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EXPERIMENTAL STUDY ON MECHANICAL AND HYDRAULIC PROPERTIES OF POROUS GEOPOLYMER CONCRETE

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ABSTRACT: Normal porous concrete is a special type of concrete with high porosity, allowing water to percolate into the sub-grade, but using Portland cement. On the other hand, geopolymer concrete is an environmentally friendly concrete using fly ash, blast furnace slag and kaolinite alkaline activator. This experimental study proposes a fabrication procedure to combine the two above-mentioned concrete types to produce a sustainable material – porous concrete made of fly ash-based geopolymer with alkaline activators. Various parameters affecting the compressive strength, such as aggregate size, the water-to- (fly ash and blast furnace slag) ratio, the concentration of alkaline activator have been studied, together with two major hydraulic properties such as water permeability and porosity. The results show that the porous geopolymer concrete using local fly ash and blast furnace slag can achieve the compressive cube strength greater than 23MPa and the average values of water permeability are in the range of 6.4 to 17.8 mm/s depending on the mix design. Increasing coarse aggregate size increases the porosity and water permeability, however, lowers the compressive strength of porous geopolymer concrete. Increasing the activator-to-binder ratio, the compressive strength increases, not affecting the porosity and water permeability.

Keywords: Porous concrete, Geopolymer concrete, Fly ash, Alkaline, Activators.

1. INTRODUCTION

Porous concrete is a special type of concrete with high porosity, allowing water to percolate into the sub-grade. Normal porous concrete is mixture of cement, aggregates, water, with no or only a small amount of fine aggregate. As summarized by many researchers [1,2], the porosity of porous concrete is in the range of 15 to 35% by volume, the typical water permeability is from 2 to 12 mm/s, while the corresponding compressive strength varies from 5 to 25 MPa. The aggregate-to-binder ratio of cement based porous concrete is in the range of 4 to 6 by mass. Some studies showed that if the aggregate-to-binder ratio increases, the compressive strength and elastic modulus will decreases significantly [3]. Addition of fine aggregate contributes to increase mechanical strength, and to improve the freeze-thaw resistance of porous concrete [4,5]. Dong et al. [6] studied how to improve the characteristic of binder by separately using silicafume (SF) and Fly Ash (FA) with a content of 10%; 20% and 30% and by using the combination compound of 10% SF with 10-30% FA. The two typical properties of binders are: the viscosity of the binders through the flowing time of Marsh cone, the instantaneous viscosity determined by the SV-10 viscosimeter and the strength of the binders. Tung et al. [7] conducted an laboratory experiment to evaluate the effect of using different types of fly ash on the properties of concrete, and applied the material to construct a large scale road. However, the cement based porous concrete are not environmentally friendly material, since it still uses a lot of Portland cement.

One of the alternatives for normal concrete using Portland cement is using Geopolymer concrete to produce environmentally friendly material. Geopolymer was introduced the first time by Davidovits [8], who used kaolinite and alkaline activators. Recently, due to many environmental problems, it has reactivated numerous researches worldwide on alkali-activated concrete using Fly Ash (FA) and Blast Furnace Slag (BFS). This type of concrete has been applied in buildings and infrastructure with several practical applications [9].

Recently, polymers have been used to produce porous concrete with a purpose of creating a sustainable material. The study [10] showed that polymer fibers are helpful in increasing permeability, improving tensile strength, or enhancing the freeze-thaw resistance of cement pervious concrete. However, type of polymer has to be chosen carefully, since some macro-synthetic fibers reduce the permeability of resulting pervious concrete [10].

Using FA geopolymer as binder, an environmentally friendly pervious concrete has been developed [11,12]. In those studies, the compressive strengths reached about 8.4 to 11.4 MPa if increasing the aggregate-to-binder mass ratio to 8. Sata et al. [13] investigated the effect of aggregate type on performance of FA geopolymer pervious concrete. They found that the FA geopolymer porous concrete attained the highest mechanical strength if using natural coarse aggregate, and if using recycled aggregate from crushed structure concrete, the best water permeability was achieved.

Recently, many studies [14-16] on Geopolymer Concrete (GPC) and the behaviour of GPC beams have been conducted. The results show that GPC can be fabricated locally with good mechanical properties, and the GPC beams perform well both in ultimate and serviceability limit state. Tung, Trung and Thuan [17] studied on mechanical properties of GPC made from FA, BFS, alkaline activator, especially with sea sand and sea water. The results show that using local materials, GPC can be fabricated with a compressive strength up to 40MPa to 60MPa. Its compressive and tensile strengths as well as the elastic modulus are not affected by sulphate salts in sea sand and sea water.

There is no study been conducted yet on porous concrete made of fly ash-based geopolymer with alkaline activator. Therefore, as part of the research on the development of cementless concrete, this study focuses on porous geopolymer concrete. The creation of air voids is achieved by using no or little fine aggregate from the mix design, and by using well-sorted coarse aggregate. An experimental program was conducted to investigate mechanical and hydraulic properties of the porous geopolymer concrete. Various parameters affecting the compressive strength, such as aggregate size, the water-to- (fly ash and blast furnace slag) ratio, concentration of the alkaline activator have been studied, together with two major hydraulic properties such as water permeability and porosity.

2. MATERIALS

Geopolymer binder is a product through the geopolymerization process between alkali solution and the materials rich in Silica (Si) and Alumina (Al), thus it can be called as alkali-activated geopolymer binder. The geopolymerization process is a chemical reaction between Al-Si oxides which form the three-dimensional polymer chain Si–O–Al–O proposed by Davidovits [6]. It includes three types: poly(sialate) (–Si–O–Al–O–), poly(sialate-siloxo) (Si–O–Al–O–Si–O), and poly(sialate-disiloxo) (Si–O–Al–O–Si–O–Si–O). The typical geopolymer composition is generally expressed as $nM_2O.Al_2O_3.xSiO_2.yH_2O$, where M denoted the alkaline metal.

In this study, the raw materials for porous geopolymer concrete include FA, BFS, Alkali-Activated Materials (AAM or ‘‘activator’’), coarse aggregate, fine aggregate, and water.

2.1 Fly Ash (FA) and Blast Furnace Slag (BFS)

The low-calcium FA (class F) as defined by ASTM standard C618 [18] from Pha Lai Thermo-power Plant (Vietnam) was used. BFS from Hoa Phat Metallurgy Factory was mixed with FA to improve the reactivity of low-calcium content fly ash. It was ground to reduce particle size of slag, resulting in an increase of concrete compressive strength [19]. Fig.1 shows photos of FA, BFS and activator, while the chemical compositions of FA and BFS are presented in Table 1.

Fly ash consists of finely divided ashes produced by pulverized coal in power plants. The chemical composition of FA includes about 30 different chemical elements, in the form of oxides such as SiO_2, Al_2O_3, CaO, MgO, Fe_2O_3, etc. Within them, the four oxides of SiO_2, Al_2O_3, CaO, MgO are the most important elements since they decide the FA properties. The percentage of these oxides in FA depends on the mineral composition of coal.

a) Fly ash b) Blast-furnace slag

c) Activator (AAM)

Fig.1 Fly ash and blast-furnace slag

For BFS, the main chemical compositions include CaO, MgO, SiO_2 và Al_2O_3 with the total percentage of 90% to 95%. The percentage of other oxides varies in a small range depending on chemical composition of iron ore and slag.

As can be seen in Table 1, from the results of chemical component analysis, FA from Pha Lai Thermo-power Plant and BFS from Hoa Phat Metallurgy Factory consist of high percentage of SiO_2 and CaO. These elements once dissolved in the alkaline solution will create the formation of hydrates such as C–S–H (calcium silicate hydrate).

Table 1 Chemical composition of fly ash and Blast furnace slag (%)

	MKN	SiO2	Al2O3	Fe2O3
FA	9.52	56.25	20.04	6.60
Slag	-	32.92	14.49	0.96
	CaO	MgO	R2O	TiO2
FA	1.90	1.30	2.49	0.40
Slag	37.95	6.57	-	-
		SO3	Na2O	K2O
FA		0.58	-	-
Slag		-	0.08	0.13

2.2 Alkaline Activator

Alkali-Activated Materials (AAM) can be sodium hydroxide (NaOH), potassium hydroxide (KOH), sodium silicate (Na_2SiO_3) and potassium silicate (K_2SiO_3). Compared to NaOH, KOH is better because it has a greater level of alkalinity. However, Duxon, Fernández, Provis, Lukey, Palomo and Deventer [20] had found that NaOH possesses greater capacity to liberate silicate and aluminate monomers.

AAM can be classified as one-part or "just add water" AAM and the conventional two-part AAM [21]. In this study, alkali-activator is one-part AAM and supported by APTES Pty – Australia. This activator, namely M-activator, in a solid state as a white powder is a form of sodium silicate holding *n* water molecules ($Na_2SiO_3.nH_2O$). The solid activator is dryly mixed with FA and BFS before they are dissolved in water to create the binder. Using the activator in the dry state has many advantages such as easy to maintain and transport, uniformly contact between FA-BFS and activator to increase the quality of GPC.

2.3 Aggregate

Generally, fine aggregate (sand) should be limited in porous concrete because it significantly affects the water permeability, although helping to increase the concrete compressive strength. Therefore, it is necessary to determine a suitable amount of sand depending on requirements of the water permeability and target compressive strength.

The grading of coarse aggregate shall comply with the requirements of ASTM C29 [22].

Size of coarse aggregate (stone) for all design mix (CP2 to CP6) was of maximum 10mm, except for design mix CP1 which used the stone size from 10 to 20mm.

3. CONCRETE MIX DESIGN

The experimental study was conducted by the authors at the Laboratory of Construction Testing and Inspection, National University of Civil Engineering in 2018. The target compressive cube strength of porous geopolymer concrete is 20MPa with a minimum water permeability rate of 4.0 mm/s. Thus, it is important to find a suitable aggregate composition and a mix design to achieve those targets.

3.1 Mix Design

The porous geopolymer concrete contains the same basic ingredients as the conventional GPC, but the proportion of the ingredients varies significantly. The major difference is the requirement of void content within the porous concrete, relating directly to the permeability. Therefore, the porous GPC uses little or no fine aggregate.

Aggregate proportion is chosen based on the test method in standard ASTM C29 [22]. This method allows to determine the bulk density value necessary for many methods of selecting proportions for concrete mixtures. Hence the mix design for porous geopolymer is determined by trial and errors with the recommendations from standard ACI 211.3R-02 [23].

Total volume of the binder paste plays an important role in concrete compressive strength. However, the more it increases, the more water permeability coefficient and porosity reduce. It is important to find a balance point to achieve the desired target. The total volume of the binder paste of geopolymer V_H includes *FA*, *BFS* and *W* (water) as shown in Eq. (1).

$$V_H = (FA + BFS)/2780 + \left[\left(W/(FA + BFS) \times (FA + BFS)/1000\right)\right](m^3) \quad (1)$$

The ratio of *W*/(*FA*+*BFS*) is the key factor to ensure compressive strength and porosity of porous geopolymer concrete. If this ratio is too high, bonding between geopolymer paste and aggregate will be reduced. If this ratio is low, workability of concrete cannot be achieved. As found by the authors [14,17], the ratio of *W*/(*FA*+*BFS*) should be in the range of 0.25 to 0.35, resulting in balance of the compressive strength and workability. This range is adopted in this study.

Six design mixes were tried and tested as shown in Table 2, in which the first mix was chosen as the control mix. The design mixes were then achieved by varying the content of FA, BFS and the amount of alkali activator (ACT). Mix CP2 was similar with CP1, except that stone size of CP1 was in the range of 10–20mm. From mixes CP2 to CP6, the coarse aggregate size was kept at 5 to 10mm. The ratio of *W*/(*FA*+*BFS*) was changed between CP2 and CP3, while the ratio of ACT/binder was varied between

CP3 and CP4. Fine aggregate was added in the design mix CP6 with an amount of 10% of coarse aggregate to attain the desired compressive strength.

Table 2 Porous geopolymer mix design

N°	W / (FA+BFS)	(FA+BFS) / Aggregate	Binder composition FA (kg)	Binder composition BFS (kg)	Water (kg)	Stone (kg)	Sand (kg)	ACT (kg)	ACT / Binder
CP1	0.30	0.25	132.5	265	119.3	1590	0	41.3	8%
CP2*	0.30	0.25	132.5	265	119.3	1590	0	41.3	8%
CP3	0.23	0.25	132.5	265	91.5	1590	0	39.1	8%
CP4	0.23	0.25	132.5	265	91.5	1590	0	49.1	10%
CP5	0.21	0.28	111.0	333	91.5	1590	0	53.5	10%
CP6	0.21	0.23	111.0	333	91.5	1590	160	53.5	10%

* CP2 mix is similar with CP1 but the stone size of CP1 is 10 to 20mm.

3.2 Casting and Curing

The specimens were cast in the 100x200 cylinders for compressive strength test and for water permeability test. For each design mix, three group of 3 samples were cast, including two groups to determine the compressive strength at 7 and 28 days (36 samples), one group for permeability test (18 samples).

It is noted that the solid activator AAM adopted in this study was dryly mixed with FA and BFS before being dissolved in water to create the binder. Thus, the manufacturing process of GPC is quite similar with that of OPC.

Fig.2 shows the casting procedure for porous geopolymer concrete. Firstly, the amount of all components was determined. Weighted coarse aggregate was mixed for one minute in a mechanical mixer. Seventy percent of water amount was then poured to the mixer and mixed for two minutes, so that the whole aggregate surface had enough water and humidity. Thirdly, the binder including FA, BFS and activator was dryly mixed outside and poured to the mixer. Thirty percent of water amount was then poured to the mixer and further mixed for 2 minutes to obtain a homogeneous blend.

The mixture was molded and tamped for compaction. The amount of concrete for one mold is divided into 3 times, about 1/3 of the mold height for each time, for ease of compaction.

For each group, three cylinders with dimension of 100x200mm were made for compressive strength measurement and for density, porosity and permeability study; and three prism samples with dimension of 150x150x600mm for flexural tensile test.

After removal from the molds, the porous GPC specimens were left air cured in the laboratory conditions (temperature of about 25^{0}C – 28^{o}C, air moisture of 80%) until the test date. The specimens after casting and demolding are shown in Figs.3,4.

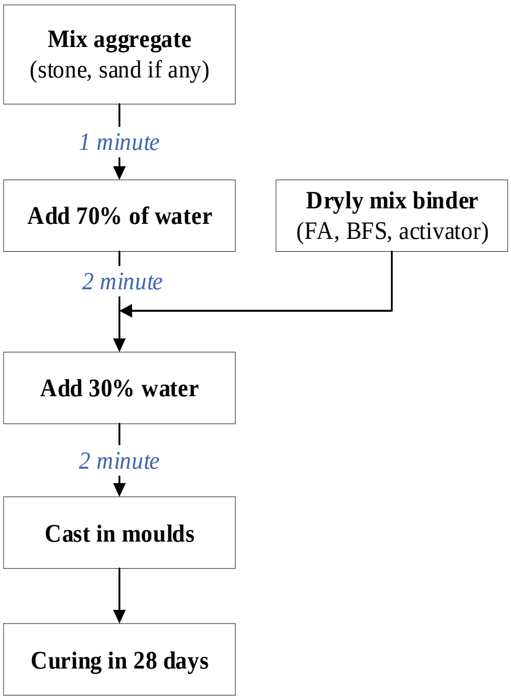

Fig.2 Casting procedure for porous GPC using solid activator

4. RESULTS AND DISCUSSIONS

4.1 Compressive Strength

The samples were tested after 7 and 28 days of casting. The cylinder strength of 100x200 samples was then converted to the cube strength of 150x150x150 samples by the conversion factor of 1.16 [24]. Development of compressive strength with time is shown in Fig. 5 where the values shown are the average value of each sample group, while Fig. 6 shows the typical failure mode of the samples.

Fig.3 Samples after casting

Fig.4 Samples after demoulding

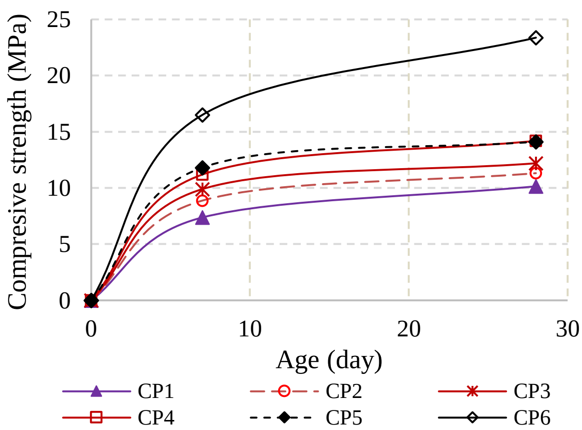

Fig.5 Compressive strength – time relationship

CP1, which used stone size of 10 to 20mm, only achieved the compressive strength at 28 days of 10.1MPa; while CP2 with stone size of 5 to 10mm can reached a value of 11.3MPa. It is greater than about 12% even though the other compositions were unchanged. Therefore, size of coarse aggregate affects considerably to the concrete compressive strength.

Fig.6 Sample after compression test

The water-to-binder ratio also has influence on the concrete compressive strength of porous GPC. The more this ratio increases, the more the compressive strength reduces. CP2 with the water/binder ratio of 0.3 has a strength of 11.3MPa, while CP3 with this ratio of 0.23 can reach a strength of 12.2MPa (an increment of 8%).

On the other hand, a different trend is observed for the activator-to-binder ratio. The more this ratio rises, the more the compressive strength increases. CP3 with 8% of ACT/binder attained a compressive strength at 28 days of 12.2MPa, while CP4 with 10% can achieve 14.2MPa, higher than 16.4%.

All the design mixes CP1 to CP5 are found to have a compressive strength lower the target value (20MPa), however the water permeability of those mixes is greater than the desired value (see section 3.4). Therefore, little fine aggregate was added in mix CP6 with an amount of 10% of coarse aggregate. It results in a compressive cube strength at 28 days of 23.4MPa, higher than the target value.

4.2 Flexural Tensile Strength

The samples for flexural tensile strength test were only cast with three design mixes CP4, CP5 and CP6, because these three mixes had achieved a relatively high compressive strength. The size of samples is 150x150x600, the testing procedure is complied with the standard TCVN 3119 [25]. The specimens and the sample after tensile test are shown in Figs.7,8.

After 28-day curing period, the porous GPC beams were tested for flexural tensile strength. The tests were conducted in accordance with the four-point loading of TCVN 3119 [25]. At failure, the sample was broken in the middle third of the span. The flexural tensile strength can be determined by Eq. (2).

$$R_{bt} = \gamma \frac{Pl}{ab^2} \quad (2)$$

where: P is the failure mode, in daN; l is the distance betwen two supports, in cm; a is sample width, in cm; b is the sample height, in cm;

Fig.7 Sample for flexural tensile test

Fig.8 Samples after tensile test

Fig.9 shows the results of flexural tensile strength with time. Mix CP6 can reach a tensile strength of 2.56MPa after 7 days, and 3.2MPa after 28 days; while the values are 2.14MPa and 2.41MPa for CP4, and 2.25MPa and 2.6MPa for CP5 after 7 and 28 days, respectively. It is found that the flexural tensile strength of porous geopolymer concrete increases rapidly with time. After 7 days, the strength has already reached about 80% to 88% of the strength at 28 days. It is an advantage of GPC when used to fabricate porous concrete.

4.3 Porosity

The total porosity can be determined following ASTM C1754 [26]. Firstly, the sample volume V_o was calculated. The samples were dried using the moderate temperature (40ºC) drying procedure in ASTM C1754 to measure the dry weight W_2 (g). The dried samples were then submerged into water to measure the sample weight under water W_1 (g) using test setup shown in Fig. 10. The porosity can be determined by Eq. (3), where ρ_w is water density (g/mm^3).

$$n = \left(1 - \frac{W_2 - W_1}{\rho_w V_0}\right) \times 100\% \quad (3)$$

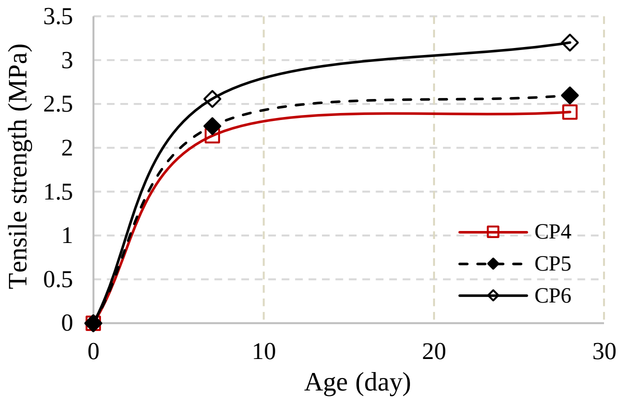

Fig.9 Flexural tensile strength – time relationship

The average values of porosity tests and water permeability tests are shown in Table 3.

Table 3 Porosity and water permeability

Nº	CP1	CP2	CP3	CP4	CP5	CP6
Porosity V_r (%)	24	18	17	18	16	11
Permeability (mm/s)	17.8	10.4	10.8	10.4	8.7	6.4

Mix CP1 had the lowest compressive strength (10.1MPa at 28 days), but the highest porosity, about 24%. It should be noted that mix CP1 used the largest stone size (10mm to 20mm), compared to all other mixes (only from 5 to 10mm). The porosity of mixes CP2 to CP4 was almost similar (18%), while that of CP6 is the lowest (only 11%). It is reasonable since fine aggregate was added in CP6 to be able to achieve the target compressive strength.

4.4 Water Permeability

Water permeability is the key parameter, referring to the ease for which water can flow through the porous concrete. The schematic of water permeability test is shown in Fig.11.

The samples were covered all round by a thin rubber sheet, enclosed in a mold and tightened with clamps to minimize any flow along the sides of the mold. The specimen was then connected to a vertical PVC pipe on both upper and lower sides. The apparatus was filled with water up to H_1, waiting to expel any air voids that may present in the porous concrete sample. Once the water level was stable, opened rapidly the water tap and measured the time. When the water level lowered down to H_2, recorded the time and finished the test. The water permeability can then be determined by Eq. (4).

$$K_{th} = \left(\frac{2.3 \times a \times L}{F \times t} \right) \times \log \frac{H_1}{H_2} \quad (cm/s) \tag{4}$$

where a is cross-sectional of pipe, cm^2; L is specimen length, cm; F is cross-section area of tested specimen, cm^2; t is time of water collection, corresponding to the time when the water column reduces from H_1 to H_2, s; H_1 is the initial length of water column (131cm); H_2 is the length of water column after permeability (88cm).

Fig.10 Setup to measure sample weight

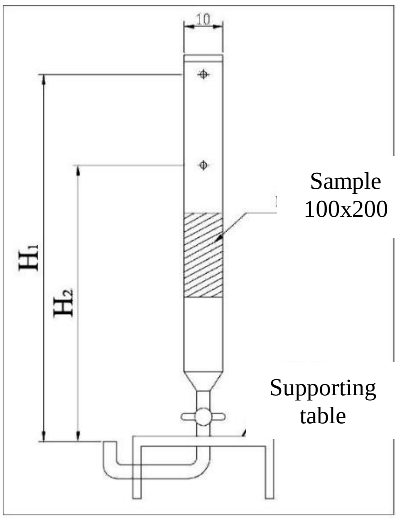

Fig.11 Schematic of water permeability test

Fig.12 shows that size of coarse aggregate affects significantly to water permeability. Mix CP1 with aggregate size of 10 to 20mm has water permeability of 17.8mm/s, while the permeability of other mixes using 5 to 10mm stone is only in the range of 6.4 to 10.4mm/s.

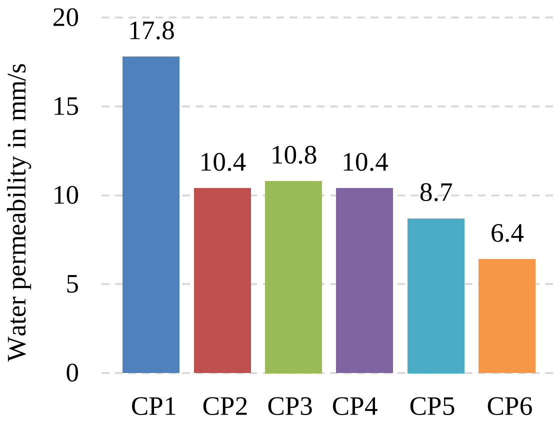

Fig.12 Water permeability of porous geopolymer concrete

When the water-to-binder ratio and the activator-to-binder ratio are changed, it only affects the compressive strength (mixes CP2, CP3, CP4), but the porosity and water permeability vary inconsiderably, around 10 mm/s. If sand is added into a design mix, the water permeability reduces significantly. As in mix CP6, the value is only 6.4mm/s.

5. CONCLUSIONS

The paper presents an experimental program on the porous concrete made of fly ash-based geopolymer with alkaline activators. This is an environmentally friendly and sustainable material since it does not use cement and allows water to go through. Few key parameters affecting the concrete compressive strength have been studied, including aggregate size, ratio of water over binder, concentration of the alkaline activator. The following conclusions can be withdrawn:

- The porous geopolymer concrete using local fly ash and blast furnace slag can achieve a compressive cube strength greater than 23MPa and a water permeability greater than 6.0 mm/s.
- The average values for the water permeability are in the range of 6.4mm/s to 17.8 mm/s depending on the mix design. These values were within the expected range found in the literature.
- Increasing coarse aggregate size increases the porosity and water permeability, however, lowers the compressive strength of porous

geopolymer concrete.

- Increasing the water-binder ratio reduces the compressive strength, but the porosity and water permeability are almost unchanged.
- Increasing the activator-binder ratio, the compressive strength increases, but not affecting the porosity and water permeability.
- Adding fine aggregate reduces the porosity and water permeability but increases the compressive strength of porous geopolymer concrete.

6. ACKNOWLEDGMENTS

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