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Permeability and abrasion resistance of concretes containing high volume fine fly ash and palm oil fuel ash

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Abstract. In this paper, compressive strength, water permeability and abrasion resistance of concretes containing high volume fine fly ash (FFA) and fine ground palm oil fuel ash (GPA) were studied. Portland cement type I was replaced with FFA and GPA at dosages up to 70% by weight of binder. Ground river sand (GRS) was also used to replace Portland cement in order to indicate the level of filler effect. Results indicated that FFA was slightly more reactive than GPA. The replacement of 40-70% of FFA produced concretes with compressive strength, permeability and abrasion resistance comparable to those of normal concretes. The incorporation of GPA slightly reduced the performances of concretes as compared to those of FFA concretes. The reduction of Portland cement was partly compensated by the increase in pozzolanic activity of the fine fly ash and palm oil fuel ash and thus enabled the large replacement levels.

Keywords: concrete; water permeability; abrasion resistance; fly ash; palm oil fuel ash.

1. Introduction

Strength, water permeability and abrasion resistance of concrete are recognized as important properties of concrete. They indicate the quality of concrete, its durability and service life. The most critical parameters controlling durability of concrete are governed by the transportation of liquid or fluid in concrete. Therefore, durability of concrete can be monitored as a function of water permeability. The deterioration of concrete during its service life arises primarily from its high permeability (Naik *et al.* 1996, Basheer *et al.* 2001, Khan 2003). It has been shown that incorporation of pozzolans with suitable dosage level can improve the permeability of concrete (Vedalakshmi 2003).

Abrasion resistance also indicates the durability, especially for concretes which require strong surface such as hydraulic structure, traffic pavement and parking lots. The abrasion is caused by the rolling or grinding of any element against the concrete surface. This phenomenon induces damage to concrete and can jeopardize the whole structure integrity. Abrasion resistance of concrete is

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influenced by various factors, such as mixture proportion, aggregate property and supplementary cementitious materials. Researches indicated that the abrasion resistance depended primarily on the strength of concrete (Siddique 2003, Li *et al.* 2006).

Fly ash, a well-known pozzolan, has been extensively used in concrete work. Its use increases the durability of concrete through pore refinement and reduction in calcium hydroxide of cement paste matrix (Chindaprasirt *et al.* 2007, Malhotra 2002). Properties of concrete are affected by both quality and quantity of fly ash. It is generally agreed that fine fly ash is more reactive and thus improves the properties of mortar and concrete than as-received coarse fly ash (Chindaprasirt *et al.* 2004, Chindaprasirt *et al.* 2010a, Erdogdu and Turker 1998, Sata *et al.* 2011).

Palm oil fuel ash has been recently introduced as a new pozzolanic material. It has to be properly ground to obtain satisfactory reactivity (Tangchirapat *et al.* 2009). Properties of concrete such as compressive strength, chloride penetration resistance and alkali-silica reaction can be improved when incorporated with palm oil fuel ash (Awal and Hussin 1997, Chindaprasirt *et al.* 2010b, Rukzon and Chindaprasirt 2009a, 2009b, Tay 1990). However, palm oil fuel ash is not yet being used commercially in concrete industry and almost all of it is discarded in landfills.

Because the global price of Portland cement is increasing and the production process consumes large amount of energy which leads to greenhouse effect (Malhotra 2002), many attempts are being made to utilize higher percentage of supplementary cementitious materials or pozzolans to replace conventional Portland cement. It is generally accepted that the use of supplementary material at low replacement level produced good concrete with reduced porosity, increased durability and acceptable strength (Chindaprasirt *et al.* 2005, Malhotra 2002, Ramezanianpour and Malhotra 1995). The reactivity of the pozzolanic materials increases with the increase in their finenesses (Chindaprasirt *et al.* 2004, Erdogdu and Turker 1998, Sathonsaowaphak *et al.* 2009). This should allow a higher replacement level of these pozzolanic materials in the concrete industry.

Inert materials such as ground sand are incorporated to Portland cement to produce silica cement (Neville 1995). This is to adjust some of the properties of the cement, lower the cost and reduce the use of Portland cement. It is also successful to use inert material to replace part of cement to study the filler effect on the strength development of concrete (Tangpagasit *et al.* 2005).

This work aims to investigate the water permeability and abrasion of concrete containing high volume FFA and GPA. The results will be useful and lay some ground work for utilization of high fine pozzolan replacement of Portland cement.

2. Experimental program

2.1 Materials and concrete mixtures

Ordinary Portland cement (OPC) was used for all concrete mixtures. Lignite fly ash from Mae Moh power plant in the north of Thailand was used. FFA was obtained from air classifier. GPA was obtained from ball mill grinding of palm oil fuel ash; a waste material from the palm oil extraction factory. In addition, ground river sand (GRS) with similar fineness to FFA and GPA was used to indicate the filling effect (Isaia *et al.* 2003, Nehdi 1998, Tangpagasit *et al.* 2005). Physical properties and chemical compositions of the OPC and replacement materials (R) are reported in Tables 1 and 2. FFA, GPA and GRS finenesses were similar with percentages retained on No. 325 sieve (45 μm opening) of 1.0-2.5% by weight. Natural river sand with a fineness modulus of 2.44 and specific

Table 1 Physical properties of cement and replacement materials

Material	Specific gravity	Retained on a sieve No. 325 (%)	Median particle size, d_{50} (μm)
Portland cement type I (OPC)	3.14	-	14.7
Classified fly ash (FFA)	2.52	2.43	5.5
Ground palm oil fuel (GPA)	2.43	1.0	8.1
Ground river sand (GRS)	2.65	2.02	6.0

Table 2 Chemical composition of cement and replacement materials

Compositions	OPC	FFA	GPA	GRS
SiO_2	20.9	41.1	57.8	92.8
Al_2O_3	4.8	22.5	4.6	3.2
Fe_2O_3	3.4	11.6	3.3	0.3
CaO	65.4	15.3	6.6	0.6
MgO	1.2	2.8	4.2	0.5
Na_2O	0.2	1.7	0.5	0.4
K_2O	0.3	2.9	8.3	0.3
SO_3	2.7	1.5	0.3	0.5
LOI	0.9	0.2	10.1	0.6

Table 3 Concretes mix proportions

Mixes	OPC (kg)	FAA (kg)	GPA (kg)	GRS (kg)	Fine (kg)	Coarse (kg)	Water (kg)	*W/C+R*	Slump (mm)
Control	300	-	-	-	915	1080	213	0.71	75
FFA20	240	60	-	-	920	1084	200	0.67	85
FFA40	180	120	-	-	933	1098	185	0.62	80
FFA55	135	165	-	-	928	1093	189	0.63	80
FFA70	90	210	-	-	902	1067	202	0.67	90
GPA20	240	-	60	-	907	1072	220	0.73	65
GPA40	180	-	120	-	900	1064	222	0.74	70
GPA55	135	-	155	-	894	1059	225	0.75	90
GPA70	90	-	210	-	889	1011	228	0.76	70
GRS20	135	-	-	60	905	1070	212	0.71	75
GRS40	180	-	-	120	896	1060	216	0.72	60
GRS55	135	-	-	165	882	1046	222	0.74	65
GRS70	90	-	-	210	886	1050	228	0.76	60

gravity of 2.65 and crushed limestone with nominal size of 20 mm and specific gravity of 2.67 were used as fine and coarse aggregates in concrete mixtures, respectively.

Table 3 shows the concrete mixture proportions. The controlled concrete with water to cement ratio of 0.71 and slump of 75 mm was selected so that the effects of incorporating FFA and GPA can be gauged with confidence. Slumps were maintained at 75±15 mm and water to cement and replacement material ratios ($W/(C+R)$) were controlled within 0.71±0.05 except for FFA as it improved workability and slightly lowered the $W/C+R$ ratios of concretes. These were achieved without the aid of plasticizer. The concretes with Portland cement replaced with 20, 40, 55 and 70% of FFA, GPA and GRS were prepared and tested.

2.2 Testing procedure

2.2.1 Compressive strength

Concrete cylinders of 100 mm in diameter and 200 mm in height were cast, demolded at 24 hours and cured in water. The compressive strength of concretes was tested at 28 and 90 days. The report results are the average of three samples.

2.2.2 Water permeability

For permeability testing, concrete cylinder was sliced to discs of 40 mm thickness and the ends were discarded. The disc was installed in permeability cell as suggested by Khatri and Sirivivatnanon (1997). Distilled water was used as fluid to flow through concrete disc under constant pressure. The pressure of 0.5 MPa (5 bars) recommended by concrete society (1987) was employed. Report results are averages of four samples. Flow rate was monitored and the steady flow rate was used to calculate permeability using equation based on Darcy's law and equation of continuity.

$$K = \frac{\rho L g Q}{PA}$$

K - coefficient of permeability, ρ - density of water, L - thickness of concrete sample, g - gravity acceleration, Q - flow rate, P – pressure of water, A - cross sectional area of sample

2.2.3 Abrasion resistance

Abrasion resistance of concrete was evaluated according to ASTM C1138 (Underwater method). Samples of 300 mm in diameter and 100 mm in height were cast and cured in moist condition for 28 days. The samples were installed in the abrasion machine containing 70 chrome steel balls placed on the concrete upper surface. Fresh water was filled to the specified level and stirring of steel balls with blade was performed for 12 hours. This procedure was repeated 6 times. The abrasion of concrete was calculated from the weight loss of the samples.

3. Results and discussion

3.1 Properties and particle shape of materials

The chemical compositions of the materials as shown in Table 2 revealed that the classified fly ash could be assigned as class F as prescribed by ASTM C 618. For GPA, the contents of SiO_2 + Al_2O_3 + Fe_2O_3 were 65.7%, while the GRS consisted of 92.8% SiO_2.

Fig. 1 shows the particle size distribution curves of OPC, FAA, GPA and GRS and their median particle sizes (d_{50}) are 14.7, 5.5, 8.1 and 6.0 μm, respectively. The particle size distribution curves of FFA, GPA and GRS are similar. Their particle sizes are slightly finer than the OPC. As shown in Fig. 2, the FFA is spherical in shape and its surface is relatively smooth. On the other hand, OPC, GPA and

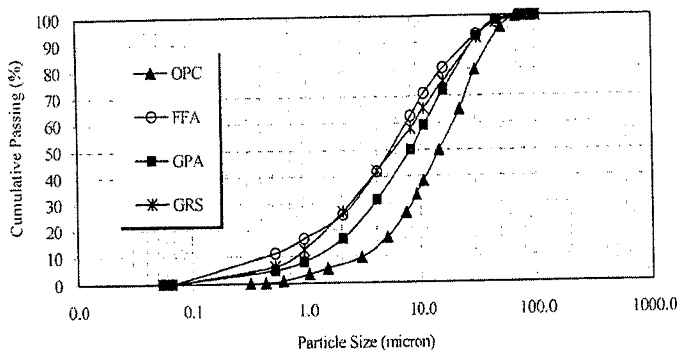
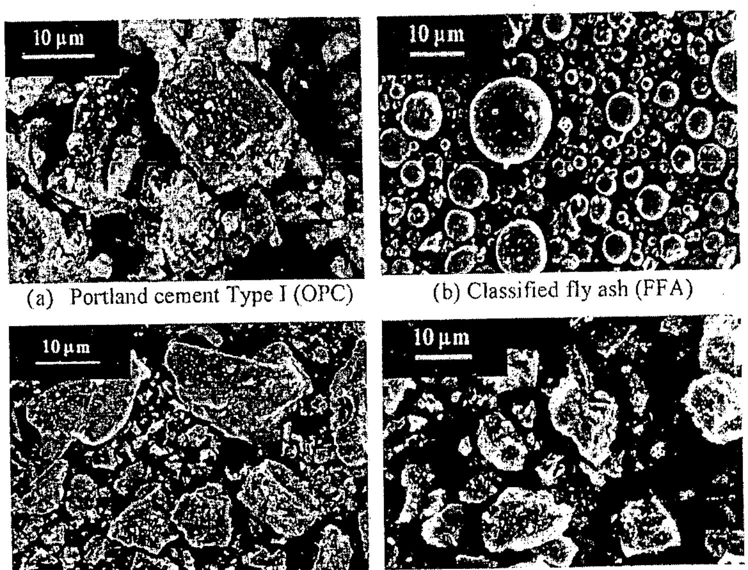


Fig. 1 Particle size distribution of cement and replacement materials



(a) Portland cement Type I (OPC) (b) Classified fly ash (FFA)

(c) Ground palm oil fuel ash (GPA) (d) Ground river sand (GRS)

Fig. 2 Scanning electron microscopy (SEM) of cement and replacement materials

GRS contain particles with angular and irregular shape as a result of crushing and milling processes.

3.2 Water requirement in concrete mixes

The amounts of mixing water are shown in Table 3. The use of FFA reduced the $W/(C+R)$ ratios of fly ash concrete compared to that of the control concrete. For example, the $W/(C+R)$ ratios of the control concrete, FFA20 (mix with 20% FFA), FFA40, FFA55 and FFA70 concretes were 0.71, 0.67, 0.62, 0.63 and 0.67, respectively. The reduction in water requirement was the result of the ball bearing effect of the spherical FFA particles. For the GPA and GRS concretes, the opposite trend of results was obtained. The $W/C+R$ ratios of both GPA and GRS concretes were slightly higher than that of control concrete and increased with the increase in the replacement level. The angular and irregular particles of GPA and GRS increased the water requirement to maintain the same workability compared to that of the control concrete.

3.3 Compressive strength

Table 4 shows compressive strengths and normalized compressive strengths of concretes containing FFA, GPA and GRS in comparison with that of control concrete. The relationship between the compressive strengths of concretes and the replacement levels are shown in Fig. 3.

The compressive strengths of FFA20 were 32.5 and 35.4 MPa or 123% and 126% of the control concrete at 28 and 90 days, respectively. The strengths of FFA concretes with the 55% replacement

Table 4 Compressive strength, water permeability and abrasion of concretes

Mixes	Comp. Strength (MPa) -Normalized (%)		$k \times 10^{-12}$ (m/s) - k/k_{CON}		Abrasion depth (mm)
	28 days	90 days	28 days	90 days	
Control	26.1 – 100	28.2 - 100	2.89 - 1.00	2.05 - 1.00	2.55
FFA20	32.5 – 123	35.4 - 126	1.32 - 0.46	0.44 - 0.21	2.38
FFA40	31.9 – 122	34.0 - 121	0.51 - 0.18	0.32 - 0.16	2.41
FFA55	29.1 – 111	31.8 - 113	0.72 - 0.25	0.42 - 0.21	2.67
FFA70	25.5 – 98	27.1 - 96	1.85 - 0.64	1.54 - 0.90	3.45
GPA20	23.9 – 92	29.4 - 104	0.59 - 0.20	0.25 - 0.12	2.75
GPA40	20.7 – 79	23.7 - 84	0.41 - 0.14	0.26 - 0.13	3.23
GPA55	18.1 – 69	22.3 - 79	3.30 - 1.14	2.38 - 1.16	3.67
GPA70	14.9 – 57	17.5 - 62	37.30 - 12.9	23.10 - 11.27	4.34
GRS20	22.2 – 85	25.9 - 92	8.16 - 2.83	5.91 - 2.88	3.54
GRS40	16.0 – 61	17.2 - 61	22.60 - 7.83	10.20 - 4.98	4.62
GRS55	9.1 – 35	9.3 - 33	630 - 218	447 - 218	5.73
GRS70	5.1 - 20	5.2 - 18	2250 - 780	2450 - 1195	6.52

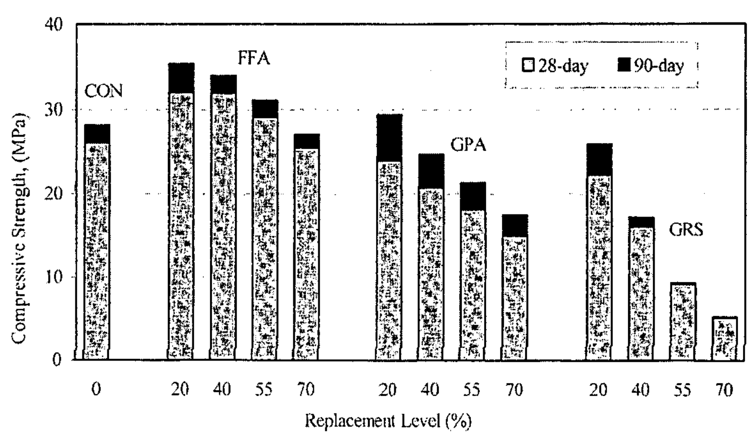


Fig. 3 Relationship between the compressive strength of concrete and the cement replacement level

were still higher than that of the original concrete. When the cement replacement by FFA was 70%, the compressive strength of FFA concrete was slightly lower than that of control concrete. The results indicated better performance of high volume FFA concrete compared to that of high volume normal fly ash concrete (Jiang and Malhotra 2000, Serdar *et al.* 2007). The good performance of FFA was due to the ball bearing effect, the dispersion effect and the enhancement of the pozzolanic reaction of small particle size of FFA (Erdogdu and Turker 1998, Chindaprasirt *et al.* 2004).

The compressive strength of GPA concretes decreased with the increase in the replacement levels. The 28-day compressive strengths of GPA20, GPA40, GPA55 and GPA70 concretes were 23.9, 20.7, 18.1 and 14.9 MPa or 92, 79, 69 and 57% of the control concretes, respectively. These results were due to the less Portland cement content and the slightly larger amount of water in the concrete mixture. At 90 days, the compressive strength of GPA20 concrete was, however, improved compared to the compressive strength at 28 days. This confirmed that a substantial amount of pozzolanic reaction was obtained with the use of GPA in concrete. High volume 40-70% GPA could also be used to produce concrete with acceptable 28-day compressive strength of 15-20 MPa. It should be pointed out here that higher strength concretes could be obtained with lower water to cement ratio with the aid of superplasticizer (Jiang and Malhotra 2000, Serdar *et al.* 2007).

For GRS concretes, the 28-day and 90-day normalized compressive strengths of GRS20 concrete were 85 and 92% of control concrete. At low level of replacement, the filler effect is significant and this resulted in only slight reduction in strengths. The compressive strengths of GRS concretes, however, decreased substantially as the level of replacement was increased. The GRS produced filler effect from its small particle size without pozzolanic effect (Tangpagasit *et al.* 2005) and was thus not effective in terms of maintaining the acceptable strengths with high replacement level. At high replacement level, the pozzolanic effect played the dominant role in maintaining the acceptable level of strengths.

3.4 Permeability of concrete

The permeability of concretes and the ratios of permeability are given in Table 4. The ratio of permeability is defined as the permeability of concrete containing replacement materials divided by that of the control concrete. The values of water permeability of the control concrete at 28 and 90 days were 2.89×10^{-12} m/s and 2.05×10^{-12} m/s, respectively.

Fig. 4 shows the relationship between permeability and replacement levels of materials. The values of permeability of concretes decreased with the age of samples. This was the result of the increase in hydration and pozzolanic reaction with time (Ramezanianpour and Malhotra 1995). The permeability values of FFA concretes were lower than those of the control concretes for all replacement levels. The lowest permeability was obtained with the replacement of 40%. This result can be attributed to the pozzolanic reaction from FFA, and the less amount of mixing water influenced the reduction in volume and size of pores in cement paste (Poon *et al.* 2001). Moreover, the filler effect of the smaller particles of FFA also assisted to produce a denser cement matrix (Govindarajan and Gopalakrishnan 2009).

GPA concretes also showed the same characteristic of permeability as FFA concretes when the replacement levels were up to 40% by weight of binder. The 90-day water permeability of GPA20 and GPA40 concretes were 0.25×10^{-12} m/s and 0.26×10^{-12} m/s or 0.12 and 0.13 of those of the control concretes, respectively. For the GPA40 concrete, its water permeability was also lower than that of control concrete in spite of the slightly higher water content (0.74 for GPA40 concrete and

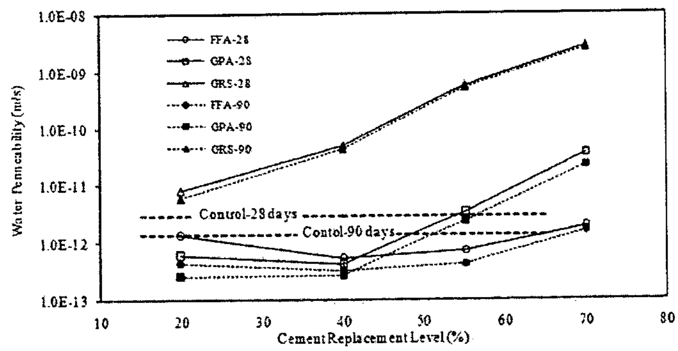


Fig. 4 Relationship between water permeability of concrete and cement replacement level

0.71 for control concrete). Although the pozzolanic reaction of GPA was lower than that of FFA as indicated by the strength development characteristics, the permeability values were similar at this range of replacement. This suggested that filler and pozzolanic effects were comparatively high up to replacement level of 40% of GPA and contributed to the low permeability of the concretes.

At higher replacement level of 55 and 70% of GPA, the permeability increased significantly. The 90-day ratios of permeability of GPA55 and GPA70 concretes were 1.16 and 11.27, respectively. This resulted from the slightly higher water content of the mixes, the low pozzolanic reaction and the low filler effect which were not sufficient at the high level of replacement.

The ratios of water permeability of GRS20, GRS40, GRS55 and GRS70 concretes at 28 days were 2.83, 7.83, 218 and 780, respectively. Only the GRS20 concrete gave the acceptable level of permeability. For high level of replacement, the filling effect alone was not able to maintain the low level of permeability of the concretes. At high replacement level, the pozzolanic effect also played the dominant role similar to that of strength.

The relationships between water permeability and compressive strength of concrete at 90 days are presented in Fig. 5. In general, the permeability decreased when concrete compressive strengths

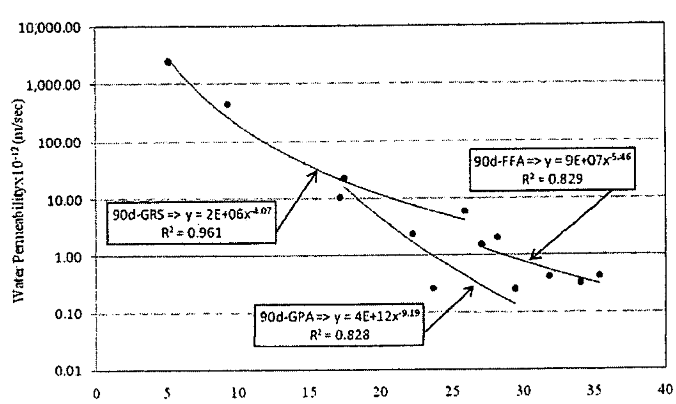


Fig. 5 Relationship between water permeability and compressive strength of concrete at 90 days

were higher. The high volume FFA concrete showed both high strength and low permeability. The high volume GPA concrete showed slightly lower strength and higher permeability than those of FFA concrete. At high level of replacement, the filler effect became less significant and the performances of concrete relied mainly on the pozzolanic reaction.

3.5 Abrasion resistance of concrete

The abrasion of concretes is shown in Table 4 and the relationship between abrasion and replacement levels of materials is shown in Fig. 6. The abrasion of concrete in this investigation ranged from 2.38-5.52 mm. The abrasion of FFA concrete was slightly lower than that of the OPC concrete with the replacement level up to 40% and the lowest value was 2.38 mm for FFA20 concrete compared to 2.55 mm of the OPC concrete. A similar trend of result of decreasing abrasion resistance with OPC replacement level of above 50% with class C fly ashes was reported by Naik *et al.* (2002).

For GPA concretes, the abrasion increased as the content of GPA increased. The depth of wear of GPA20 was slightly higher at 2.75 mm than those of FFA and OPC concretes. The abrasion resistance of GRS concrete significantly increased with the increase in the replacement level. This indicated that although the incorporation of GRS produced filling effect, it had an adverse effect on the abrasion resistance of concrete. The filling of GRS did not have a cementing property which helped to resist the abrasion.

Fig. 7 presents the relationships between the depth of abrasion, permeability and compressive strength of concrete at 28 days. The compressive strength of concrete with the incorporation of supplementary material is related to the abrasion resistance. The abrasion resistance increased with increasing compressive strength and could be expressed in terms of exponential equation with R^2 of 0.945. The previous researches also reported that the abrasion resistance was strongly governed by its compressive strength (Siddique 2003, Li *et al.* 2006).

The relationship between water permeability and depth of abrasion of concrete is also shown in Fig. 7. As expected, the high permeability concrete produced low abrasion resistance. The relationship

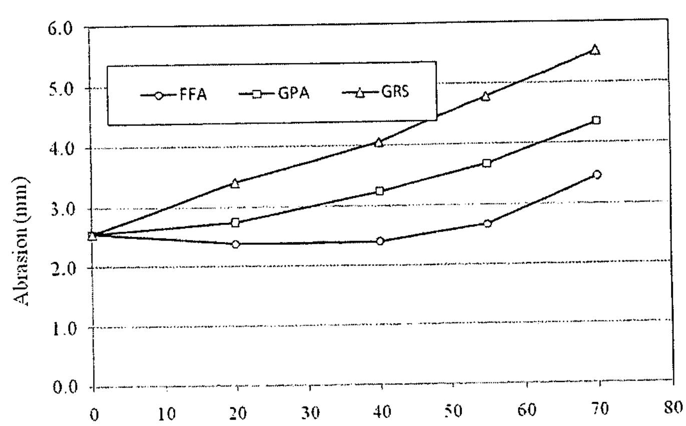


Fig. 6 Relationship between abrasion and replacement level at 28 days

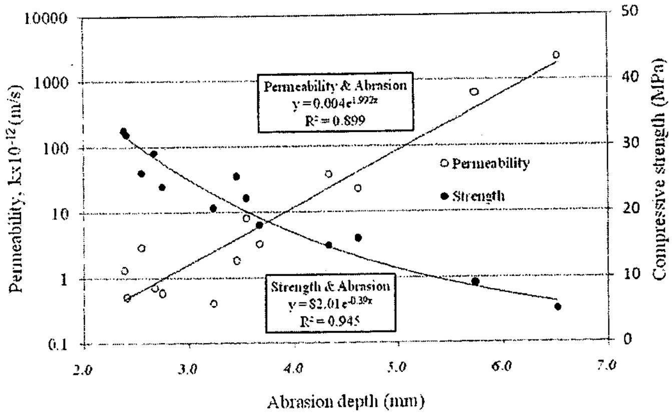


Fig.7 Relationship between abrasion, permeability and compressive strength at 28 days

could also be expressed in terms of exponential relation with R^2 of 0.899. This result agreed with that of Liu *et al.* (2006) who studied the abrasion erosion of concrete using the water-borne sand and found that the concrete with high coefficient permeability exhibited the low abrasion erosion resistance.

4. Conclusions

From this study, it can be concluded that high volume fine fly ash (FFA) and fine ground palm oil fuel ash (GPA) can produce concrete with acceptable strength, water permeability and abrasion resistance. FFA is an effective pozzolan for use in high volume as it produces good pozzolanic reaction through the small particle size and requires less water through the ball bearing effect of the spherical particles. GPA is slightly less effective pozzolan compared to FFA and its use in high volume resulted in slightly lower strength and higher water permeability.

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