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PROPERTIES OF HIGH PERMEABLE CONCRETE UTILIZING POZZOLANIC MATERIALS

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ABSTRACT

To investigate the possibility of using pozzolanic materials in producing high permeable concrete (HPC), five materials were used to partially replacement to Ordinary cement: Silica fume, fly ash, paper mill ash, palm oil ash and rice husk ash. Several tests were conducted on the cementitious paste and also on the HPC. Results revealed that 5% of pozzolanic material replacement to Ordinary cement would yield the best results. However, the good performance of HPC can be determined through balancing the several characteristics such as compressive strength, void ratio, permeability, skid resistance and infiltration rate.

Keywords: high permeable concrete, pozzolanic materials, skid resistance, infiltration rate.

1. INTRODUCTION

The ACI Committee 522[1] defines the term of permeable concrete as a zero-slump, open graded materials consisting of Portland cement, coarse aggregate, little to no fine aggregate, admixtures, and water [2]. High permeable concrete (HPC) pavement has been used for over 30 years in many countries for roadway applications to improve the skid resistance and to reduce traffic noise. In addition, researchers have reported various environmental benefits of HPC such as controlling storm water runoff, restoring groundwater supplies, and reducing water and soil pollution [3, 4, 5]. Due to the requirement of permeability of the HPC, it is typically designed with the high void content ranging from 15% to 25% [6]. Therefore, single graded size aggregates were used to achieve such void content [7]. The compressive strength of HPC is relatively low and ranging from 2.8MPa to 28MPa [6]. Characteristically, concrete is made of three phases namely: matrix phase (hardened cement paste), coarse aggregate phase and the interfacial transition zone (ITZ) between matrix and coarse aggregate. The cement paste in HPC mixture is very little and also very thin to bond coarse aggregate together. Hence, under low applied loading, HPC is likely to fail at the ITZ resulting in a low compressive strength. Therefore, HPC pavement is incapable of carrying heavy loads in car parks and walkways [8].

The use of pozzolans in combination with Ordinary cement leads to greatly increase in the bond between the cement paste and the coarse aggregate in the crucial interfacial zone and consequently increases the compressive strength of the HPC without compromising the permeability. Silica fume, fly ash, rice husk ash, palm oil ash, and paper mill ash are among the commercially available pozzolanic materials.

Silica fume has a high content of glassy phase of silicon dioxide (SiO_2) and it consists of very small solid spherical particles [9]. It has been a popular mineral admixture to use as partial replacement to cement. Researchers investigated the effect of adding silica fume to the HPC and reported that 5% replacement to cement can increase the compressive strength by enhancing the bond between the cement paste and coarse aggregate and improved the porosity as well [2]. Fly ash is another popular pozzolan used in concrete to replace the cement which can improve concrete properties such as workability, durability, and ultimate strength in hardened concrete. However researchers [2] found that there was no any significant effect on the workability as the porosity of the HPC increased as the percentage of the replacement increased. The authors were also found that the cement replacement to rice husk ash, palm oil ash, and paper mill ash improved the compressive strength of HPC [10].

2. MATERIALS

2.1. Cement and incorporated pozzolanic materials

The physical properties and chemical compositions of OPC and pozzolanic materials used in preparations of high permeable concrete mixtures are shown in Table-1. Normal Portland cement Type 1 conform to the requirements of ASTM C150 was used in all the mixtures. The pozzolanic materials were classified in accordance to the requirements of ASTM C618. The fly ash used in this study is classified class F with total amount of silicon dioxide (SiO_2), aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3) is 94.74 % and loss on ignition is less than 6%.While, paper mill ash and palm oil ash are classified Class C pozzolan and rice husk ash is Class N pozzolan. These pozzolanic materials were used to partially replace OPC in HPC mixtures. To evaluate the pozzolanic activities, strength activity index (SAI) was conducted on mortar cubes of these materials. At age of 28 days, SAI for silica fume, fly ash, paper mill ash, palm oil ash, and rice husk ash were 106%, 76%, 84%, 80%, and 88%, respectively. In accordance to the requirements of

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ASTM C618, the pozzolanic material is active if the SAI is greater than 75%. Therefore, silica fume, fly ash, paper mill ash, palm oil ash, and rice husk ash used in this study are active pozzolanic materials as shown in Table-1.

Table-1. Physical properties and chemical compositions of OPC and pozzolanic materials.

Chemical composition (%)	**Cement** (OPC)	**Silica fume**	**Fly ash**	**Paper mill ash**	**Palm oil ash**	**Rice husk ash**
SiO_2	27.37	89.22	63.42	23.03	47.52	90.68
Al_2O_3	10.05	0.065	25.63	10.97	3.96	0.14
FeO_3	5.94	0.421	5.69	0.72	7.50	0.17
CaO	51.92	0.073	5.01	49.74	8.19	0.77
MgO	1.50	0.061	0.56	4.84	2.86	1.19
Na_2O	0.07	0.029	0.13	0.33	0.10	0.03
K_2O	0.69	0.268	0.64	0.41	11.00	4.51
SO_3	2.92	-	0.59	0.56	1.50	0.40
$SiO_2 + Al_2O_3 + FeO_3$	-	-	94.74	34.72	58.88	90.99
Loss of ignition	2.5	0.85	5.61	3.17	5.45	8.64
Specific gravity	3.15	2.27	2.05	2.24	1.85	1.82
Fineness (cm^2/g)	3091	-	2262	2314	1910	656
Strength activity index (SAI) (%)	-	106	76	84	80	88

2.2. Aggregate

Single size of 10 mm coarse aggregates with specific gravity of 2.55 are used in the preparations of HPC mixtures. No fine aggregates are considered in this study.

3. MIX DESIGN

The design mix of HPC mixtures consist of two parts: 1) design of the cementitious paste mix and 2) design of the coarse aggregate ratio.

4. RESULTS AND ANALYSIS

4.1 Mix design of cementitious paste

Based on the guidelines detailed in the National Ready Mixed Concrete Association [4], three w/cm ratios have been selected which are: 0.27, 0.33, 0.35.The workability has measured through flow table and the acceptable ranges of flow values are from 150mm to 230mm.A total of 78 cementitious paste mixtures were prepared utilizing three different water-cementitious (w/cm) ratios and five types of pozzolanic materials with six levels of cement replacement (0%, 5%, 10%, 15%, 20%, and 25%) for each pozzolan. Table 2 shows the mix proportions of the cementitious paste for various pozzolanic materials. The compressive strength and the push out test were evaluated for all 78 mixtures. Based on the obtained results, only one level of pozzolan replacement at one water-cementitious ratio is selected for second stage of producing HPC mixtures.

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Table-2. Mix proportions for cementitious paste using w/cm: 0.27, 0.31, and 0.35.

Replacement (%)	**Mix proportions** (kg/m^3)					
	Cement (OPC)	**Silica fume** (SF)	**Fly ash** (FA)	**Paper mill** (PM) ash	**Palm oil** (PO) ash	**Rice husk ash** (MIHRA)
0	500	-	-	-	-	-
5	475	18	16	17	15	14
10	450	36	33	36	29	29
15	425	54	49	53	44	43
20	400	72	65	71	59	58
25	375	90	81	89	73	72

4.1.1. Compressive Strength of cementitious paste

The compressive strength test was conducted in accordance with the requirements of ASTM C109. For each mixture, three cubes of size 50 mm x 50 mm x 50 mm were prepared, cast, cured and tested at age of 28 days. The compressive strengths of hardened cementitious paste for different water-cementitious ratios are shown in Figures 1, 2 and 3. The compressive strength increases with increasing in the water-cementitious ratio from 0.27 to 0.35. This is because of that the best workability (flow value 230 mm) has been achieved with w/cm of 0.35, therefore, the microstructure of the hardened cementitious paste is more solid and densified. Nevertheless, at 5% cement replacement, higher compressive strengths were obtained in comparison with the control mix. This is due to the reacting ability of the pozzolanic materials with the free lime or calcium hydroxide $Ca(OH)_2$ generated from the hydration process of cement to form calcium silicates hydrate compound (C-S-H) gel, which is responsible for strength. However the compressive strengths of the hardened cementitious paste have started to decrease at 10 % of cement replacement. This is due to the reduction in the amount of the cement which resulting in lesser amount of $Ca(OH)_2$.

The compressive strength containing silica fume achieved the highest compressive strength compared to other pozzolan materials. Beside its chemical reaction, this is also due to its high fineness which enables filling the micro voids in the hardened cementitious paste. This leads to modify the microstructure of the hardened cementitious paste and consequently improving the compressive strength. On the other hand, the compressive strengths of mixtures containing fly ash decreased gradually. This could be due to the slower reaction of fly ash with $Ca(OH)_2$ at early age of hardened cement paste as reported by other researchers [11].

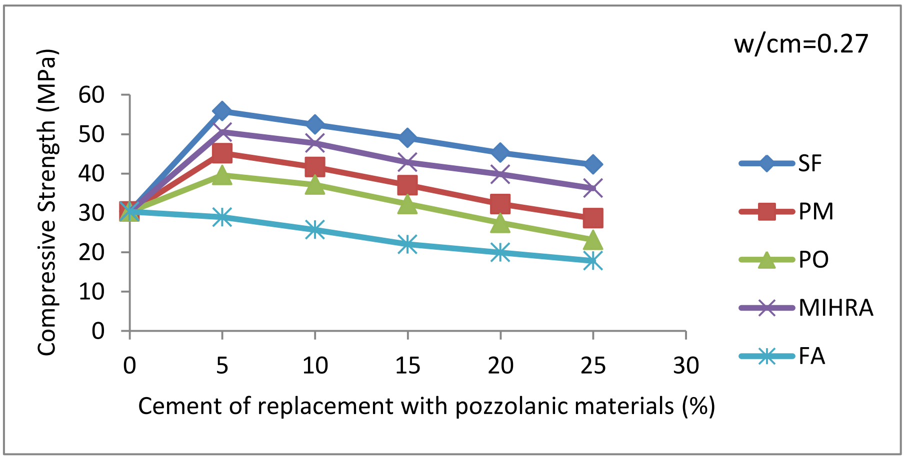

Figure-1. Compressive strength of hardened cementitious paste at w/cm=0.27.

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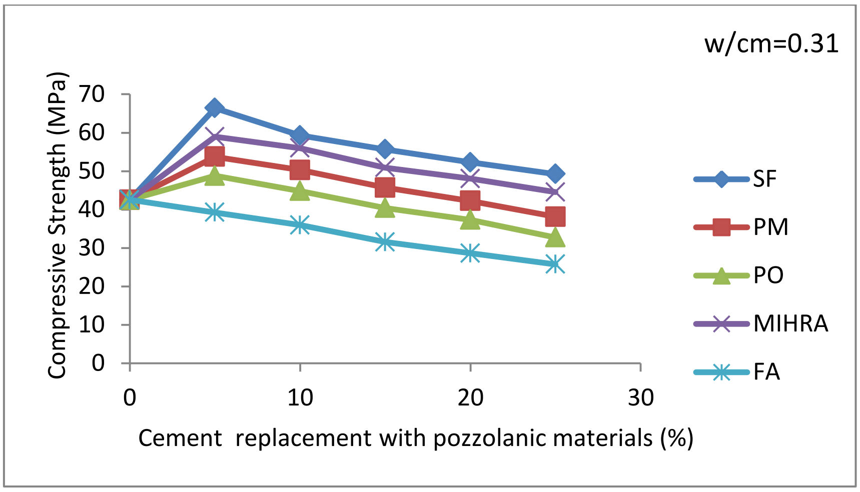

Figure-2. Compressive strength of hardened cementitious paste at w/cm=0.31.

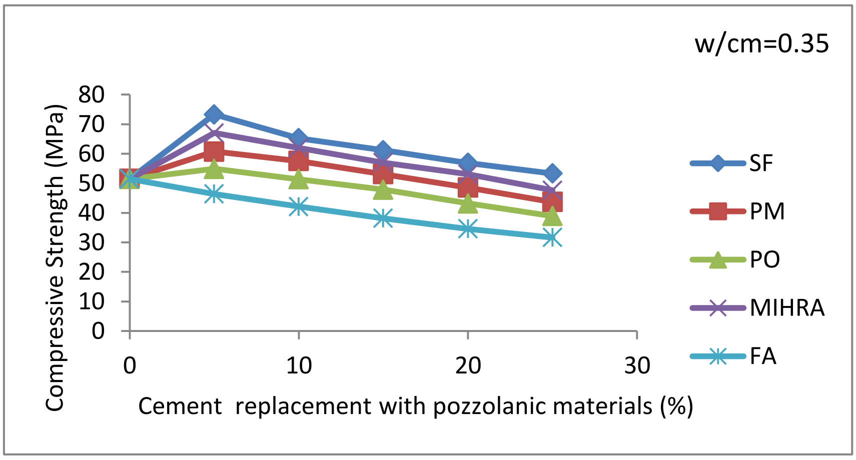

Figure-3. Compressive strength of hardened cementitious paste at w/cm=0.35.

4.1.2 Push out test of cementitious paste

The interfacial bond strengths (τ, N/mm^2) of the mixtures were evaluated through push out test. The schematic diagram of the push out test apparatus is shown in Figure 4. Bond strengths were computed using equation 1:

$$\tau = \frac{p_{max}}{2\pi\, r\, L} \quad (1)$$

Where, p_{max} is the maximum load in N; r is the radius of the cylindrical aggregate (10 mm); L is the length of the cylindrical aggregate (20 mm).

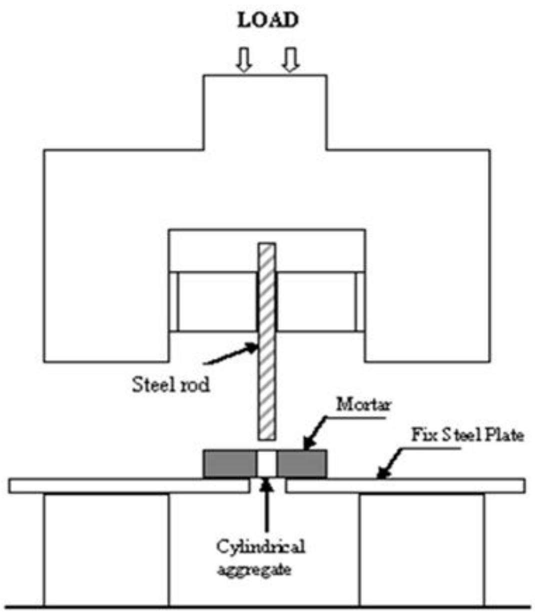

Figure-4. The schematic diagram of the push out test.

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Figures 5, 6 and 7 show bond strengths of hardened cementitious paste at water-cementitious ratios of 0.27, 0.31 and 0.35 respectively. The results showed that interfacial bond strengths at 5% replacement of pozzolanic materials were significantly higher than those of control mixtures for all water-cementitious ratios except fly ash among the other pozzolans, silica fume achieved the highest value. However as the replacement of pozzolanic materials increased, the interfacial bond strength begins to decrease. It is worthy to note that bond strength results are in good agreement with compressive strength results and showing same patterns. The cement replacement materials beyond 5% increases the water demand which is leading to increase in the thickness of the porous interfacial transition zone (ITZ) and consequently decreasing the bond strength. While, the ideal replacement amount of 5% is leading to densify the ITZ and sequentially increasing the bond strength.

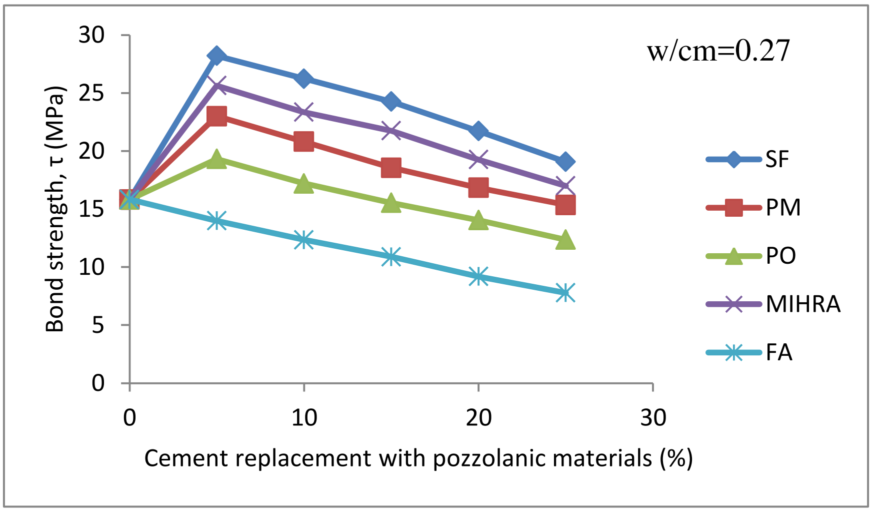

Figure-5. Bond strength of hardened cementitious paste at w/cm=0.27.

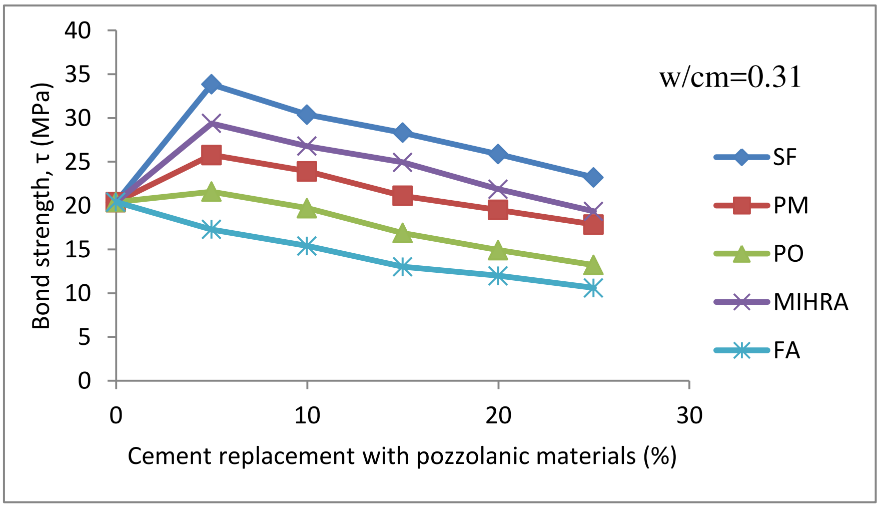

Figure-6. Bond strength of hardened cementitious paste at w/cm=0.31.

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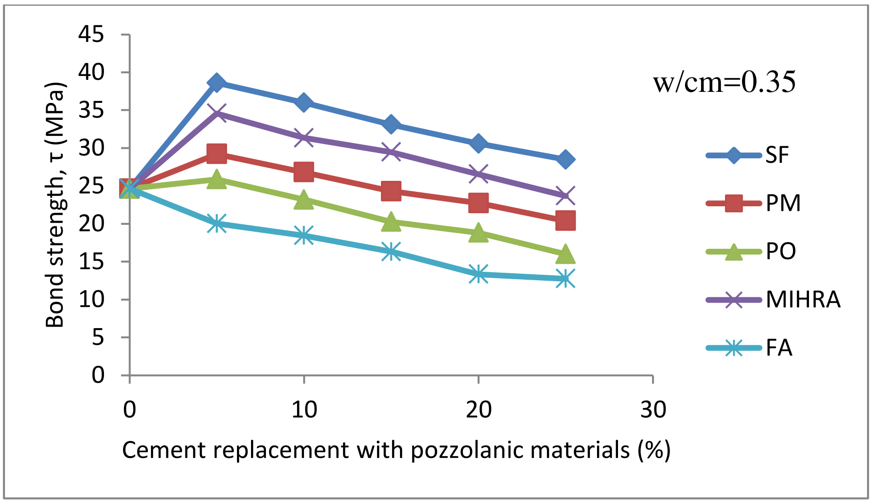

Figure-7. Bond strength of hardened cementitious paste at w/cm=0.35.

4.2. Design mix of HPC

Based on the results of compressive strength and push out tests of the hardened cementitious pastes, mixtures with 5% replacement of pozzolanic materials and water-cementitious ratio of 0.35 were selected for producing HPC. Three paste/aggregate ratios: 0.297, 0.382 and 0.466 were selected. Mix proportions of HPC are shown in Table-3. However, it is worthy to note that fly ash mixtures are not considered in producing the HPC due to the poor performance of its hardened paste.

Table-3. Mix proportions for HPC.

Mixture name	w/cm	Paste/Aggregate ratio	Pozzolan materials		Cement kg/m^3	Water kg/m^3	Coarse Aggregate kg/m^3
			%	kg/m^3			
SF1	0.35	0.297	5%	18	475	173	2970
SF2		0.382					2310
SF3		0.466					1890
PM1	0.35	0.297	5%	17	475	172	2970
PM2		0.382					2310
PM3		0.466					1890
PO1	0.35	0.297	5%	15	475	172	2970
PO2		0.382					2310
PO3		0.466					1890
RHA1	0.35	0.297	5%	14	475	171	2970
RHA2		0.382					2310
RHA3		0.466					1890

4.2.1. Compressive strength of HPC

The compressive strength test of the HPC was conducted in accordance with the requirements of ASTM C39.Three HPC cylinders of 150 mm in diameter and 300 mm in height were prepared, cast, cured and tested at age of 28 days.

As shown in Figure-8, the paste/ aggregate ratio of 0.466 has yielded the highest compressive strength in comparison to the other ratios. While, the silica fume mixture has achieved the highest compressive strength in comparison to other pozzolanic materials. Due to the good correlation between the compressive strengths of HPC and its hardened cementitious paste, the results provide evidence that the compressive strength of HPC is a function of its hardened paste strength. However, the results show that increasing the paste/aggregate ratio leads to increase in the compressive strength of HPC. This is due to availability of cementitious paste in coating of

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coarse aggregate and sequentially improving the compressive strength.

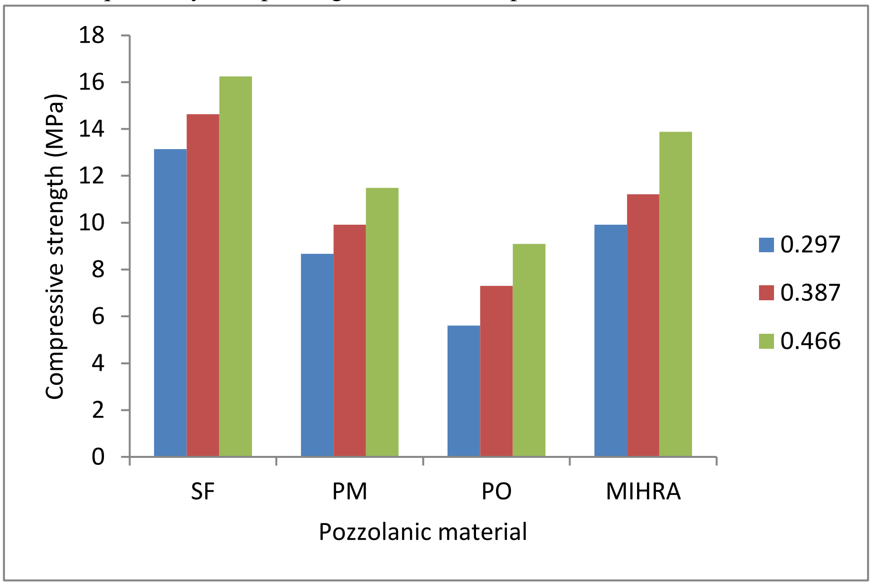

Figure-8. Compressive strength of HPC with different paste/aggregate ratios.

4.2.2 Void ratio of HPC

Three cylinders of 150mm dia x 300mm height were prepared, cast, cured and tested at age of 28 days. The void ratio of HPC has been computed using equation 2:

$$V = \left[1 - \left(\frac{W_2 - W_1}{\rho_w Vol}\right)\right] \times 100\% \qquad (2)$$

Where, V is the void ratio in percentage, W_1 is the mass of saturated sample in kg, W_2 is the mass of oven dry sample in kg, Vol is the volume of sample in cm^3 and ρ_w is the density of water in kg/cm^3.

Figure-9 shows the void ratios of the HPC using different range of paste/aggregate ratios. The results indicate that as the paste/aggregate ratio increased, the void ratio in the hardened concrete will decrease and this is due to the excess amount of paste leading to decrease in the void ratio. Therefore, the primary reason to contribute in achieving higher void ratio is the amount of the coarse aggregates that have been used in HPC mixtures. When a right amount of aggregates are used in the mixture, the cementitious paste has the sufficient amount to cover the aggregate. However, it is worthy to note that the higher compressive strength of HPC has the lower void ratio and vice versa.

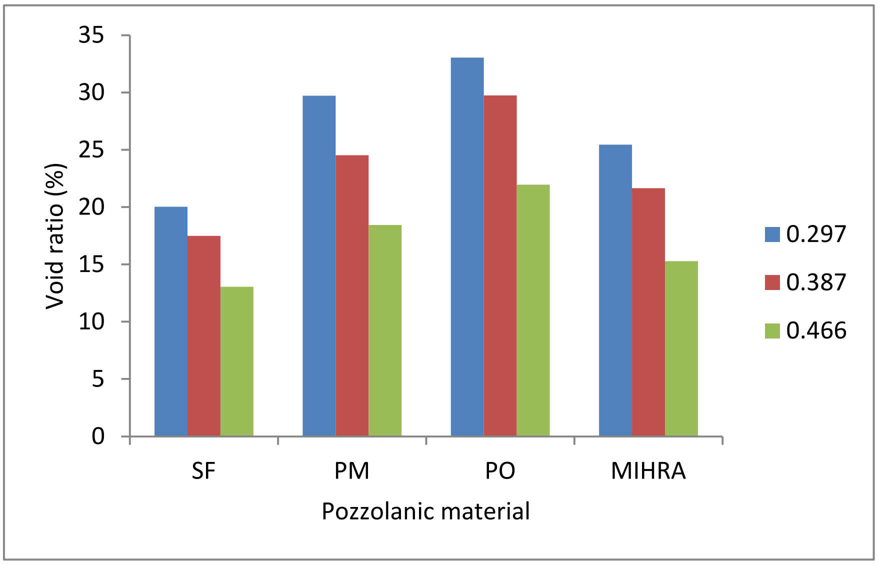

Figure-9. Void ratio of HPC with different paste/aggregate ratios.

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4.2.3 Permeability

The permeability of HPC could be evaluated using Yang's method and the device used in conducting the tests depicted in Figure-10 [12].

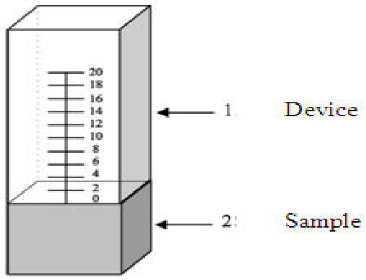

Figure-10. Permeability device [12].

Three cubes of size 100mm x 100mm x 100mm were prepared, cast, cured and tested at age of 28 days. The water penetration coefficient is computed using equation (3).

$$V=H/t \quad (3)$$

Where, V = the water penetration coefficient (mm/s), H = the height of the water line from 160 to 140 mm (20 mm), t = the time (s) when the water line fell from 160 to 140 mm.

Figure-11 shows the permeability of HPC with different paste/aggregate ratios. The results have the same pattern of the void ratios results. The increasing in void ratios of HPC leads to increase in the permeability and vice versa. This indicates that the voids are highly interconnected.

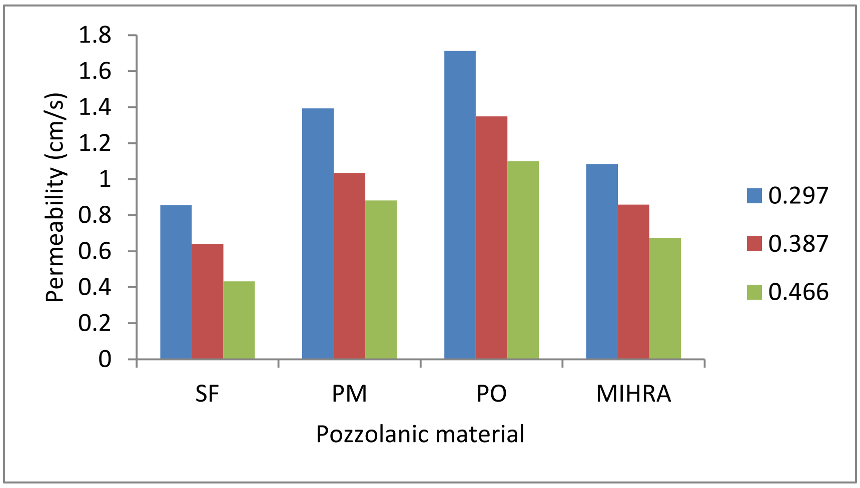

Figure-11. Permeability of HPC with different rate of paste/aggregate ratio.

4.3 Hardened properties of HPC

Based on the results reported in section 4.2, HPC with best paste/aggregate ratio were selected for further investigation. The selection for achieving best high permeable characteristics was based on the balance between compressive strength, void ratio and permeability. Therefore HPC mixtures with paste/aggregate ratio is 0.387 has been selected. For these HPC mixtures; Flexural strength, splitting strength, skid resistance and infiltration rate were evaluated in accordance with the requirements of ASTM C293–02, ASTM C496-90, ASTM E303-93 and ASTM C1701 respectively.

As shown in Table-4, silica fume has the highest flexural strength and palm oil ash has the lowest flexural strength. However the typical construction application using high permeable concrete does not require measurement of flexural strength for design.

Similarly, HPC containing silica fume achieved highest tensile splitting strength of 1.93 MPa while sample containing palm oil ash has exhibited the lowest value of 1.72 MPa. It has been reported that for pavement construction, the tensile splitting strength is 65 % of the flexural strength [13]. However, all HPC mixtures have achieved the aforementioned ratio.

High skid resistance of pavement is important in reducing the number of accident on the roadway where it helps to drivers in controlling their vehicles, especially during rainy season. The results also show that HPC mixture containing paper mill ash exhibits the highest skid resistance value. This indicates that HPC containing paper mill ash has a rough surface texture in comparison to other mixtures. However the HPC containing palm oil ash has yielded the lowest skid resistance value and this indicates that palm oil ash has the tendency to reduce the friction between the pavement and tyres of the vehicles.

The high permeable concrete that contains silica fume has the lowest infiltration rate, as the small particles of the silica fume closed up some of the HPC pores and this leads in decreasing the infiltration rate, as the water required longer period to penetrate the HPC. On the other hand, the HPC containing palm oil ash has the highest infiltration rate due to its lower pozzolanic activity.

Table-4. Hardened properties of high permeable concrete containing different pozzolanic materials.

Pozzolan material	Test method			
	Flexural strength (MPa)	**Tensile splitting strength** (MPa)	**Skid resistance**	**Infiltration rate** (mm/h)
Silica fume	3.25	2.13	97	12446
Rice husk ash	3.15	2.03	105	23208
Paper mill ash	3.00	1.97	110	33338
Palm oil ash	2.88	1.92	88	38467

5. CONCLUSIONS

The following conclusion can be drawn from the present study

a) High permeable concrete (HPC) with good characteristics can be produced by partially replacing cement with pozzolanic materials. This leads to multiple advantages such as improving HPC properties, reducing production cost and also decreasing the CO_2 emission due to the reduction in amount of cement.

b) In production of HPC, the optimum amount of pozzolanic materials to partially replacing cement is 5%.

c) The good performance of HPC cannot be measured through one characteristic; instead correlation of many aspects has to be considered.

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