Emerging Technology in Construction Materials

Proceedings of the International Conference on Construction and Building Technology 2008

Edited by

Assoc. Prof. Dr. Hashem Al-Mattarneh
Head, Structures and Materials
Department of Civil Engineering
Universiti Tenaga Nasional

Assoc. Prof. Dr. Kamal N. Mustapha
Head, Civil Engineering Department
Faculty of Engineering
Universiti Tenaga Nasional

and

Assoc. Prof. Dr. Mohd Fadhil Nuruddin
Head, Department of Civil Engineering
Universiti Teknologi PETRONAS

IACT
International Association
for Concrete Technology
Kuala Lumpur, Malaysia

University Publication Centre (UPENA)
Universiti Teknologi MARA · SHAH ALAM · 2008

PREFACE

Upon the recommendations of the participants attending the annual meeting of IACT during the 7th International Conference on Concrete Technology in Developing Countries that was held in October 2004 in Kuala Lumpur, Malaysia and endorsement of the recommendations by the Board of the Internatioal Association for Concrete Technology (IACT) in 2006, this ICCBT2008 was brought to Malaysia and becomes part of a series of successful conferences.

The conference was organized by three main parties, Universiti Tenaga Nasional, Universiti Teknologi PETRONAS and Internatioal Association for Concrete Technology. ICCBT2008 was co-organized and supported by several national and international organizations, Universiti Kebangsaan Malaysia (UKM), Universiti sains Malaysia (USM), Universiti Teknikal Melaka (UTeM), Universiti Malaya (UM), Universiti Tun Hussain Malaysia (UTHM), Universiti Teknologi Malaysia (UTM), Tenaga Nasional Berhad (TNB) and the Construction Industry Development Board Malaysia (CIDB), and sponsored by several national organizations including the Concrete Society of Malaysia (PERKOM), American Concrete Institute (ACI), Malaysian Institute of Transportation (MITRANS), Malaysian Hydraulic Society (MHS), Structural Earthquake Engineering Research (SEER).

The support of the international organizations and the sponsoring national organizations was a major contribution to the success of the conference. Six one-day pre-conference short courses in recent advancement in concrete materials and structures, and an exhibition formed an integral part of the event. The work of the conference was an immense undertaking and all of those involved are gratefully acknowledged, in particular, the members of IACT; members of the International Advisory Committee and National Advisors; members of the Technical and Proceeding Committee on the selection and reviewing of papers; the authors and the Chairman of Technical Sessions for their invaluable contributions to the conference.

The keynote papers were delivered by prominent scholars and professors from well-established organizations and institutions all over the world. The keynote paper presenters were Prof. Dr. Mohsen A. Issa, University of Illinois at Chicago, USA; Prof. Dr. Semih Yucemen, Middle East Technical University (METU), Turkey; Prof. Dr. M Hadi, University of Wollongong, Australia; Prof. Dr. K. U. Muthu, M. S. Ramaiah Institute of Technology, India; Prof. Dr. Abdallah Malkawi, Jordan University of Science and Technology, Jordan; Prof. Dr. Musa Resheidat, Chairman of International Association for Concrete Technology (IACT); Professor Dr. ir. H.J.H. Brouwers, University of Twente, Netherlands; Professor Dr. Ali Al-Gadhib, King Fahd University of Petroleum & Minerals, Saudi Arabia; Professor Dr. Pierre Y. Julien, Colorado State University, USA; Professor Dr. Takara Kaoru, Kyoto University, Japan; Datuk. Ir. Hamzah Hasan, Construction Industry Development Board (CIDB), Malaysia; Tan Sri Dato' Ir. Jamilus bin Md. Hussin, Construction Industry Development Board (CIDB), Malaysia; Prof. Dr. R. Narayanan University of Manchester, Manchester, U.K.; Dato' Abd Razak Abdul Majid, TNB, Malaysia; Datuk Paduka Ir. Keizrul Abdullah, President, Institute Engineering Malaysia.

The response from scientists, researchers, academicians, professionals and practicing engineers was overwhelming. The committee had 340 abstracts from 36 countries. The Scientific Committee screened them and accepted 280 in the first review process. Then, the final accepted papers, after the peer review stage, came to 250 papers for presentation and inclusion in the conference proceedings.

The proceedings have been prepared directly from the camera-ready manuscripts submitted by the authors. Editing has been made where it was considered necessary. The proceedings have been issued in six volumes. They have also been produced electronically in a CD form.

Kuala Lumpur, Malaysia
16 June 2008

Associate Professor Dr. Hashem Al-Mattarneh
General Chair of ICCBT2008

New Develop

H. J. H. Brouwer

ABSTRACT

The present pape concrete based o concerning the su constituent, from the hydration and which are found i results among oth building products concrete is treated moist concrete. B (cement, fillers), properties are obt all technical requi paper concludes introduction of bo in the construction

Keywords: *ceme sustainable buildi*

**Correspondence Auth Tel: +31 (0)53 489 40*

ICCBT 2008 - A - (0

ICCBT2008

Water Penetrability of Low Calcium Fly Ash Geopolymer Concrete

M. Olivia*, Curtin University of Technology, ***AUSTRALIA***
P. Sarker, Curtin University of Technology, ***AUSTRALIA***
H. Nikraz, Curtin University of Technology, ***AUSTRALIA***

ABSTRACT

This paper presents a study on water penetrability properties, namely water absorption, volume of permeable voids, permeability and sorptivity of low calcium fly ash geopolymer concrete. In this research, geopolymer concrete is made from fly ash with a combination of sodium hydroxide and sodium silicate as alkaline activator. Seven mixes were cast in 100x200mm cylinders and cured for 24 hours at 60^{0}C in the steam curing chamber. After 28 days, the cylinders were cut into slices for permeability, sorptivity and volume of permeable voids tests. In addition, a microstructure characteristic of geopolymer concrete was studied using Scanning Electron Microscopy (SEM). Results indicate that geopolymer concrete has low water absorption, volume of permeable voids and sorptivity. It is found that the geopolymer concrete could be classified as a concrete with an average quality according to water permeability value. Moreover, a low water/binder ratio and a well-graded aggregate are some important factors to achieve low water penetrability of geopolymer concrete.

Keywords: *absorption, durability, geopolymer, porosity, sorptivity, water permeability*

**Correspondence Author: Monita Olivia, Curtin University of Technology, Australia, Tel: +619266 2652, E-mail: monita.olivia@postgrad.curtin.edu.au*

1. INTRODUCTION

Water penetrability, namely absorption, permeability and sorptivity are some important measurements to control concrete durability. Penetrability of liquid into the concrete consists of permeability through a porous medium, diffusion and absorption. Regarding to this, pores in concrete have an important role to allow the liquid/fluid move through the concrete. However, the tendency of concrete to absorb and transmit water by capillary action not only depends on the porosity but also on its pore diameter, distribution, continuity and tortuosity.

Geopolymer concrete is a new type of concrete that can be made from fly ash/metakaolin/slag and activated with alkaline solutions. Many studies confirmed that fly ash geopolymer concrete has good engineering properties (Hardjito, 2005; Fernandez-Jimenez, *et al*. 2006; Sofi, *et al*. 2007). Other studies also show that low calcium fly ash geopolymer concrete has good durability on acid and sulphate condition (Wallah, 2005), alkali-aggregate reaction (Garcia-Lodeiro, *et al*. 2007), corrosion (Yodmunee & Yodsujai, 2006) and fire resistance (Kong, *et al*, 2007). Despite the superior resistance of the low calcium fly ash geopolymer concrete in various severe environments, according to Kong, *et al*. (2007) and Sindhunata (2006), the fly ash geopolymer paste contains higher proportion of pores in the mesopores size. This condition may lead water to penetrate easily and will affect the durability of the material.

Limited studies made on geopolymer concrete show that metakaolin geopolymer concrete has permeability 10^{-11} m/s (Davidovits, 1994a), while Shi (1996) found that permeability of slag geopolymer concrete is more than 10^{-12} m/s. Since the water penetrability of fly ash geopolymer concrete is rarely reported, hence the aim of this investigation is to determine water penetrability of low calcium fly ash geopolymer, namely water permeability, sorptivity and water absorption.

2. GEOPOLYMER CONCRETE

Geopolymer is a mineral polymer from the geochemistry process (Davidovits, 1994b). This alumina silicate polymer is synthesised from silica and alumina in the source material. Silica and alumina are obtained from natural material and industry by-products such as fly ash, metakaolin and slag. Although different source materials are used to manufacture geopolymers, basically, the activation of the source materials using an alkaline solution results in compact well cemented composites.

The geopolymerization process consists of chemical reaction of Si-Al mineral in alkaline condition that involves the dissolution of Si-O-Al-O bond. The process is described as $Mn\,[-(Si - O_2)_z - Al - O\,]_n, wH_2O$, with Mn = alkaline element, - = bond, z = 1, 2, 3, and n = degree of polymerization. The alkaline chemicals used in geopolymerization are $Ca(OH)_2$, $NaOH$, Na_2SiO_3 (sodium silicate), a combination of NaOH and sodium silicate, a combination of KOH and NaOH, KOH, potassium silicate and its combination, and sodium carbonate. A combination of alkaline solution determines the final product and geopolymer strength. Research on the effects of alkaline solution on the final product of geopolymer (Fernandez-Jimenez, *et al*. 2005) showed that a combination of NaOH and Na_2SiO_3 (sodium silicate) produced a solid material almost without pores and has a strong bond between aggregate and geopolymer matrix.

Some researchers reported a mesoporous character of geopolymer paste/concrete (Chang, *et al*. 1999; Kong, *et al*. 2007; Shindunata, *et al*. 2006). This has resulted from a fusion of fly ash highly in Si and Al elements with alkaline solution. Fernandez-Jimenez, *et al*. (2005), revealed that type of activator plays an important role to convert fly ash into mesoporous product. According to Sindhunata *et al*. (2006), the fly ash geopolymer gel is porous because evaporation of the aqueous pore solution leaving the empty voids, insufficient geopolymer gel to fill the gaps in between an unreacted fly ash, and porosity of partially reacted fly ash particles. It is found that the total pore volume of concrete increases as the curing temperature is elevated.

4. EXPERIMENTAL PROGRAM

4.1 Materials and Mixtures

Geopolymer concrete in this study was made from low calcium fly ash with a combination of sodium hydroxide (NaOH) and sodium silicate solution (Na_2SiO_3). Table 1 shows the chemical composition of fly ash from Collie power station, Western Australia.

Table 1. Chemical analysis fly ash

Elements	Fly ash
SiO_2	50.3
Al_2O_3	26.3
Fe_2O_3	13.6
CaO	2.27
K_2O	0.55
MgO	1.44
Na_2O	0.36
P_2O_5	1.58
SO_3	0.32
LOI	0.54

Table 2 displays the mixture proportion of fly ash geopolymer concrete in this research. The basic geopolymer mixture proportion (mix GP1) was selected from some mixtures proposed by Hardjito (2005). The mixture is primarily used to produce geopolymer concrete with properties and performance that is equivalent to OPC concrete with strength 35 MPa. Different mixes of low calcium fly ash geopolymer concrete were made by varying the water/binder ratio (0.20-0.25), aggregate/binder ratio (3.5, 3.9, 4.7) and aggregate grading (7:10mm, 7:10:20mm). Two mixes of OPC concrete were made by varying the water/cement ratio to achieve the same level of strength with geopolymer concrete.

Sodium hydroxide in a form of pellets was dissolved in the water. In this research, the concentration of sodium hydroxide used was 14M. Sodium silicate solution with SiO_2 to Na_2SiO_3 ratio approximately 2 was supplied by PQ Australia. Superplasticizer (naphthalene based) was included in the mixes to improve workability. The granite coarse aggregate used was 20mm maximum size. The aggregates were conditioned to meet SSD requirement (3-5% moisture content).

Table 2. Mixture proportion

Mixture no	w/c	w/b	a/b	Quantity (kg/m^3)									
				Water	Cement	Coarse Aggregate			Sand	Fly ash	NaOH (14M)	S.S	S.P
						7mm	10mm	20mm					
C1	0.53	-	-	205	386	621	562	-	637	-	-	-	-
C2	0.50	-	-	188	377	635	574	-	642	-	-	-	-
GP1	-	0.23	3.9	25.8	-	647	554	-	647	408	41	103	6.1
GP2	-	0.22	3.9	20.7	-	647	554	-	647	408	41	103	6.1
GP3		0.20	3.9	16.5		647	554		647	408	41	103	6.1
GP4	-	0.25	3.9	36.2	-	647	554	-	647	408	41	103	6.1
GP5	-	0.22	3.5	25.8	-	630	540	-	630	444	44	111	6.1
GP6		0.24	4.7	25.8	-	672	576	-	672	356	36	89	6.1
GP7	-	0.23	3.9	25.8	-	645	370	277	554	408	41	103	6.1

Note: A = OPC/control mixture, B = Geopolymer mixture, S.S = Sodium Silicate; S.P = Superplasticizer

4.2 Specimens preparation and curing

OPC concrete specimens were prepared according to AS 1012.2-1983. Low calcium fly ash geopolymer concrete were made using a mixing procedure developed by Hardjito (2005). A chemical solution consists of NaOH (14M), Sodium Silicate, extra water and Superplasticizer was prepared approximately 2 hours before mixing process. In this process, firstly, the fly ash and aggregates were mixed for three minutes. Then a chemical solution was poured slowly to the dry mix. The pan mixer continued to mix all ingredients for another four minutes to achieve uniform mix.

All OPC and geopolymer concrete specimens were cast in concrete cylinders of 100mm diameter by 200mm height. Fifteen concrete cylinders from each of the nine concrete mixtures were cast. Those samples were cured using a steam curing process at temperature of 60^0C for 24 hours. Then the specimens were left for air curing in a control environment with a temperature of 23-25^0C until testing. Six cylinders from each mixture were used to determine compressive strength at 7 and 28 days (three specimens tested as each date). Three specimens for each mixture were prepared for water absorption and AVPV test, while other three were used for sorptivity test at 28 days age of concrete. For water permeability test, only two slices of individual specimens were used. Small samples with a thickness 5mm and area of $1cm^2$ were taken for Scanning Electron Microscopy (SEM) analysis. These samples were coated with carbon and undergone a vacuuming process for overnight prior to SEM.

4.3 Test Procedure

Compressive strength tests were performed at 7 and 28 days using an Avery testing machine with a loading rate 16 MPa/minute.

Water absorption and volume of permeable voids determination were carried out according to ASTM C 642. For each concrete mix, three specimens were cut into slices with maximum thickness of 50mm for water absorption and AVPV test. These specimens were dried in the oven at 105^0C until constant mass. Water absorption is measured by drying the specimen to constant mass, immersing it in water and measuring the increase in mass as a percentage of dry mass. Volume of permeable voids is determined by boiling the concrete for at least 5 hours, weighing them in water, then measuring the percentage of boiled specimens with dried mass and mass in the water.

Sorptivity test was carried out according to Hall (1989). In this test, three specimens were dried in the oven at 105^0C to constant mass. After cooling, the bottom surface of the specimen was cut and this cut surface was made to contact with water. The test was carried out by measuring the weight gain of the specimen at the set time intervals of 5 min, 10 min, 30 min, 1 h, 2 h, 3 h and 4 h. Then uptake of water per unit area of concrete surface I (g/mm) followed a linear relationship with the square root of time for the suction periods (t), hence

$$I = C + St^{0.5} \qquad (4.3.1)$$

where S, the sorptivity is the slope of the I vs $t^{0.5}$ plot and can be obtained by linear regression.

Water permeability test were carried out for mixes GP1, GP2, GP4 and GP5 based on GHD Water Permeability method (previously Taywood Engineering Ltd), that modified according to DIN 1048. These specimens were dried in the oven at 105^0C until constant mass. The specimens were coated with epoxy coating in the circular side to prevent water penetration from that side during the test. A pressure of 850 kPa was given to the samples at pressure head of 92.5 m. After the specimen saturated, then the flow rate reading was taken using burette by measuring the changing of volume of water with time. Permeability is defined using Darcy's Law,

$$k = \frac{QL}{AH} \qquad (4.3.2)$$

where k = permeability coefficients (m/s), Q = flow rate (m^3/s), A = area (m^2), L = depth of specimen (m), H = head of water (m).

5. RESULTS AND DISCUSSIONS

5.1 Properties of fresh and hardened concrete

The slump and compressive strength of OPC and geopolymer concrete are shown in Table 3. The high slump of geopolymer mixes were achieved by addition of superplasticizer. Although the slump values are higher than 200mm for the geopolymer concrete, the compressive strength values are different for each mixture. It shows that geopolymer concrete has high workability for compressive strength than 30 MPa. It was found that an increase of amount of water will improve the workability, but decrease the strength of concrete (Hardjito, *et al*. 2004). When the water content is increased drastically, it will tend to produce bigger crystals of geopolymer and decrease the specific surface area of concrete. This will eventually lead to a decrease in strength (van Jaarsveld, *et al*. 2002).

Table 3. Properties of fresh and compressive strength of hardened concrete

Mixture no	Slump (mm)	Compressive strength	
		7 days	28 days
C1	200	-	34.09
C2	80	39.68	47.50
GP1	260	30.92	34.86
GP2	230	38.32	41.36
GP3	270	67.09	67.53
GP4	270	-	25.28
GP5	260	45.96	48.06
GP6	240	24.19	25.44
GP7	260	32.45	36.13

5.2 Water Absorption and Apparent Volume of Permeable Voids

The results of water absorption and AVPV of geopolymer concrete for mixes with different water/binder ratio is presented in Figure 1. The water absorption and AVPV increases with an increase in water content of the mix. The results indicated that the water absorption and AVPV were much affected by the extra water added into the mixture since it increases capillary porosity of concrete. As shown, water absorption and AVPV for mix GP4 with water/binder ratio 0.25 was siginificantly higher than those for other geopolymer mixes. Geopolymer concrete uses a very small amount of water in the mixture. The additional extra water is useful to achieve a particular strength. However, a relatively higher water/binder ratio produces a weaker and pervious matrix, leading to higher capillary porosity that is turn responsible for the increase in water absorption and AVPV of geopolymer mixes.

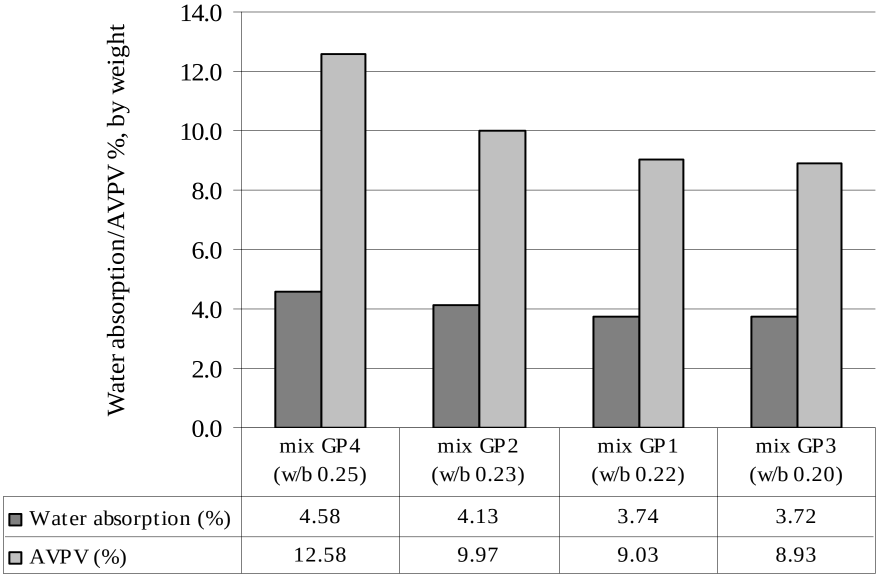
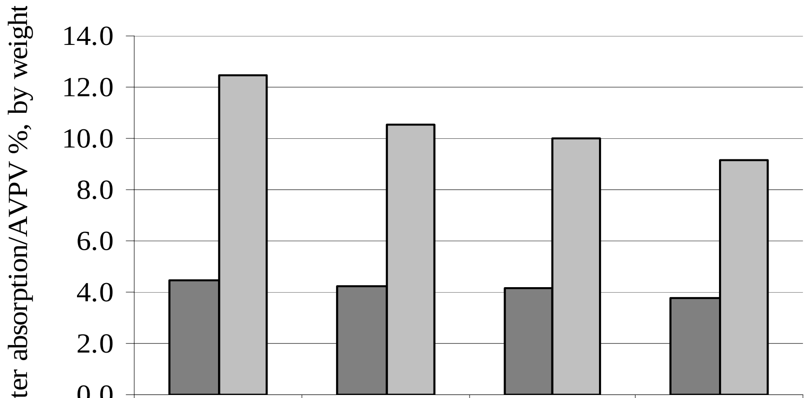


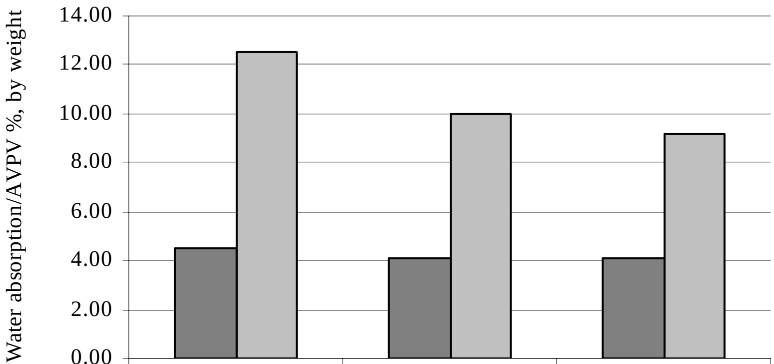
Figure 1. Water absorption and AVPV of geopolymer concrete for mixes with different water/binder ratio



	mix C1	mix GP5 (a/b 3.5)	mix GP1 (a/b 3.9)	mix GP6 (a/b 4.7)
Water absorption (%)	4.50	4.24	4.13	3.74
AVPV (%)	12.49	10.57	9.97	9.17

Figure 2. Water absorption and AVPV of OPC concrete and geopolymer concrete with different variation of aggregate binder ratio

Figure 2 shows water absorption and AVPV for different variation of aggregate binder ratio. Furthermore, mix GP5 resulted in higher compressive strength with high water absorption and AVPV than mix GP1. This mix represents more binder content than aggregate results on more porous concrete. Inclusion of sodium silicate addition in high amount is vulnerable to create more channels in the concrete during the steam curing process. This phenomenon confirmed the observations made by Sindhunata (2006) and Chang (1999).

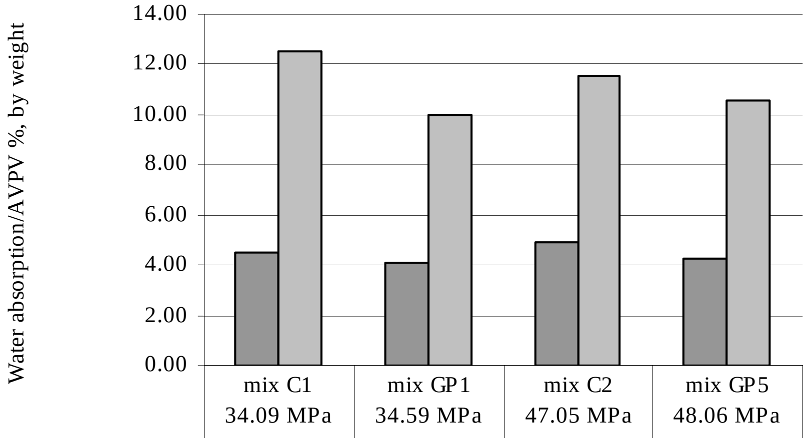


	mix C1	mix GP1 (7:10 mm)	mix GP7 (7:10:20 mm)
Water absorption (%)	4.50	4.13	4.07
AVPV (%)	12.49	9.97	9.16

Figure 3. Water absorption and AVPV of OPC concrete and geopolymer concrete with different variation of aggregate grading

It can be seen from Figure 3 that for all mixes with the same water binder ratio, except for mix C1, a well-graded aggregate result on lower absorption and AVPV. In this case, aggregates composition using 7, 10, 20mm shows a lower capillary porosity compared to mix GP1 with only two different types of aggregates, which is 7 and 10mm. A better distribution of aggregate size reduces the size and continuity of concrete pores.

OPC concrete mixes (C1 and C2) that steam cured with the same strength with geopolymer concrete exhibits higher water absorption and AVPV (Figure 4). It indicates that for OPC concrete cured with steam curing resulted on high capillary porosity concrete. In this stage, there is no continuous hydration to fill and reduce the continuity of the pores. This condition results on coarser microstructure and higher porosity on the concrete. A similar increase in water absorption for steam cured OPC was reported by Ho, *et al*. (2003) and Campbell & Detwiler (1993).



	mix C1 34.09 MPa	mix GP1 34.59 MPa	mix C2 47.05 MPa	mix GP5 48.06 MPa
Water absorption (%)	4.50	4.13	4.94	4.24
AVPV (%)	12.49	9.97	11.53	10.57

Figure 4. Water absorption and AVPV of control mixes and geopolymer concrete with the same strength

For both OPC and geopolymer mixes, a decrease in water/binder or water/cement ratios exhibits a marginal reduction of water absorption and AVPV. From the results, it can be seen that durability is more related to water/binder ratio than compressive strength. As the water content reduces, the paste content increases reducing the volume of capillary pores and thus showed a decreasing trend of water absorption and AVPV.

5.3 Sorptivity

Table 4 shows sorptivity values for control and geopolymer concrete at various water/binder ratio, aggregate binder ratio and aggregate grading. As shown, the results indicated that the sorptivity was significantly lower for all the geopolymer mixes than for the control mix with a water/cement ratio 0.50 (around 40 MPa strength level). For all geopolymer mixes, the sorptivity reduces with a decrease of water content and better grading distribution. These sorptivity values are in the range of Hall (1989) observation on concrete with water cement ratio 0.40-0.60 with sorptivity values in the range 0.094-0.170.

Table 4. Sorptivity of control and geopolymer concrete with regression coefficients

Mixture no	Sorptivity (mm/min$^{0.5}$)	R^2 value
C2	0. 2080	0.9971
GP1	0.1262	0.9897
GP2	0.1503	0.9924
GP4	0.2038	0.9963
GP5	0.1478	0.9912
GP7	0.1507	0.9930

Figure 5 shows comparison of sorptivity value of geopolymer with different water/binder ratio. It is revealed that the water/binder ratio has significantly influenced the sorptivity as per water absorption and AVPV. This suggests that the increase of amount of water resulted in high porosity concrete, hence increases capillary suction.

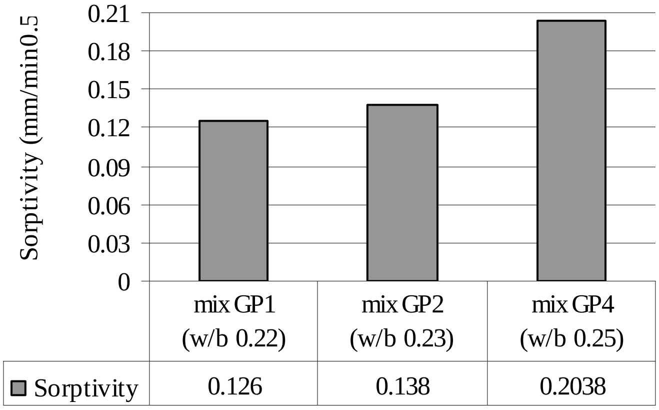


Figure 4. Sorptivity of geopolymer concrete with different water/binder ratio

Figure 5 shows comparison of sorptivity of geopolymer concrete and the corresponding control mix. A typical geopolymer concrete mix (GP2) exhibits lower sorptivity than the corresponding control mix (A2), which again illustrates the effect of binder content and thus the capillary pores on the sorptivity. Lower slope of geopolymer concrete showed reduced moisture intake as compared to the corresponding control mix. Although geopolymer concrete is known to have more pores in mesopore size, in general the results show that it has a lower capillary porosity than OPC concrete cured with steam. There is a need to investigate such a phenomenon to correlate the lower sorption characteristics with the pore structure of geopolymer concrete.

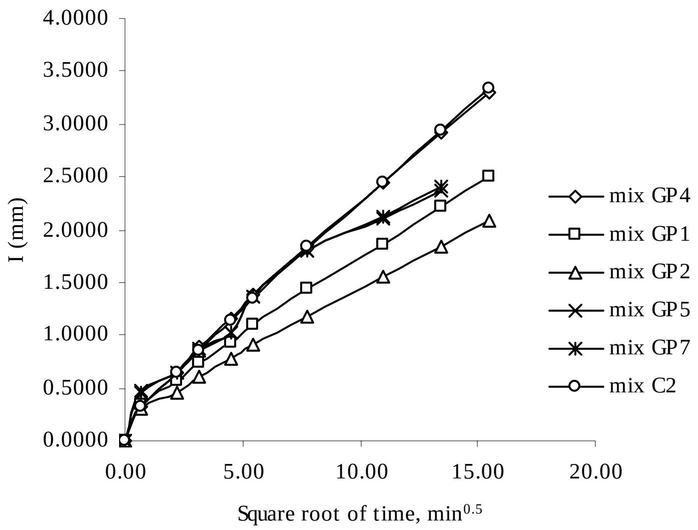


Figure 6. Comparison of capillary absorption rate of geopolymer concrete with control mix

5.4 Water Permeability

Table 5 indicates that the water permeability coefficient of geopolymer also has a tendency to increase with an increase of water/binder ratio. The permeability of high water/binder ratio concrete is greater because of the presence of larger capillary pores. However, those values are still in the range of water permeability coefficient for concrete with an average quality (10^{-11}-10^{-12} m/s) according to Concrete Society Technical Report 54 (Rendell, *et al*. 2002).

It is also obvious that the percentage of void content might not affect the water permeability coefficient of geopolymer concrete significantly. It can be assumed that pore continuity has more contribution to higher water permeability coefficient for mix GP1. In the case of geopolymer concrete, blocking of the pores may be stopped after the accelerated steam curing process ceased. Thus, the ability to fill the pore structure depends mainly on the curing process. The increase of strength, eventually, is only a continuing effect of geopolymerization without any hydration.

Table 5. Water permeability coefficients of geopolymer concrete with different mixes

Mixture no	Water permeability coefficient (x10^{-11} m/s)	Void content (%)
GP1	4.67	10.5
GP2	3.95	13
GP3	2.46	10.8
GP5	2.91	10
GP7	2.61	8.2

As observed from Table 5, mix GP3 with water/binder ratio 0.20 shows the lowest water permeability coefficient. It is found also that mix GP7 with aggregate grading (7, 10, 20mm) shows low water permeability and void content. This indicates that the low water/binder ratio and a well-graded aggregate have large influences on geopolymer concrete permeability. As for OPC concrete, low water content and continuous grading contributes to lower porosity and discontinuity of concrete pores.

5.5 SEM Analysis

The microstructure of fly ash based geopolymer concrete is presented in Figures 6a and 6b. Figure 7 shows a typical SEM micrograph of mix GP2. This micrograph shows the geopolymer gel with partially or completely unreacted fly ash particles. Geopolymer product has unshaped and uniform microstructure. Some cracks were observed in the surface that might be due to mechanical damage during the sample preparation. The geopolymer microstructure from this research looks like many types of geopolymer from similar observations by Fernandez-Jimenez, *et al*. (2005) and Skvara, *et al*. (2006).

Figure 8 shows the holes in the microstructure resulted from air bubbles in the mixture. Those voids are distributed around the layer of geopolymer matrix. It is also found that there are some unreacted fly ash particles in the microstructure. Fly ash is known to have a significant proportion of particles with hollow spheres that possible to create porosity when they partially dissolved. As the result, the geopolymer matrix contains more dispersed small sized pores that can contribute to the overall porosity.

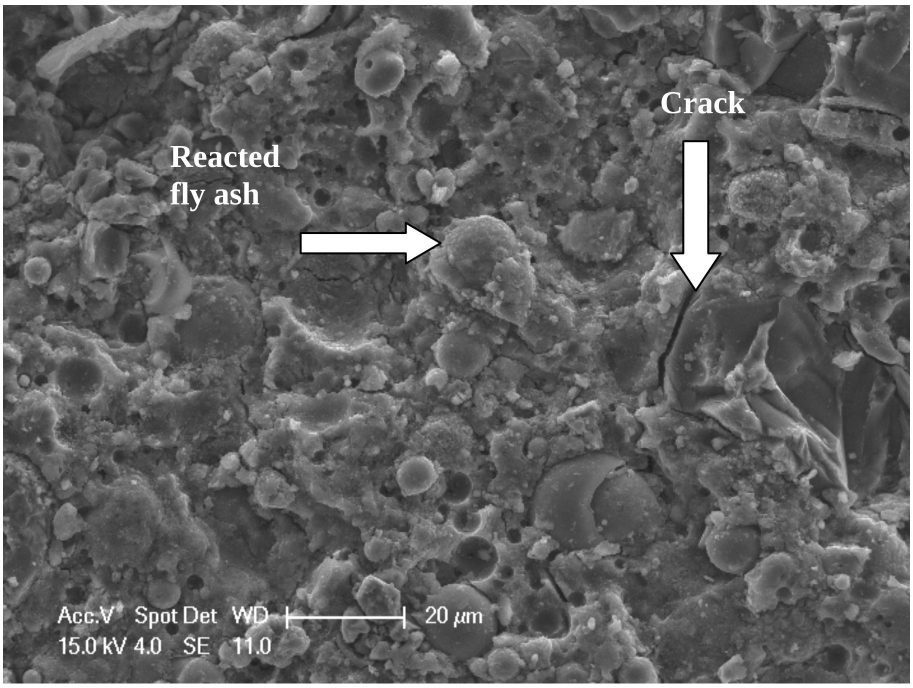


Figure 7. Typical SEM micrograph of geopolymer concrete (mix GP2)

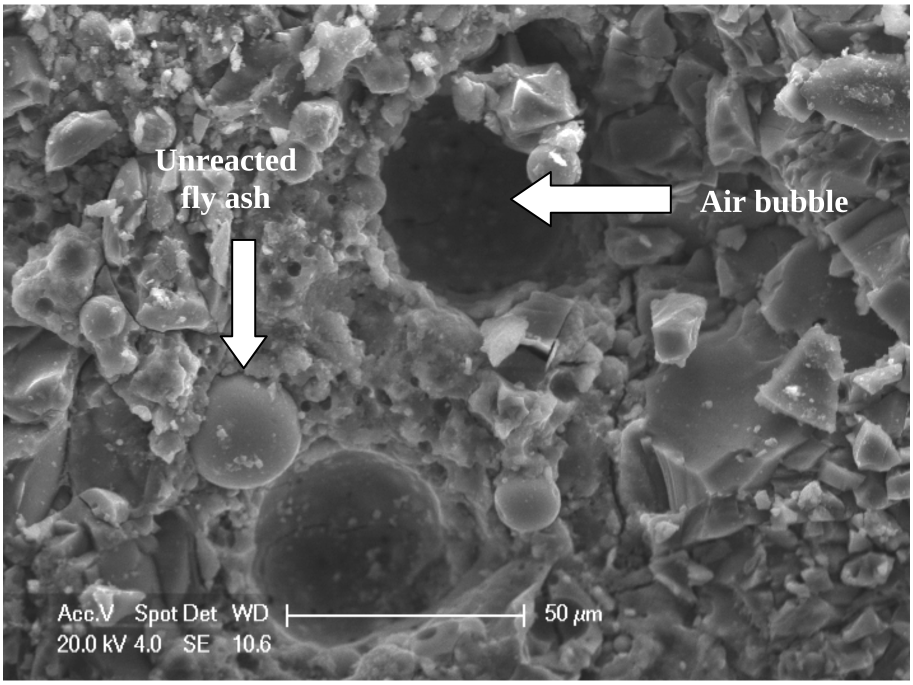


Figure 8. Air bubbles and unreacted fly ash of geopolymer concrete (mix GP2)

6. CONCLUSIONS

The following conclusions can be drawn based on the test results and discussion of the present study for measuring water penetrability of geopolymer concrete:

1. Fly ash geopolymer concrete exhibits low water absorption and sorptivity.
2. Geopolymer could be classified as a concrete with average quality according to water permeability coefficient values.
3. A water/binder ratio and well-graded aggregate are some important parameters that influence the water penetrability of low calcium fly ash geopolymer concrete. It is found that the higher water/binder ratio, then the lower water absorption and AVPV, sorptivity and water permeability. It is recommended to have low water/binder ratio and a better grading to reduce the capillary porosity and the overall porosity of geopolymer concrete.
4. Water absorption, AVPV, and sorptivity of low calcium fly ash geopolymer concrete are lower than the corresponding OPC concrete mixes. Steam cured OPC concrete shows higher capillary porosity than steam cured geopolymer concrete.
5. Geopolymer concrete with lower aggregate/binder ratio also indicates a high porous matrix. Sodium silicate inclusion to the mix might be the main cause of this finding.
6. From the microstructural analysis, the partially dissolved fly ash particles with hollow spheres mainly contribute to the porosity of the geopolymer matrix.

Acknowledgments
The authors are grateful to Nhu Nguyen from GHD Lab Testing Material for water permeability test assistance, and Elaine Miller from Dept of Applied Physics, Curtin University of Technology for SEM assistance. The first author would like to thanks the Australian Development Scholarship for their constant support and encouragement.

REFERENCES

[1]. Campbell, G.M. & Detwiler, R.J. Development of mix designs for strength and durability of steam-cured concrete. *Concrete International*: 37-39. July 1993.

[2]. Chang, H.L., Chun, C.M., Aksay, I.A. & Shih, W.H. Conversion of fly ash into mesoporous aluminosilicate. *Ind. Eng. Chem. Res*. 1999. 38: 973-977.

[3]. Davidovits, J. Properties of geopolymer cements. 1st International Conference on Alkaline Cements and Concretes (Krivenko, ed.). Kiev, Ukraine, 1: 131-149. 1994a.

[4]. Davidovits, J. High alkali cements for 21st century concretes. In Concrete Technology, Past, Present and Future. Proceedings of V Mohan Malhotra Symposium. Mehta, K. (ed.). ACI SP. 1994b.

[5]. Fernandez-Jimenez, A., Palomo, A. & Criado, M. Microstructure development of alkali-activated fly ash cement: a descriptive model. *Cement & Concrete Research*. 2005. 35: 1204-1209.

[6]. Fernandez-Jimenez, A., A. Palomo, *et al*. Engineering properties of alkali-activated fly ash concrete. *ACI Materials Journal.* 2006. 103: 106-112.

[7]. Garcia-Loreido, I., Palomo, A. & Fernandez-Jimenez, A. Alkali-aggregate reaction in activated fly ash systems. *Cement & Concrete Research*. 2007. 37: 175-183.

[8]. Hall, C. Water sorptivity of mortars and concretes: a review. *Magazine of Concrete Research*. 1989. 41: 51-61.

[9]. Hardjito, D., Wallah, S.E., Sumajouw, D.M.J. & Rangan, B.V. On the development of fly ash based geopolymer concrete. ACI Materials Journal 101: 467-472. 2004.

[10]. Hardjito, D. 2005. Development and properties of low calcium fly ash based geopolymer concrete. PhD Thesis of Civil Engineering & Computing Department. Perth: Curtin University of Technology. 2005.

[11]. Ho, D.W.S., Chua, C.W. & Tam, C.T. Steam-cured concrete incorporating mineral admixtures. *Cement & Concrete Research*. 2003. 33: 595-601.

[12]. Kong, D.L.Y, Sanjayan, J.G., & Sagoe-Crentsil, K. Comparative performance of geopolymers made with metakaolin and fly ash after exposure to elevated temperatures. *Cement and Concrete Research*. 2007. 37: 1583-1589.

[13]. Neville, A.M. Properties of Concrete. Essex: Longman. 1995.

[14]. Rendell, F., Jauberthie, R. & Grantham, M. Deteriorated concrete: Inspection and physicochemical analysis. London: Thomas Telford. 2002.

[15]. Shi, C. Strength, pore structure and permeability of alkali-activated slag mortars. *Cement and Concrete Research*. 1996. 26: 1789-1799.

[16]. Sindhunata, van Deventer, J.S.J., Lukey, G.C. & Xu, H. Effect of curing temperature and silicate concentration on fly ash based geopolymerization. *Ind. Eng. Chem. Res*. 2006. 45: 3559-3568.

[17]. Skavara, F., Kopecky, L., Nemecek, J. & Bittnar, Z. Microstructure of geopolymer materials based on fly ash. *Ceramics-Silikaty*. 2006. 50: 208-215.

[18]. Sofi, M., van Deventer, J.S.J., Mendis, P.A. & Lukey, G.C. Engineering properties of inorganic polymer concretes (IPCs). *Cement & Concrete Research*. 2007. 37: 251-257.

[19]. Wallah, S.E., Hardjito, D., Sumajouw, D.M.J. & Rangan, B.V. Sulfate resistance of fly ash based geopolymer concrete. In Proceedings of Concrete in the Third Millenium: Then 21st century Biennial Conference of the The Concrete Institute of Australia. 2003.

[20]. Yodmunee, S. & Yodsujai, W. Study on corrosion of steel bar in fly ash based geopolymer concrete. International Conference on Pozzolan, Concrete and Geopolymer. Khon Kaen, Thailand, May 24-25. 2006.