STRENGTH AND WATER PENETRABILITY OF FLY ASH GEOPOLYMER CONCRETE

Monita Olivia[1] and Hamid R. Nikraz[2]
[1,2]Civil Engineering Department, Curtin University, Perth, Western Australia, Australia
[1]Civil Engineering Department, University of Riau, Jalan HR Subrantas km 12,5 Pekanbaru, Riau, Indonesia
E-Mail: monita.olivia@postgrad.curtin.edu.au

ABSTRACT

This paper presents a study on the strength development, water absorption and water permeability of low calcium fly ash geopolymer concrete. Geopolymer mixtures with variations of water/binder ratio, aggregate/binder ratio, aggregate grading, and alkaline/fly ash ratio were investigated. OPC (Ordinary Portland Cement) concrete with the same strength level was used as a control mix. Strength was measured by compressive strength, while water penetrability was evaluated by water absorption and water permeability. In addition, the AVPV (Apparent Volume of Permeable Voids) was measured. The results show that the strength of fly ash geopolymer concrete was increased by reducing the water/binder and aggregate/binder ratios; and the water absorption of low calcium fly ash geopolymer was improved by decreasing the water/binder ratio, increasing the fly ash content, and using a well-graded aggregate. There was no significant change in water permeability coefficient for the geopolymer with different parameters. The test data indicates that a good quality of low calcium fly ash geopolymer concrete can be produced with appropriate parameterisation and mix design.

Keywords: fly ash, geopolymer concrete, water penetrability, compressive strength, water permeability.

INTRODUCTION

Fly ash-based geopolymer concrete has emerged as a new technology in construction materials. The addition of fly ash adds value to the cement, and also reduces the OPC contribution to CO_2 emissions during concrete production. The production of only 1 tonne of OPC cement is estimated to release 1 tonne of CO_2 gas emission. It was calculated that combining OPC cement with slag could produce 248 kg/m^3 of CO_2, while the geopolymer only produces 78 kg/m^3 [1]. The geopolymer can be manufactured from a reaction of the alkaline solution with the sodium and alumina in the fly ash to produce a compact cementing material. This material possesses good mechanical properties and durability in aggressive environments [2-4]. Previous findings showed that the final properties of geopolymer are affected by the concentration and type of alkaline solution; curing method and temperature; rest period; water content; nature of source material; and the ratio of fly ash to alkaline solution [5-7].

The performance of concrete is usually determined by its strength and durability. To obtain good quality concrete, these properties can be improved by: reducing the water content; increasing the binder and aggregate content; using a well-graded aggregate; and using a good curing method and better compaction [8-10]. Further, the strength and durability of concrete are also influenced by the amount, size and type of the pores. Strength is determined by the number of pores, while durability is affected by the volume, size and continuity of the pores [8]. Since geopolymer concrete is a concrete-like material, then incorporating factors that affect normal concrete may change the final strength and durability of geopolymer. This concept of improvement is based on varying parameters such as fly ash content, alkaline activators content, and the curing method; thus producing a high strength concrete with less continuous pores. For example, high alkaline solution content could significantly change the strength of the concrete and its porosity.

Water penetrability can be defined as the degree to which a material permits the transport of gases, liquids, or ionic species through it. These properties are linked to the performance of porosity, since the harmful ions penetrate into the concrete paste through the pores. Water can be harmful to concrete because of its ability to: leach calcium hydroxide from the cement paste; carry harmful dissolved species, such as chlorides or acids, into the concrete; form ice in large pores in the paste; cause leaching of compounds from the concrete [11]. Water absorption, sorptivity and water permeability measurement are some methods to determine the water penetrability of concrete.

The objective of this study was to investigate the effectiveness of changing the following parameters: water/solids ratio; grading of aggregate; aggregate/solids ratio; fly ash content on compressive strength; water absorption; AVPV; and water permeability of the geopolymer concrete. Based on the results, this paper will discuss the influence of these parameters on the concrete properties. OPC concrete with the same strength level was tested to compare the properties.

MATERIALS AND METHOD

Fly ash class F (ASTM C618) from the Collie power station in Western Australia and Ordinary Portland Cement Type I (AS 2350) were used as the main materials. The chemical composition of fly ash and cement is presented in Table-1.

Table-1. Chemical composition of fly ash and cement (%).

Oxides	Fly ash	Cement
Silica (SiO_2)	50.50	21.10
Alumina (Al_2O_3)	26.57	4.70
Calcium Oxide (CaO)	2.13	63.80
Ferric oxide (Fe_2O_3)	13.77	2.80
Potassium oxide (K_2O)	0.77	-
Magnesium oxide (MgO)	1.54	2.00
Sodium oxide (Na_2O)	0.45	0.50
Phosporus pentoxide (P_2O_5)	1.00	-
Sulphuric anhydride (SO_3)	0.41	2.50
Loss on ignition (LOI)	0.60	2.10
Chloride	-	0.01

Coarse and fine aggregates in saturated surface and dry conditions were used in this research. Crushed granite, with grain sizes of 7 mm, 10 mm and 20 mm, was obtained from local quarries, as was uncrushed dune sand. The coarse aggregates had specific gravities of 2.65, 2.62, and 2.58, and water absorptions of 0.58%, 0.74%, and 1.60%, for diameters 20 mm, 10 mm and 7 mm, respectively.

A combination of sodium hydroxide and sodium silicate was used as an alkaline activator in the study. The sodium hydroxide, in pearl form, was diluted in distilled water to produce sodium hydroxide solution with 14 M concentration. The sodium silicate with a specific gravity of 1.52 and a modulus silicate ratio (*Ms*) of 2 (where $Ms = SiO_2/Na_2O$, Na_2O = 14.7%, SiO_2 = 29.4%) was provided in the alkaline activator's preparation. A commercially available naphthalene sulphonate polymer-based superplasticiser was included in the mixture to improve workability.

In this research, the geopolymer mixes were designed to obtain concrete with consistent compressive strength. Parameters have been chosen to produce concrete with good strength and durability properties for particular applications, such as in a seawater environment. The concrete needs to be workable, have high strength, low porosity and permeability. The water to solids ratios, alkaline to fly ash ratios, aggregate to solids ratios, and aggregate gradings were derived from Hardjito [12] in the previous investigation of fly ash geopolymer concrete at Curtin University. A new set of parameters was designed from these initial values and is presented in Table-2.

Table-2. Parameters and values of trial mix.

Parameters	1	2	3
Water to solids ratio	0.20	0.22	0.23
Aggregate to solids ratio	3.50	3.90	4.70
Alkaline/fly ash ratio	0.30	0.35	0.45
Aggregate grading	7:10	7:10:20	10:20

A control mix, or GP1 mix, was intended to produce geopolymer concrete with properties and performance equivalent to OPC concrete with strength of 35 MPa. This particular mix has a water/solids ratio of 0.23, an aggregate/solids ratio of 3.90 and an alkaline/fly ash ratio of 0.35. It uses 7:10 mm grading of coarse aggregates. Some other mixtures (GP2-GP9) were developed by varying the water/solids ratio (0.20, 0.22), aggregate/solids ratio (3.5, 4.7); alkaline to fly ash ratio (0.30, 0.45) and grading of coarse aggregates (7:10:20 mm, 10:20 mm). The preliminary mixture proportions are shown in Table-3.

Table-3. Mixture proportions of preliminary study.

Mix No.	w/s	a/s	alk/ FA	**Quantity** (kg/m^3)								
				Water	Coarse aggregate (mm)			Sand	Fly ash	NaOH (14M)	SS	SP
					7	10	20					
GP1	0.23	3.90	0.35	25.8	647	554		647	408	41	103	6.1
GP2	0.22	3.90	0.35	20.7	647	554	-	647	408	41	103	6.1
GP3	0.20	3.90	0.35	16.5	647	554	-	647	408	41	103	6.1
GP4	0.22	3.50	0.35	25.8	630	540	-	630	444	44	111	6.1
GP5	0.24	4.70	0.35	25.8	672	576	-	672	356	36	89	6.1
GP6	0.23	3.90	0.30	25.8	647	554	-	647	424	36	91	6.1
GP7	0.23	3.90	0.45	25.8	647	554	-	647	381	49	122	6.1
GP8	0.23	3.90	0.35	25.8	645	370	277	554	408	41	103	6.1
GP9	0.23	3.90	0.35	25.8	-	924	370	554	408	41	103	6.1

GP = Geopolymer mixture, w/b = water/solids ratio, a/b = aggregate/solids ratio,
alk/FA = alkaline/Fly ash ratio, SS = sodium silicate,
SP = superplasticizer.

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The specimens were tested for compressive strength, water absorption, AVPV and water permeability. The results were intended to indicate the effect of changing some basic parameters on the strength and durability performance of fly ash geopolymer concrete.

Water absorption and volume of permeable voids determination were carried out according to ASTM C642. The water absorption and AVPV percentages were calculated by equations:

$$Water\,absorption = (\frac{M_s - M_d}{M_d})100 \qquad (1)$$

$$AVPV = (\frac{g_2 - g_1}{g_2})100 \qquad (2)$$

Where

M_s = mass of surface-dried sample (g)
M_d = mass of oven-dried sample (g)
g_2 = apparent density (Mg/m^3),
g_1 = bulk density, dry (Mg/m^3)

A water permeability test was carried out based on the GHD Water Permeability method, previously Taywood Engineering Ltd [13]. The specimens were dried in the oven at 105^{0}C until constant mass was attained. The specimens were then coated with epoxy on the circular side to prevent water ingress from that side during the test. A pressure of 850kPa was applied to the samples at a pressure head of 92.5m. After the specimens were saturated, the flow rate reading was taken with a burette by measuring the changing of volume of water over time. The permeability was measured by applying Darcy's Law:

$$k = \frac{QL}{AH} \qquad (3)$$

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)

RESULTS AND DISCUSSIONS

Compressive strength, slump and density

The average slump and density of the concretes at 28 days are presented in Table-4. The slump values of all geopolymer mixes were in the range 230-270 mm. Although slump values indicated a high workability, the fresh geopolymer workability was actually poor. The mixes were stiffer than the OPC concrete due to lack of water content, and also the cohesive sodium silicate used in the fly ash geopolymer system. Similar cohesive fresh geopolymer mixes have been confirmed by previous authors [14, 15]. The hardened geopolymer concrete density at 28 days was in the range 2248-2294 kg/m^3.

Table-4. Slump and density at 28 days.

Mixture No.	**Slump** (mm)	**Density** (kg/m^3)
GP1	260	2248.49
GP2	230	2294.55
GP3	270	2336.04
GP4	260	2281.61
GP5	240	2282.43
GP6	250	2288.71
GP7	250	2290.70
GP8	260	2289.01
GP9	240	2315.68

The density of geopolymer is close to a density of normal weight concrete in practice, which varies in the range 2200-2600 kg/m^3.

The average compressive strength at 7, 28 and 91 days is shown in Figure-1. Overall, it was noticed that the compressive strength of all mixes increased with concrete age. In the case of the water/solids ratios in Figure-1(a): GP3, with w/s 0.20, had the highest compressive strength of 76.00MPa at 91 days. A decrease in compressive strength was observed as the w/s ratio increased from 0.20 to 0.23. This data illustrates the effect of w/s ratio on geopolymer strength development, which is similar to OPC concrete. When low water content is used in the geopolymer mixes, the alkaline activator concentration tends to increase in the system. Thus, the available high alkalinity could accelerate the geopolymerisation process, and increase the concrete's final strength [16].

In the case of aggregate/solids ratios, a high compressive strength was shown by GP4 at 91 days. An increase of a/s ratio was observed to quite significantly decrease the compressive strength (Figure-1(b)). For example, at 28 days, the compressive strength of mixes with a/s ratios of 3.50 and 4.70 were 25.44MPa and 48.06MPa, respectively. This data clearly shows an increase of solids or dried alkaline activator, which is advantageous in producing more aluminosilicate bonds and in improving the final strength of geopolymer concrete [17].

The strength development of mix GP6 was slightly higher after 7 days and continued to gain strength after 28 days (Figure-1 (c)). At an alkaline/fly ash ratio of 0.45, GP7 had not achieved the target strength of 35MPa, but the strength gain after 28 days was comparatively high. A decrease of compressive strength was observed as the fly ash quantity was increased in the mixture. A high amount of fly ash, with a lack of alkaline activator to activate the ashes, produces an aluminosilicate covering with a lot of unreacted fly ash. The unreacted fly ash failed to develop geopolymer bonds that could have a negative impact on the strength development. In the case of aggregate grading, GP8 and GP9 obtained their target

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strength of 35MPa at 28 days and both mixes were performing similarly (Figure-1(d)).

The results indicate there was no significant strength development of fly ash geopolymer concrete with variations of aggregate grading. Hence, among the parameters studied, the water/solids ratios, aggregate/solids ratios, and alkaline/fly ash ratios were shown to improve the strength to a certain extent. A reduction of water content, aggregate and fly ash quantity were found more advantageous to enhance the strength development.

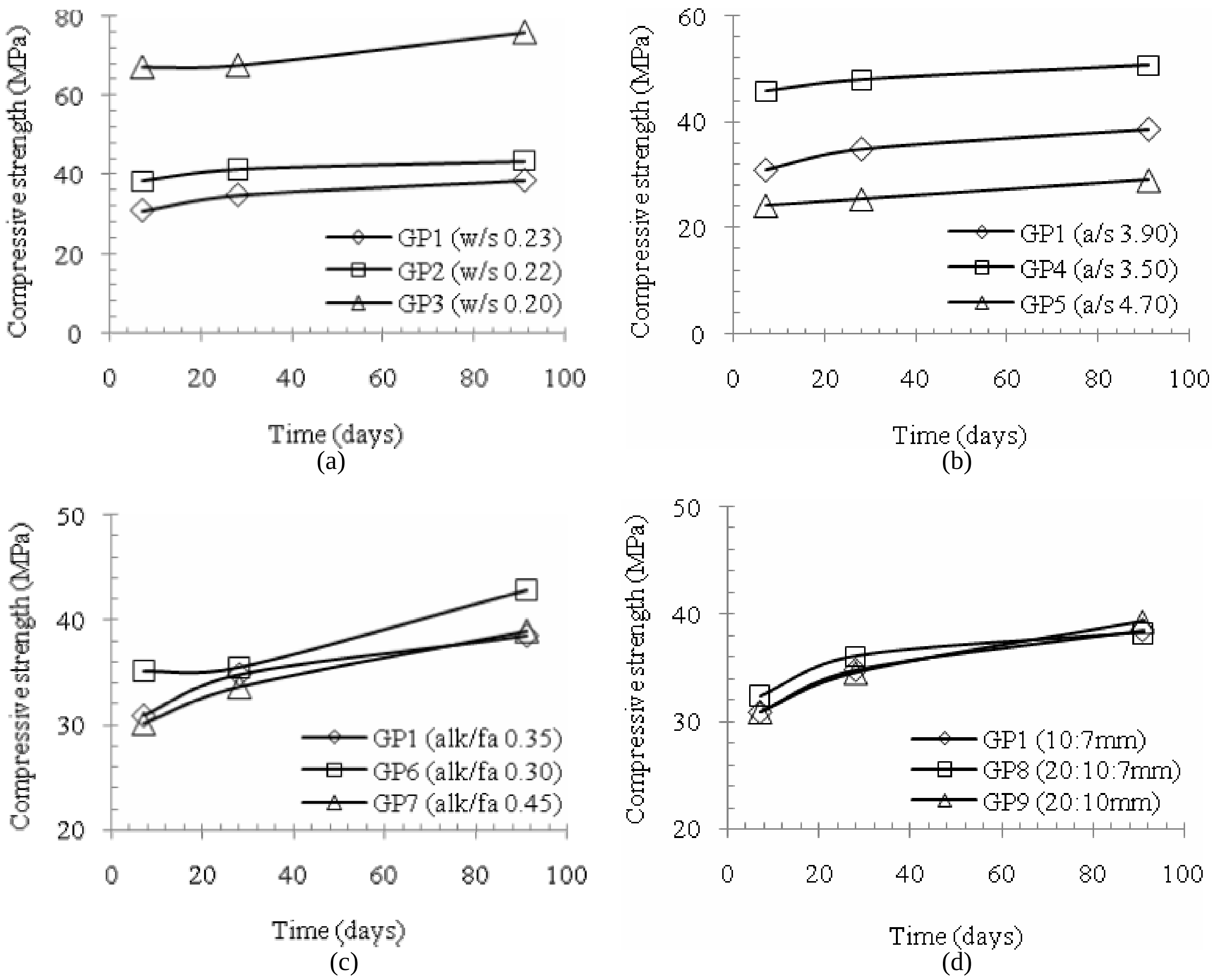

Figure-1. Strength development of concrete with various parameters (a) water/solids ratio, (b) aggregate/solids ratio, (c) alkaline/fly ash ratio, (d) aggregate grading; at 7, 28 and 91 days.

Water absorption and AVPV

A comparison of the water absorption of the geopolymer concrete with different water/solids ratios, aggregate/solids ratios, alkaline/fly ash ratios and gradings at 28 and 91 days is shown in Figure-2. Water absorption can be used to represent an open porosity of concrete paste. The measurement is taken by calculating the difference in specimen weight under oven-dried and fully saturated conditions. In general, various trends were observed from the water absorption of fly ash with various parameters. The low water/solids ratios, high aggregate/solids ratios and low alkaline/fly ash ratios were more significant in improving water absorption than the aggregate gradings. The percentage of water absorption for all specimens and parameters varied in the range 3.63% to 4.90% at 28 days and 91 days of the concrete age. The water absorption of fly ash geopolymer normally varies between 3% and 5% [18, 19]. Overall, a water absorption value of less than 5% is classified as "low"- according to Vic Road's standard specification [19]. BS 1881 specifies concrete with typical absorption values in the range 3% to 5% as "average" concrete [21]. This low water absorption level is a good indicator of limited open porosity that can inhibit the high flow of water into the concrete.

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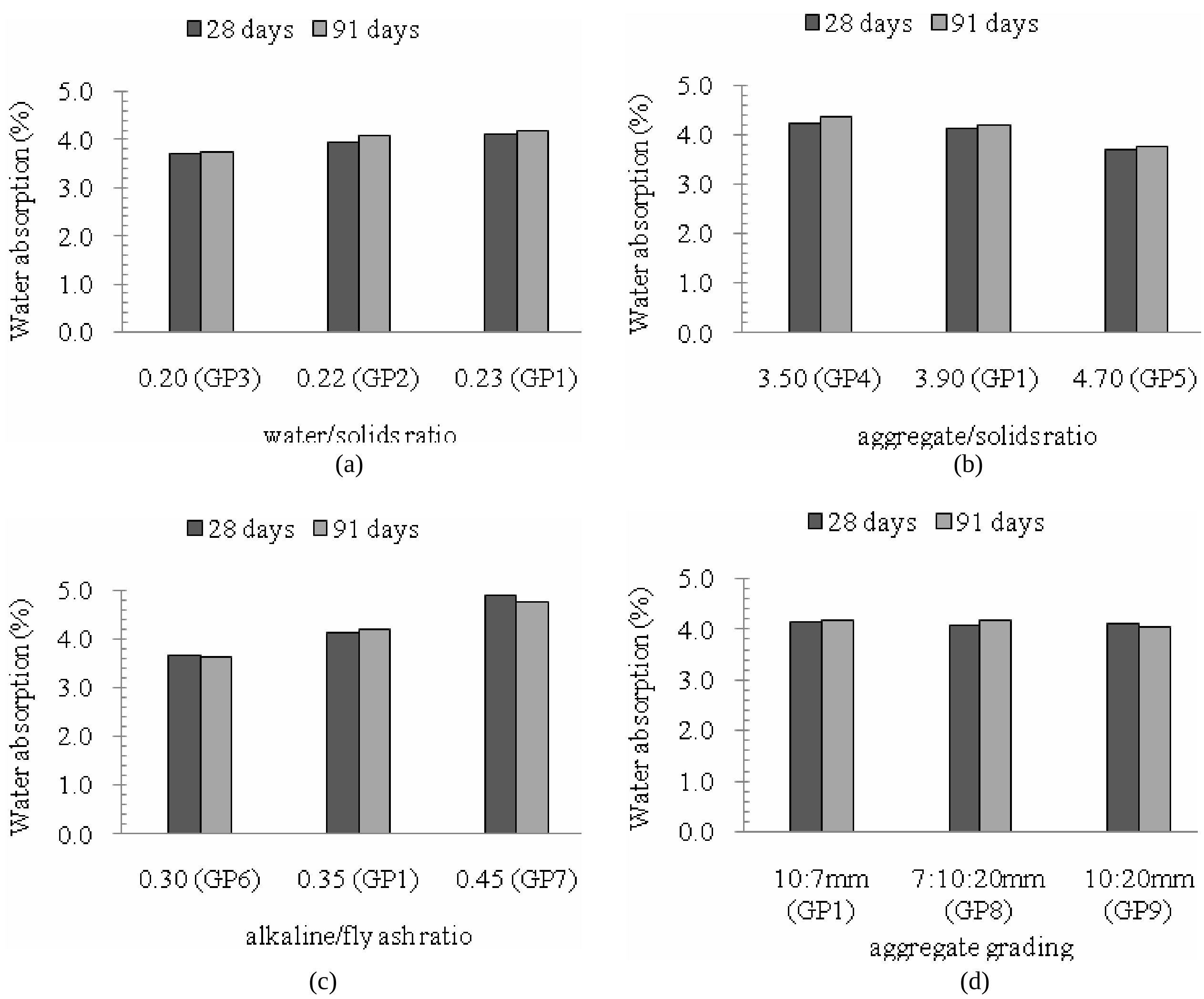

Figure-2. Water absorption of mixes with variation of (a) water/solids ratio, (b) aggregate/solids ratio, (c) alkaline/fly ash ratio, (d) aggregate grading at 28 and 91 days.

Figure-3 illustrates the AVPV of concrete with various parameters. In general, the same trend could be observed from this property with water absorption. The AVPV, or closed porosity, is a percentage of pore space measured by boiling the saturated concrete. Overall, the AVPV of specimens was in the range 8.96% to 10.73%. An AVPV value of less than 12% is classified as "good"-according to Vic Road's standard specification [20].

As indicated before, the low water/solids ratios, high aggregate/solids ratios and low alkaline/fly ash ratios are significant in improving the water absorption/AVPV. The reasons for better performance of these ratios are as follows. Low water content in the mixture does not only increase the fly ash geopolymer concrete strength, but it also limits the pore size in the geopolymer paste. When water is included in the geopolymer mix, it is excluded from reaction and fills in the aluminosilicate gel pores [22]. Conversely, when high extra water content is used in the mix, the geopolymer produces large gel crystals with trapped water inside [23]. Once the water evaporates from the pores, the result is a highly porous geopolymer paste with high water absorption and low compressive strength-such as GP1.

The inclusion of high content aggregates favours a low water absorption/AVPV of concrete, due to less porosity, and results in a high aggregate mix-such as GP5. When more alkaline solution is added to the mixture, the water absorption/AVPV tends to increase. A mix with a high amount of alkaline solution, such as the tacky sodium silicate, tends to produce a more porous geopolymer gel. The high amount of sodium silicate in the mix was found to produce concrete with large pore sizes [24]. This explained a tendency of some mixes, with a high alkaline content, to have higher porosity than mixes with a low alkaline/fly ash ratio-such as GP6. It was noticed that aggregate grading did not change the water absorption/AVPV values significantly. Perhaps constant amounts of paste/geopolymer paste, without any change in aggregate quantity, influence this behaviour.

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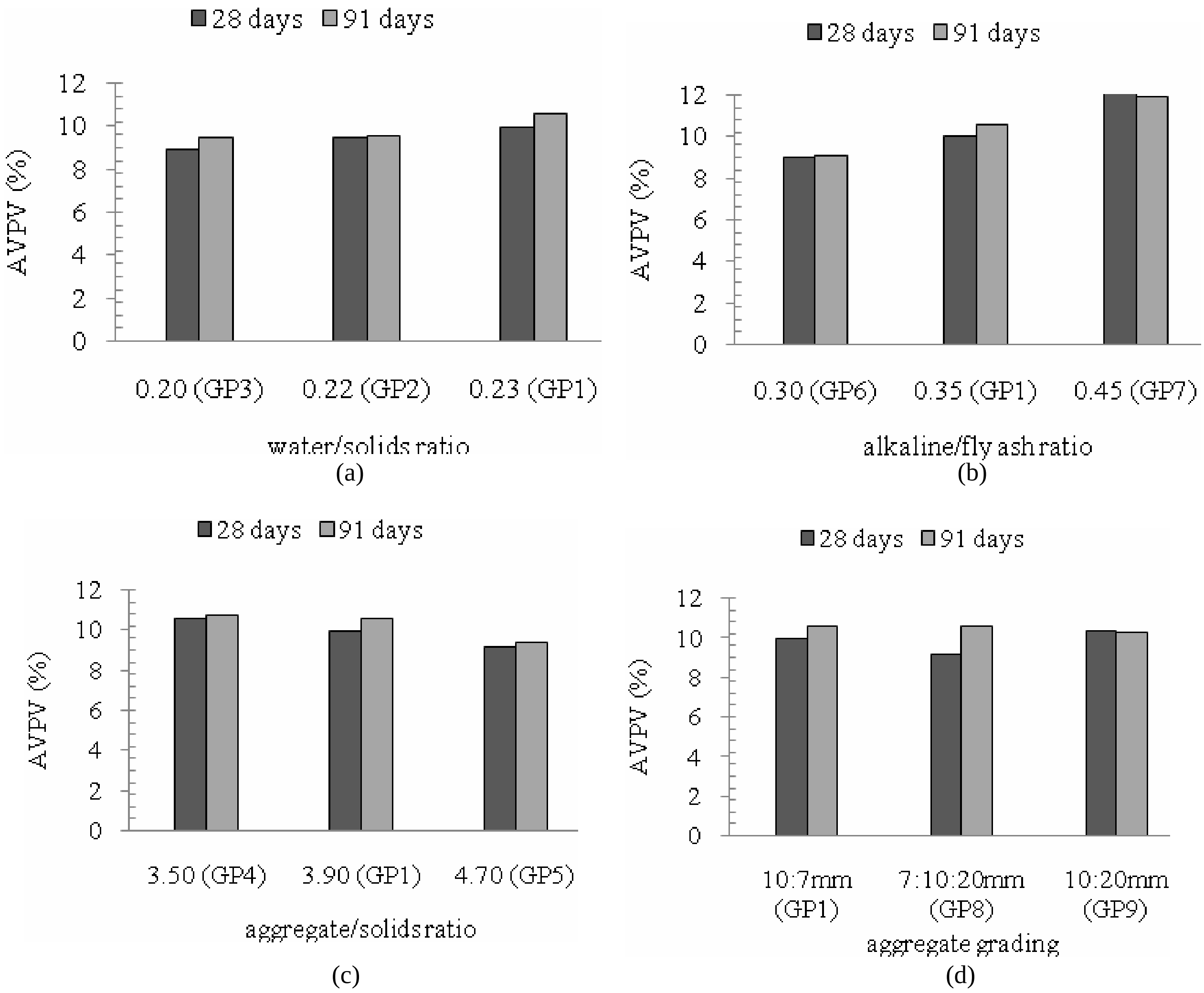

Figure-3. AVPV of mixes with variation of (a) water/solids ratio, (b) aggregate/solids ratio, (c) alkaline/fly ash ratio, (d) aggregate grading at 28 and 91 days.

A correlation between water absorption/AVPV with compressive strength is presented in Figure-4. Current findings were compared with the water absorption values from the previous author who used a geopolymer mix with 10 M NaOH concentration [25]. A linear correlation of AVPV with compressive strength shows a decrease in AVPV with an accompanying increase in compressive strength. It was observed that a minor change of water absorption with a higher compressive strength indicated that open porosity was not only affected by compressive strength.

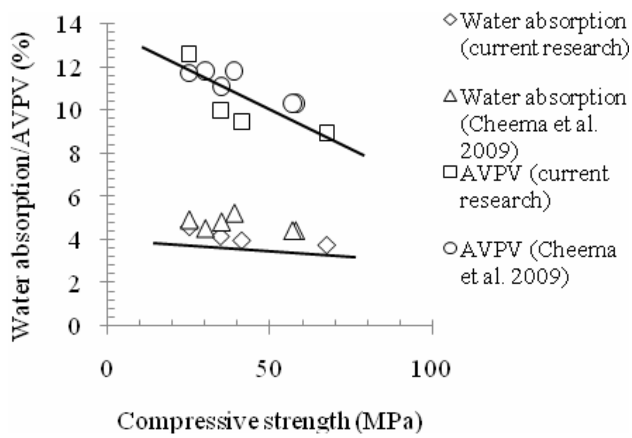

Figure-4 Correlation between water absorption/AVPV with compressive strength.

Water permeability

Table-5 displays the average water permeability coefficients and the void content percentages of fly ash geopolymer concrete for the selected mixes: i.e., GP1, GP2, GP3, GP4 and GP8. The coefficients obtained varied in the range from 2.46 x 10^{-11} to 4.67 x 10^{-11} m/s. The geopolymer concrete mixtures in this research can be classified as having an "average" quality, judging from the coefficient permeability in the range of 10^{-11} to 10^{-12} m/s [21]. To ensure the water tightness of concrete cover in extreme environments under high water pressure, it is recommended to use concrete with a water permeability coefficient of less than 1 x 10^{-12} m/s [26].

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

Mix No.	Parameter	Water permeability coefficient (x10^{-11} m/s)	Void content (%)
GP1	w/s 0.23, a/s 3.90, 7:10mm	4.67	10.5
GP2	w/s 0.22	3.95	13
GP3	w/s 0.20	2.46	10.8
GP4	a/s 3.50	2.91	10
GP8	7:10:20mm	2.61	8.2

Mix GP1 showed the highest water permeability coefficient of any other concrete. Conversely, GP3 displayed the lowest coefficient. Except for GP1 and GP2, the final water permeability coefficients of other mixes were slightly similar. Void content was obtained during the water permeability test by measuring the difference between the dry and saturated weights of concrete samples. From Table-5 it can be seen that the void varied from 8.2% to 13%, which also confirms that all concrete has an "average" quality [21]. There exists a nonlinear relation between the water permeability coefficient and the void content, since GP1 with a low void content has the highest permeability coefficient. Pore continuity-another aspect of porosity-was seen to be more influential in this flow rate measurement.

Water permeability is influenced by pore connectivity in the concrete paste. The pore development of concrete is dependent on parameters such as water content, binder content and the curing method. This is also the case for fly ash geopolymer concrete. The lower water permeability thus observed for GP3 is attributed to the denser paste and smaller pore interconnectivity. The increase in aggregate content of GP4 contributes to a decrease in capillary pores volume and the water permeability coefficient.

There exists a good correlation between the water permeability coefficient and compressive strength (Figure-5).

As the compressive strength increases, the permeability coefficient also increases. It can be seen that water permeability coefficients from previous research were lower than the previous study [25]. This may be due to the geopolymer mixture composition and the types of water permeability test used by both researchers.

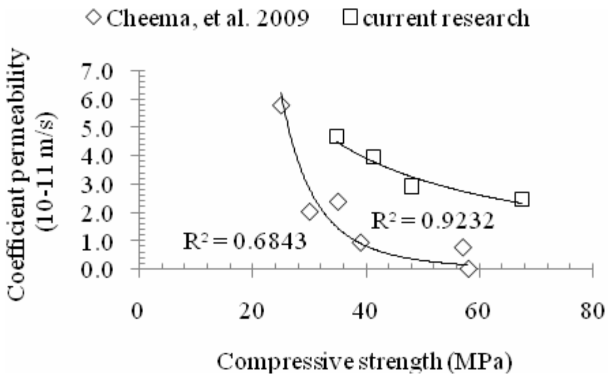

Figure-5. Correlation between coefficient permeability and compressive strength.

CONCLUSIONS

a) The strength of fly ash geopolymer concrete was improved to a certain extent by decreasing the water/solids ratio, the aggregate/solids ratio, and the alkaline to fly ash ratio. Aggregate grading showed a marginal influence in the strength development of fly ash geopolymer concrete.

b) The water absorption of fly ash geopolymer, on average, was less than 5%, which can be classified as "low". The water absorption decreased by decreasing the water/solids ratio, increasing the aggregate/solids ratio, and increasing the alkaline/fly ash ratio. The aggregate grading showed less change in water absorption with concrete age.

c) The overall percentage of Apparent Volume of Permeable Voids (AVPV) was less than 12% and was classified as "good". Water absorption showed the same trend as with AVPV. The values can be improved by decreasing the water/solids ratio, increasing the aggregate/solids ratio, and increasing the alkaline/fly ash ratio. Aggregate grading was not a significant parameter, since there was little change in AVPV with concrete age.

d) The water permeability test revealed that the concrete had "average" quality, judging by coefficient permeability in the range 2.46 x 10^{-11} to 4.67 x 10^{-11} m/s. The void content measured from the test showed similar "average" criteria, varying from 8.2% to 13%.

e) It can be inferred that the water/solids ratio is the most influential parameter to increase strength, and to decrease the water absorption/AVPV and water permeability. The alkaline/fly ash ratio of 0.30 was found to increase strength and reduce porosity significantly. An optimum aggregate/binder ratio of 3.50 contributed to the high strength of the concrete; however, to obtain a low porosity of fly ash geopolymer, the ratio needs to be increased to 4.70.

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