. In addition, an expression predicting their properties was proposed.

2. Materials

Ordinary Portland cement type I with specific gravity of 3.14 and Blaine fineness of 3300 cm^2/g was used in this study. Fly ash was obtained from Mae Moh power station from Lampang Province in Thailand with specific gravity of 2.27 and Blaine fineness of 2700 cm^2/g. The chemical composition and physical properties of ordinary Portland cement and fly ash are shown in Table 1. The sum of SiO_2, Al_2O_3, and Fe_2O_3 of fly ash was around 70.0% with a high CaO

Table 2 Mix proportions of pervious concrete

Mixes	Cement (kg/m^3)	Fly ash (kg/m^3)	Aggregate (kg/m^3)	Water (kg/m^3)	SP (% of binder)	W/B
0FA0.19-20I	438	0	1604	83	1.78	0.19
10FA0.19-20I	385	43	1604	81	1.68	0.19
20FA0.19-15I	410	102	1604	97	1.19	0.19
20FA0.19-20I	335	84	1604	79	1.55	0.19
20FA0.19-25I	260	65	1604	62	1.85	0.19
30FA0.19-20I	286	123	1604	78	1.44	0.19
20FA0.19-15II	435	109	1529	103	1.19	0.19
20FA0.19-20II	360	90	1529	85	1.56	0.19
20FA0.19-25II	285	71	1529	68	1.83	0.19
20FA0.22-20I	317	79	1604	87	0.71	0.22
20FA0.25-20I	301	75	1604	94	0.16	0.25

content of 19.5% which indicated a high-calcium fly ash according to ASTM C618 (2008). Two coarse limestone aggregates were used in this study. The first had diameter of 4.75-9.0 mm with specific gravity of 2.79, dry unit weight of 1604 kg/m^3, and void content of 44.0%. The second had diameter of 9-19 mm with specific gravity of 2.75, dry unit weight of 1529 kg/m^3 and void content of 43.2%. Water to binder ratios (W/B) of 0.19, 0.22, and 0.25 were used. Water reducing agent type F superplasticizer (SP) used in this investigation was selected based on previous work (Chindaprasirt *et al.* 2008).

3. Experimental study

3.1 Cement paste

To study the properties of paste, the water to binder ratios of 0.19, 0.22, and 0.25, the fly ash replacements of 10, 20, and 30% by weigh of binder were used. The mixing method of paste was set at 50 rpm for 30 s after the addition of binder, water, and admixture. This was followed by mixing at speed of 200 rpm for 240 s. After the mixing of paste, flow value was measured in accordance with JIS R 5201 (1997).

3.2 Concrete

3.2.1 Mixing of concrete

In this study, the designed void ratio of 15, 20, and 25% with flow values of paste of 150, 190, and 230 were selected. The mix proportions of concrete are given in Table 2. The symbol of mix proportion is given as xxFAyy-zzI., where xxFA is the amount of cement replaced by fly ash (%); yy is the water to binder ratio; zz is the designed void ratio (%); I and II stand for aggregate sizes of 9 mm and 19 mm, respectively. After the mixing of paste, the coarse aggregate was added to the mixture and mixed at 200 rpm for 120 s. The mixture was placed in two layers into 100×200 mm cylindrical mould and 150×150×500 mm beam mould on a vibrating table. The vibration time was 10 s for each layer.

3.2.2 Testing of concrete

The void of concrete was measured using test method for pervious concrete in accordance with ASTM C 1754-12 (2012) as shown in the following Eq. (1)

$$A_T(\%) = \left(1 - \frac{W_2 - W_1}{\rho_W V}\right) \times 100 \tag{1}$$

where A_T is the total void of the concrete (%); W_1 is the weight of the specimen in water (g); W_2 is the weight of air dried of the specimen after being placed in room temperature conditions for 24 hr (g); ρ_W is the density of water at temperature of water bath (g/cm^3); and V is the volume of the specimen (cm^3).

The compressive strengths of concrete were determined in accordance with ASTM C 39/C 39M-01 (2003). Compression test cylinders were capped at both ends with a sulfur capping compound. The reported strengths were the average of three specimens.

The flexural strength were determined by simple beam with the third-point loading method and determined in accordance with ASTM C 78-02 (2003). The span length of 450 mm and the load rate was about 0.15$\pm$0.05 MPa/s. The flexural strength values were acquired from three samples from each group.

Water permeability was determined using a constant head permeability test apparatus which was successfully used by Zaetang et al. (2013). The coefficient of permeability (k) was calculated in accordance with Darcy's Law, as following Eq. (2).

$$k = \frac{H}{h} \times \left(\frac{Q}{A(T_2 - T_1)}\right) \times 100 \tag{2}$$

where k is the permeability coefficient (cm/s); H is the length of sample (cm); h is the difference in level (cm); Q is the flow quantity during the period from T_1 to T_2 (cm^3); A is the cross sectional area of test piece (cm^2); and T_2-T_1 is the measurement period of time (s).

The abrasion resistant of concrete was evaluated according to ASTM C 944-99 (2003), test method for abrasion resistance of concrete or mortar surfaces by the rotating-cutter method. The abrading cutter rotated at a speed of 200 rpm and exerted a force of a normal load of 98 $\pm$ 1 N. Each specimen was abraded for 2 min. In this test, the 150 mm cubic concrete samples were used and the surface abrasion test was performed at the age of 28 days. The extent of abrasion was determined from the difference in weight before and after the abrasion test.

4. Experimental results and discussion

4.1 Effect of fly ash and SP on flow of cement paste

The results showed that for W/B ratio of 0.19 and cement paste with fly ash replacement of 0, 10, 20, and 30% by weight, the dosages of SP were between 1.55-2.06, 1.38-2.02, 1.20-1.96, and 1.04-1.93%, respectively. The use of fly ash to replace part of cement increased the workability of

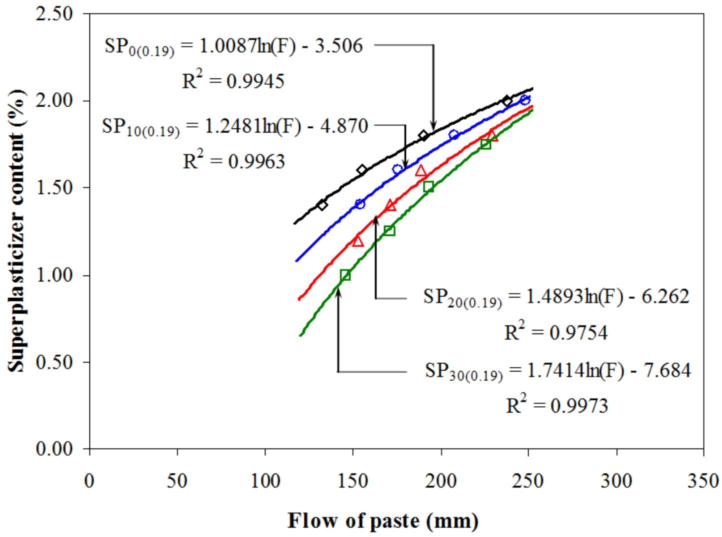

Fig. 1 Relationship between flow of paste and SP content with various fly ash replacements at W/B ratio of 0.19

paste. This was due to the spherical and the smoothness of surface texture of fly ash particles, thus allowing a better flow of cement paste (Sata *et al.* 2011, Siddique 2004). For OPC and replacements with fly ash of 10, 20, and 30% by weigh of cement and W/B ratio of 0.19, the dosage of SP can be calculated by Eqs. (3)-(6) as shown in Fig. 1. At the same fly ash replacement, the increase of water to binder ratio reduced the demand of SP as shown in Fig. 2. For the fly ash replacement of 20%, the SP dosage for W/B ratios of 0.22 and 0.25 can be calculated by Eqs. (7) and (8), respectively.

$$SP_{0(0.19)} = 1.0087\,ln(F) - 3.506\,,\ R^2 = 0.9945 \tag{3}$$

$$SP_{10(0.19)} = 1.2481\,ln(F) - 4.870\,,\ R^2 = 0.9963 \tag{4}$$

$$SP_{20(0.19)} = 1.4893\,ln(F) - 6.262\,,\ R^2 = 0.9754 \tag{5}$$

$$SP_{30(0.19)} = 1.7414\,ln(F) - 7.684\,,\ R^2 = 0.9973 \tag{6}$$

$$SP_{20(0.22)} = 1.4970\,ln(F) - 6.930\,,\ R^2 = 0.9743 \tag{7}$$

$$SP_{20(0.25)} = 1.5026\,ln(F) - 7.678\,,\ R^2 = 0.9690 \tag{8}$$

where $SP_{0(0.19)}$ is the dosage of SP with 100% OPC, W/B ratio of 0.19; $SP_{10(0.19)}$, $SP_{20(0.19)}$, and $SP_{30(0.19)}$ are the dosage of SP with 10, 20, and 30% fly ash (%), respectively, W/B ratio of 0.19; $SP_{20(0.22)}$, and $SP_{20(0.25)}$ are the dosage of SP with 20% fly ash (%), W/B ratio of 0.22 and 0.25, respectively; and F is flow of paste (mm).

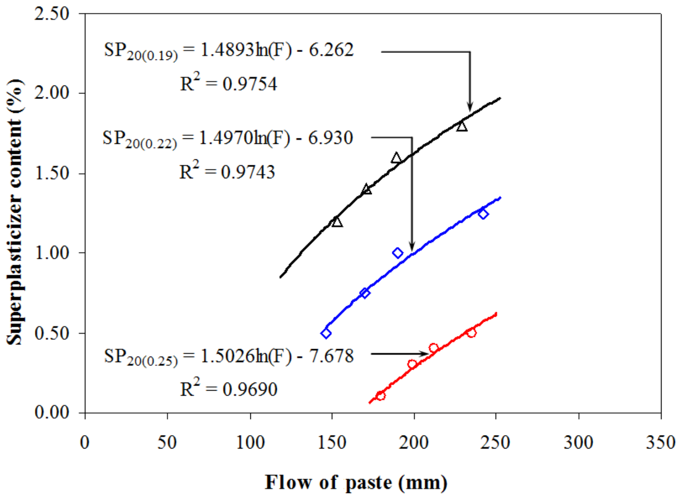

Fig. 2 Relationship between flow of paste and SP content at W/B ratios of 0.19, 0.22, 0.25 and 20% fly ash replacement

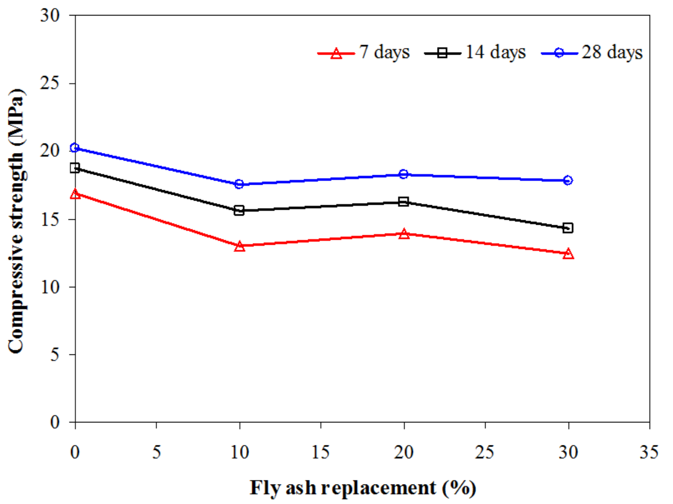

Fig. 3 Fly ash replacement and compressive strength of 9 mm aggregate pervious concrete with designed void ratio of 20% and W/B ratio of 0.19

4.2 Compressive strength

The results of compressive strength of pervious concrete with designed void ratio of 20%, W/B ratio of 0.19, fly ash replacements of 10, 20, and 30% by weigh of binder are shown in Fig. 3. The compressive strengths of pervious concrete at early ages of 7 and 14 days decreased as the amount of replacement by fly ash increased. This is because of the pozzolanic reaction of fly ash at early age is lower than the reaction of cement hydration (Siddique 2004, Tangpagasit *et al.* 2005). Thus, pervious concrete with fly ash gave compressive strength less than the pervious concrete without fly ash. At 28 days, the pervious concrete with fly ash replacements of 0, 10, 20, and 30% by

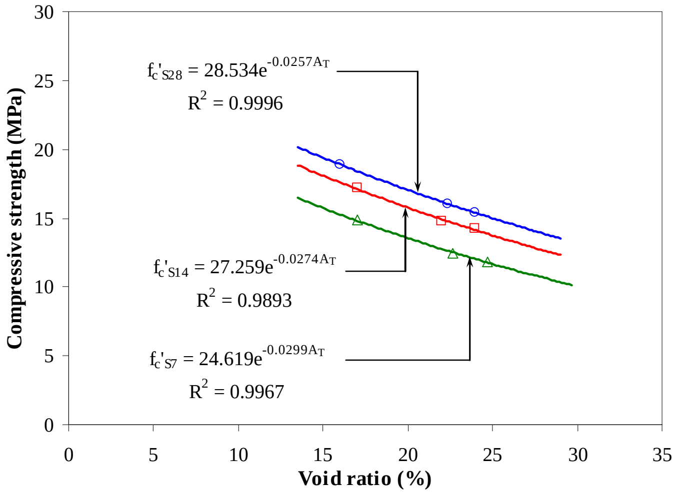

Fig. 4 Void ratio and compressive strength of 9 mm aggregate pervious concrete

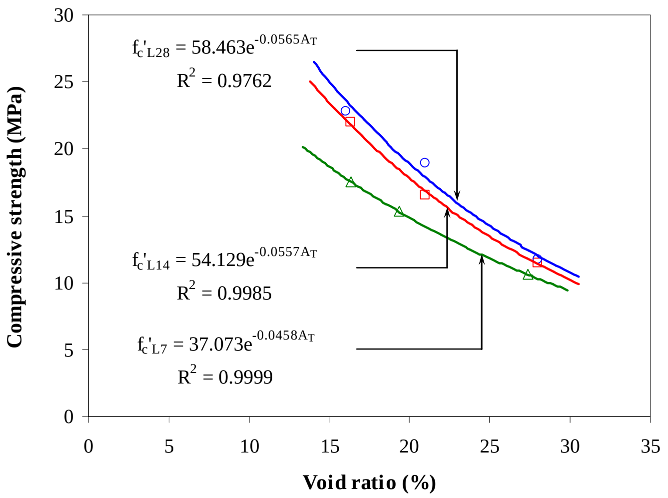

Fig. 5 Void Ratio and compressive strength of 19 mm aggregate pervious concrete

weight had the compressive strengths of 20.2, 17.5, 18.3, and 17.8 MPa with the corresponding normalized values of 100, 86.6, 90.6, and 88.1%, respectively. These values were higher than the minimum strength activity index requirement of 75% according to ASTM C 618 (2010). In addition, the compressive strength of pervious concrete was related to the void ratio as shown in Figs. 4 and 5. The compressive strength of concrete increased with a decrease of void ratio. This finding was similar to the studies of Lian *et al*. (2011), Shu *et al*. (2011), and Kim *et al*. (2010). With regard to the effect of aggregate size, the effect is significant for the small void ratio of 0.15. The strength of 9 mm aggregate concrete was significantly less than that with 19 mm aggregate concrete. As the overall surface area of large aggregate was less than that of small aggregate, the large aggregates required less paste to cover the surface and the paste covering large aggregate was thicker resulting in the better bonding between aggregates (Chindaprasirt *et al*. 2009). The

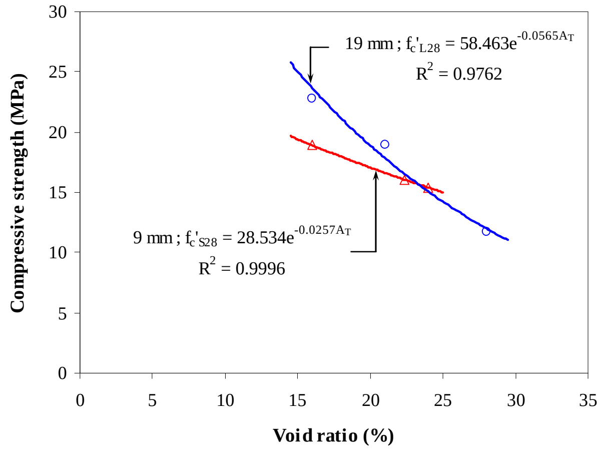

Fig. 6 Relationship between void ratio and compressive strength of pervious concrete with various aggregate sizes at 20% fly ash replacement and W/B ratio of 0.19

concrete with void ratio higher than about 23%, the 9 mm aggregate concretes had a similar strength to those of 19 mm aggregate concretes. At low paste content, the amount of surplus paste would also be low. In addition, the contact areas between the smaller aggregates were higher than those of the large aggregates and thus offset the influence of aggregate size on strength.

The relationship between void ratio and compressive strength of pervious concrete using 9 mm aggregate at 7, 14, and 28 days could be fitted using exponential curve as shown in Eqs. (9)-(11), and Eqs. (12)-(14) for 19 mm aggregate.

$$f_c'_{S7} = 24.619e^{-0.0299A_T}, \; R^2 = 0.9967 \tag{9}$$

$$f_c'_{S14} = 27.259e^{-0.0274A_T}, \; R^2 = 0.9893 \tag{10}$$

$$f_c'_{S28} = 28.534e^{-0.0257A_T}, \; R^2 = 0.9996 \tag{11}$$

$$f_c'_{L7} = 37.073e^{-0.0458A_T}, \; R^2 = 0.9999 \tag{12}$$

$$f_c'_{L28} = 54.129e^{-0.0557A_T}, \; R^2 = 0.9985 \tag{13}$$

$$f_c'_{L28} = 58.463e^{-0.0565A_T}, \; R^2 = 0.9762 \tag{14}$$

where $f_c'_{S7}$, $f_c'_{S14}$, and $f_c'_{S28}$ are the compressive strengths of pervious concretes using 9 mm aggregate at 7, 14, and 28 days, respectively (MPa); $f_c'_{L7}$, $f_c'_{L14}$, and $f_c'_{L28}$ are those of 19 mm aggregate; and A_T is the total void ratio (%).

It is generally accepted that compressive strength of pervious concrete is related to the strength of paste (Chindaprasirt *et al*. 2008). Thus, the increasing of W/B ratio in pervious concrete decreased the compressive strength. At 28 days, the pervious concretes with water to binder ratios of 0.19, 0.22, and 0.25 had compressive strengths of 18.25, 15.14, and 12.74 MPa, respectively, as shown in Fig. 7.

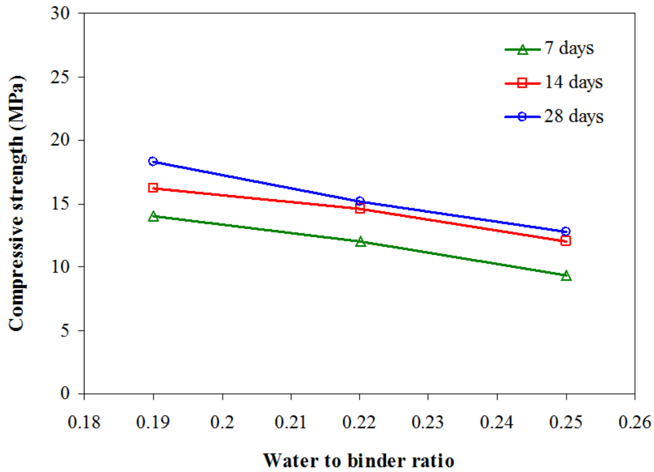

Fig. 7 W/B ratio and compressive strength of pervious concrete with 20% fly ash replacement and designed void ratio of 20%

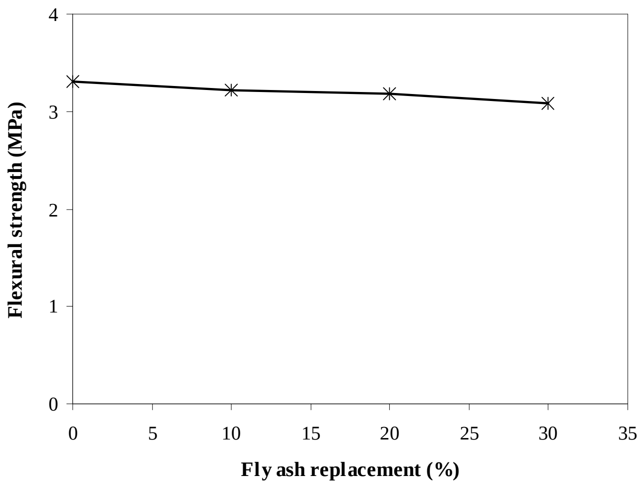

Fig. 8 Fly ash replacement and flexural strength of 9 mm aggregate pervious concrete with designed void ratio of 20% and W/B ratio of 0.19

4.3 Flexural strength

The flexural strength of pervious concretes with 20% designed void ratio with fly ash replacement levels of 0, 10, 20, and 30% were 3.31, 3.22, 3.18, and 3.09 MPa, respectively as shown in Fig. 8. At 28 days, the use of fly ash replacement in the pervious concrete had little effect on flexural strength due to the low pozzolanic reaction at early age (Park *et al*. 2009). Fig. 9 presents the flexural strength of pervious concrete with the two aggregate sizes. The flexural strength of pervious concrete with 19 mm aggregate was higher than that with 9 mm aggregate. The trend of results of flexural strength was consistent with the compressive strength of pervious concrete. At low total void ratio, the use of smaller aggregate seemed to give higher strength than that with the larger aggregate. The relationship between void ratio and flexural strength of

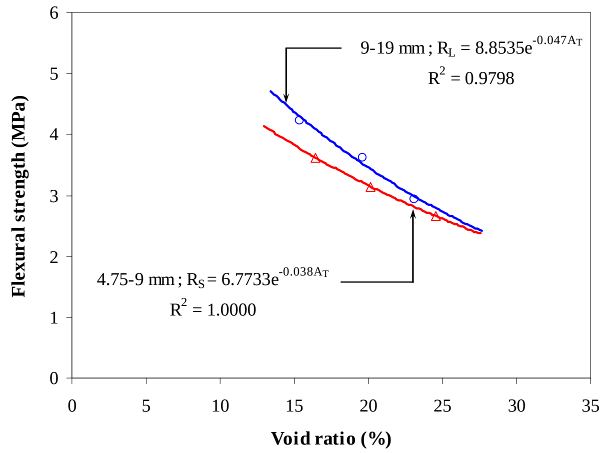

Fig. 9 Relationship between void ratio and flexural strength of pervious concrete with various aggregate sizes at 20% fly ash replacement and W/B ratio of 0.19

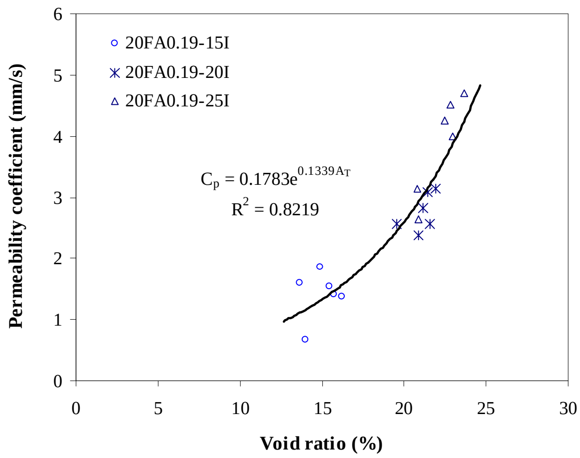

Fig. 10 Relationship between void ratio and water permeability coefficient of 9 mm aggregate pervious concrete with 20% fly ash replacement and W/B ratio of 0.19

pervious concrete using 9 mm aggregate could be fitted using exponential curve as shown in Eq. (15) and in Eq. (16) for 19 mm aggregate.

$$R_S = 6.7733e^{-0.038A_T}, \; R^2 = 1.0000 \tag{15}$$

$$R_L = 8.8535e^{-0.047A_T}, \; R^2 = 0.9798 \tag{16}$$

where R_S and R_L are flexural strengths of pervious concretes using aggregate sizes of 9 and 19 mm (MPa), respectively; and A_T is total void ratio (%).

4.4 Water permeability coefficient

Generally, the water permeability of pervious concrete is related to the continuous void, pore

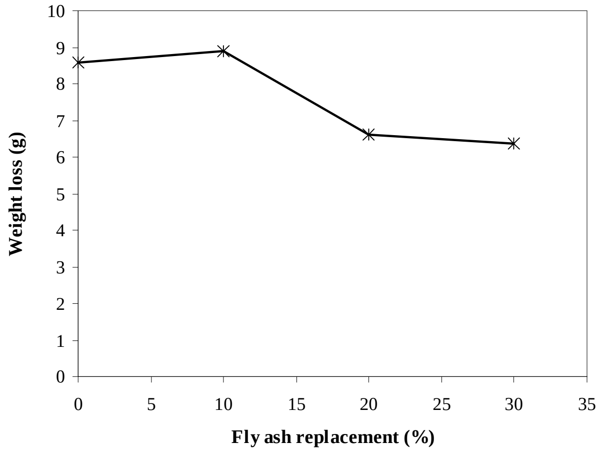

Fig. 11 Fly ash replacement and weight loss on abrasion tests of 9 mm aggregate pervious concrete with designed void ratio of 20%, W/B ratio of 0.19

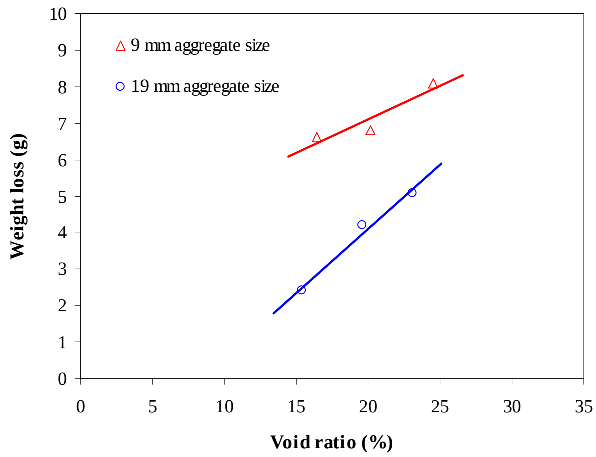

Fig. 12 Void ratio and weight loss on abrasion test of pervious concrete with fly ash replacement of 20% and W/B ratio of 0.19

size distribution, and pore roughness. Many researchers (Neithalath *et al*. 2010, Aamer Rafique Bhutta *et al*. 2012, Tho-in *et al.* 2012, Haselbach *et al.* 2006, Zaetang *et al*. 2013) found that the permeability increased exponentially with the continuous void. The result revealed that the water permeability coefficients of pervious concretes for the mixes 20FA0.19-15I, 20FA0.19-20I, and 20FA0.19-25I were in the ranges of 0.67-1.86, 2.38-3.14, and 2.64-4.70 mm/s with corresponding ranges of void ratios of 13.64-16.20, 19.57-21.96, and 20.83-23.65%, respectively. The relationship between water permeability coefficient and void ratio could also be fitted using exponential curve as shown in Fig. 10 with the equation as follows.

$$C_P = 0.1783e^{0.1339A_T}\ ,\ R^2 = 0.8219 \tag{17}$$

where C_P is water permeability coefficient of pervious concrete (mm/s) and A_T is void ratio (%).

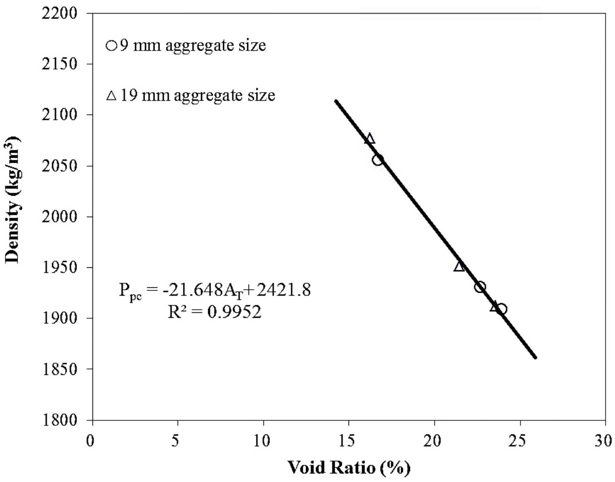

Fig. 13 Void ratio and density of pervious concrete with 20% fly ash replacement and W/B ratio of 0.19

4.5 Abrasion resistance

The abrasion resistance of pervious concrete in term of weight loss was determined at the age of 28 days. Pervious concrete using fly ash dosages of 0, 10, 20, and 30% had the weight loss of 8.6, 8.9, 6.6, and 6.4 g, respectively, as shown in Fig. 11. The weight loss of 10% fly ash concrete was similar to no fly ash concrete. As the amount of fly ash replacement increased, the abrasion resistance increased similar to the results reported by Woo *et al*. (2011) and Yen *et al*. (2007). The decreasing in weight loss with the increase in percentage of fly ash replacement was attributed to the densification of the paste structure from the pozzolanic reaction between fly ash and calcium hydroxide and the filler effect, which increased abrasion resistance (Siddique and Khatib 2010). It was also likely that the self cementing of high calcium fly ash also contribute to this dense structure. It was also found that weight loss increased with the increasing void ratio. The weight loss of pervious concrete using small aggregate was higher than that of large aggregate. This was related to the strength of concrete. Large-sized aggregates produced stronger concrete and with lower surface area required lower content of paste hence their surface areas were completely coated. On the other hand, small-sized aggregate produced lower strength concrete and with higher surface area required higher content of paste thus thinner coating of paste resulted. The relationship between void ratio and weight loss on abrasion test is given in Fig. 12.

4.6 Density

The density of pervious concrete depends on the void ratio. The pervious concrete with 20% fly ash using aggregate of 9 mm with void ratio of 16.67, 22.67, and 23.89% had the density of 2056, 1931, and 1909 kg/m^3, respectively, while the 19 mm aggregate with void ratio of 16.22, 21.44, and 23.56% had the density of 2077, 1951, and 1912 kg/m^3, respectively, as show in Fig. 13. According to the report by Tennis *et al*. (2004), pervious concrete had density of around 1600-2000 kg/m^3. The relationship between void ratio and density of pervious concrete could be fitted in linear as shown in the Eq. 18. It should be noted that this equation has a limitation and is for pervious concretes with the voids in the range of 15-25%.

$$\rho_{pc} = -21.648 A_T + 2421.8 \,,\ R^2 = 0.9952 \tag{18}$$

where ρ_{pc} is the density of pervious concrete (kg/m^3) and A_T is the total void ratio (%).

5. Conclusions

The increase in the high calcium fly ash replacement levels helped increase the workability of cement paste and also reduced the amount of superplasticizer in the mixture. The compressive strength and flexural strength of pervious concrete slightly decreased as the high calcium fly ash replacement level increased. However, up to 30% replacement level, the strengths of concrete were still higher than 85% of those of the control concretes. The slight reduction in strength at the early age is due to the lower reaction of fly ash compared to that of Portland cement. In addition, the abrasion resistance of pervious concrete increased with the increase in fly ash replacement. This was attributed to the densification of the paste structure from the pozzolanic reaction between fly ash and calcium hydroxide and the filler effect which increased abrasion resistance. The effect of aggregate size was significant at the low total void ratio (< 23%). The compressive strengths of 19 mm aggregate concretes were significantly higher than those of the 9 mm aggregate concretes due to the difference in the thickness of paste covering the aggregates. The abrasion resistance of small aggregate pervious concrete was also lower than that of large aggregate concrete which was related to the strengths of concrete.

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References

Aamer Rafique Bhutta, M., Tsuruta, K. and Mirza, J. (2012), "Evaluation of high-performance pervious concrete properties", *Constr. Build. Mater.*, **31**, 67-73.

ACI Committee 522 (2010), *ACI 522R-10 Report on pervious concrete*, American Concrete Institute, Farmington Hills, MI, USA.

ASTM C 39/C 39M-10 (2010), *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*, Annual Book of ASTM Standards, 04.02, USA.

ASTM C 78-10 (2010), *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)*, Annual Book of ASTM Standards, 04.02, USA.

ASTM C 618-08a (2008), *Standard Test Method for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*, Annual Book of ASTM Standards, 04.02, USA.

ASTM C 944/C 944M-12 (2012), *Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method*, Annual Book of ASTM Standards, 04.02, USA.

ASTM C 1754/C 1754-12 (2012), *Standard Test Method for Density and Void Content of Hardened Pervious Concrete*, Annual Book of ASTM Standards, 04.02, USA.
Chindaprasirt, P., Hatanaka, S., Chareerat, T., Mishima, N. and Yuasa, Y. (2008), "Cement paste characteristics and pervious concrete properties", *Constr. Build. Mater.*, **22**(5), 894-901.
Chindaprasirt, P., Hatanaka, T., Mishima, N., Yuasa, Y. and Chareerat, S. (2009), "Effects of binder strength and aggregate size on the compressive strength and void ratio of porous concrete", *Int. J. Minerals Metall. Mater.*, **16**(6), 714-9.
Delatte, N., Miller, D. and Mrkajic, A. (2007), *Portland cement pervious concrete pavement: Field performance investigation on parking lot and roadway pavements*, RMC Research & Education Foundation, Cleveland, Ohio, USA.
Deo, O. and Neithalath, N. (2010), "Compressive behavior of pervious concretes and a quantification of the influence of random pore structure features", *Mater. Sci. Eng.*, **528**(1), 402-412.
Deo, O. and Neithalath, N. (2011), "Compressive response of pervious concrete proportioned for desired porosities", *Constr. Build. Mater.*, **25**(11), 4181-4189.
Golroo, A. and Tighe, S.L. (2011), "Alternative modeling framework for pervious concrete pavement condition analysis", *Cement Concrete Res.*, **25**(10), 4043-4051.
Hatanaka, S., Mishima, N., Yuasa, Y., Maegawa, A., Nakagawa, T. and Kuroda, M. (2006), "Fundamentals and a few recent applications of environmentally friendly pervious concrete", *International Conference on Pozzolan, Concrete and Geopolymer*.
Haselbach, L.M., Valavala, S. and Montes, F. (2006), "Permeability predictions for sand-clogged Portland cement pervious concrete pavement systems", *J. Environ. Manage.*, **81**(1), 42-49.
JIS Committee (1997), *Physical Testing Methods for Cement (JIS R 5201)*, Japanese Industrial Standards, Japan.
Kim, H.K. and Lee, H.K. (2010), "Influence of cement flow and aggregate type on the mechanical and acoustic characteristics of pervious concrete", *Appl. Acoust.*, **71**(7), 607-615.
Leming, M.L., Malcom, H.R. and Tennis, P.D. (2007), *Hydrologic design of pervious concrete*, Portland Cement Association (PCA), Skokie, Illinois, USA.
Lian, C., Zhuge, Y. and Beecham, S. (2011), "The relationship between porosity and strength for pervious concrete", *Constr. Build. Mater.*, **25**(11), 4294-4298.
Limbachiya, M., Meddah, M.S. and Ouchagour, Y. (2012), "Use of recycled concrete aggregate in fly-ash concrete", *Constr. Build. Mater.*, **27**(1), 439-449.
Neithalath, N., Sumanasooriya, M.S. and Deo, O. (2010), "Characterizing pore volume, sizes, and connectivity in pervious concretes for permeability prediction", *Mater. Charact.*, **61**(8), 802-813.
Park, S.B., Jang, Y.I., Lee, J. and Lee, B.J. (2009), "An experimental study on the hazard assessment and mechanical properties of pervious concrete utilizing coal bottom ash coarse aggregate in Korea", *J. Hazard. Mater.*, **166**(1), 348-355.
Park, S.B. and Tia, M. (2004), "An experimental study on the water-purification properties of pervious concrete", *Cement Concrete Res.*, **34**(2), 177-184.
Putman, B.J. and Neptune, A.I. (2011), "Comparison of test specimen preparation techniques for pervious concrete pavements", *Constr. Build. Mater.*, **25**(8), 3480-3485.
Ramanathan, P., Baskar, I., Muthupriya, P. and Venkatasubramani, R. (2013), "Performance of self-compacting concrete containing different mineral admixtures", *KSCE J. Civil Eng.*, **17**(2), 465-472.
Rukzon, S. and Chindaprasirt, P. (2008), "Mathematical model of strength and porosity of ternary blend Portland rice husk ash and fly ash cement mortar", *Comput. Concrete*, **5**(1), 1-6.
Sata, V., Khammathit, P. and Chindaprasirt, P. (2008), "Efficiency factor of high-calcium Class F fly ash in concrete", *Comput. Concrete*, **8**(5), 583-595.
Shu, X., Huang, B., Wu, H., Dong, Q. and Burdette, E.G. (2011), "Performance comparison of laboratory and field produced pervious concrete mixtures", *Constr. Build. Mater.*, **25**(8), 3187-3192.
Siddique, R. (2003), "Effect of fine aggregate replacement with Class F fly ash on the abrasion resistance of concrete", *Cement Concrete Res.*, **33**(11), 1877-1881.
Siddique, R. (2004), "Performance characteristics of high-volume Class F fly ash concrete", *Cement*

Concrete Res., **34**(3), 487-493.
Siddique, R. and Khatib, J.M. (2010), "Abrasion resistance and mechanical properties of high-volume fly ash concrete", *Mater. Struct.*, **43**, 709-718.
Silva, P. and De Brito, J. (2013), "Electrical resistivity and capillarity of self-compacting concrete with incorporation of fly ash and limestone filler", *Adv. Concrete Constr.*, **1**(1), 65-84.
Sumanasooriya, M.S. and Neithalath, N. (2011), "Pore structure features of pervious concretes proportioned for desired porosities and their performance prediction", *Cement Concrete Compos.*, **33**(8), 778-787.
Sunil, B.M., Manjunatha, L.S., Ravi, L. and Yaragal, S.C. (2015), "Potential use of mine tailings and fly ash in concrete", *Adv. Concrete Constr.*, **3**(1), 55-69.
Tamai, M., Mizuguchi, H., Hatanaka, S., Nakazawa, T., Yanagibashi, K. and Kunieda, M. (2004), "Design, construction and recent applications of pervious concrete in japan", *Proceedings of the JCI Symposium on Design, Construction and Recent Applications of Pervious concrete*, JCI., Tokyo, April.
Tangpagasit, J., Cheerarot, R., Jaturapitakkul, C. and Kiattikomol, K. (2005), "Packing effect and pozzolanic reaction of fly ash in mortar", *Cement Concrete Res.*, **35**(6), 1145-1151.
Tennis, P.D., Leming, M.L. and Akers, D.J. (2004), *Pervious Concrete Pavements*, Portland Cement Association (PCA), Skokie, Illinois, USA.
Tho-in, T., Sata, V., Chindaprasirt, P. and Jaturapitakkul, C. (2012), "Pervious high-calcium fly ash geopolymer concrete", *Constr. Build. Mater.*, **30**, 366-371.
Uchida, T., Ooyabu, K., Nakano, N. and Matsumoto, H. (2004), "A method of pervious concrete work for construction of high permeability steep revetment with permeable blocks", *Proceedings of the JCI Symposium on Design, Construction and Recent Applications of Pervious concrete*, Tokyo, April.
Vimonsatit, V., Chindaprasirt, P., Ruangsiriyakul, S. and Sata, V. (2015), "Influence of fly ash fineness on water requirement and shrinkage of blended cement mortars", *KKU Eng. J.*, **42**(4), 311-316.
Woo, S.K., Song, Y.C. and Won, J. (2011), "Enhanced durability performance of face slab concrete in concrete-faced rock-filled dam using fly ash and PVA fiber", *KSCE J. Civil Eng.*, **15**(5), 875-882.
Yang, J. and Jiang, G. (2003), "Experimental study on properties of pervious concrete pavement materials", *Cement Concrete Res.*, **33**(3), 381-386.
Yen, T., Hsu, T.H., Liu, Y.W. and Chen, S.H. (2007), "Influence of class F fly ash on the abrasion-erosion resistance of high-strength concrete", *Constr. Build. Mater.*, **21**(2), 458-463.
Zaetang, Y., Wongsa, A., Sata, V. and Chindaprasirt, P. (2013), "Use of lightweight aggregates in pervious concrete", *Constr. Build. Mater.*, **48**, 585-591.

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