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**ORIGINAL ARTICLE**

# Effect of Sodium Hydroxide Molarity on Compressive Strength of Porous Concrete Containing Fly Ash-based Geopolymer Binder

*[1]Mazizah Ezdiani Mohamad, [1]Affizah Affendy, [1]Ashraf A Razak, [2]Navid Ranjbar, [1]Azrul Zulwali Kifli, and [1]Lim Yong Tat

[1]Centre of Research for Innovation and Sustainable Development (CRISD), School of Engineering and Technology, University of Technology Sarawak, 96000 Sibu, Sarawak, Malaysia
[2]Department of Mechanical Engineering, Technical University of Denmark, 2800, Kgs, Lyngby, Denmark

**ABSTRACT** - Porous concrete (PC) road surfaces are used in urban areas to mitigate the environmental impact of conventional roads on water and air, and to increase driver safety. To evaluate the recycling of coal-power plant waste, the properties of porous concrete with fly ash-based geopolymers were investigated. This study was conducted to investigate the effect of different molarities of sodium hydroxide (NaOH) on the compressive strength of porous concrete containing fly ash-based geopolymers. The alkaline activators used in this research are sodium hydroxide (NaOH) and sodium silicate ($Na_2SiO_3$). The ratio of $Na_2SiO_3$ to NaOH in each case used is 2.5. For comparison with a mixture containing a geopolymer binder with fly ash, a control mixture was prepared with ordinary Portland cement (OPC). Different geopolymer mixes were used with NaOH concentrations of 12 M, 14 M and 16 M. It is found that as the molarity increases the compressive strength of porous concrete increases. The results showed that the fly ash-based geopolymer was used to produce geopolymer porous concrete with compressive strengths ranging from 5.8 to 13.80 MPa for 28 days and achieved the optimum water permeability ranging from 2 to 30 mm/s.

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## INTRODUCTION

The global construction sector has grown at an unprecedented pace as a result of urbanisation, posing a major challenge to climate change mitigation efforts. Malaysia's climate is influenced by the southwest monsoon (April-October) and the northwest monsoon (October-February). [1]. The rainfall in Malaysia is 990 billion cubic metres (bcm) [1]. Urban areas are therefore particularly vulnerable to sudden flooding. In addition, urbanisation is increasing, making it more difficult to control runoff.

Porous or permeable concrete pavements are an alternative to rigid conventional concrete pavements [2];[3];[4];[5]. Rainwater can percolate into the ground through porous concrete, which minimises stormwater runoff and contributes to groundwater recharge. Porous concrete is a lightweight concrete with a void ratio between 14 and 31 percent. The use of porous concrete has expanded due to its advantages in terms of environmental protection and environmental concerns [2]. Voids of porous concrete result from the removal of fine aggregates [2]. Binder material, coarse aggregate, little or no fine aggregate, water, and additives, if necessary, make up the porous concrete mix. Porous concrete typically uses Portland cement as a binder, and research into the use of other binders, such as geopolymer binders, is currently limited.

Palomo et al [6] described two alternative models for the activation of fly ash or other by-products. In the first model, a low to mild concentration of an alkaline solution is used to activate the silicon and calcium. The hydration produces a calcium silicate hydrate (C-S-H), which is considered the main product of the reaction. In contrast, the material used in the second model is mainly silicon and aluminium and is activated by a very alkaline solution. Polymerization is the chemical process in this situation. The reaction

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*Corresponding Author: Mazizah Ezdiani Mohamad. University of Technology Sarawak (UTS), email: mazizah@uts.edu.my of aluminosilicate-containing materials with alkalis to form an inorganic polymer binder is known as geopolymer concrete [4];[7];[8];[9]. Sodium or potassium-based solutions are commonly used in alkali liquids [10]. Clays, metakaolin, fly ash, bottom ash, slag, and rice husk ash are examples of silicon (Si) and aluminium (Al)-rich source materials generated from geological sources or by-products like clays, metakaolin, fly ash, bottom ash, and slag. [8];[11];[12]. Due to their low cost and extensive availability, industrial waste materials such as fly ash are commonly employed as a source of aluminosilicate for the manufacturing of geopolymer concrete [10]. When compared to OPC, the geopolymer binder can save up to 80% of CO2 by efficiently utilising industrial by-products. Alkali liquids and source materials are the two main components of geopolymer binders. Geopolymer binder as concrete binder, which is widely used in normal concrete, can be used in porous concrete without using OPC, and the role of OPC can be completely replaced by activated fly ash-based geopolymer.

Previous research by George and Binu [13] investigated the effect of different ratios of $Na_2SiO_3$ (sodium silicate)/NaOH (sodium hydroxide) at 2.0, 2.5 and 3.0 and different molarities of NaOH (8M,10M,12M,14M,16M and 18M) on compressive strength in geopolymer concrete. The results have shown that 16M NaOH gives good compressive strength when $SiO_2/Na_2O$ in $Na_2SiO_3$ solution is between 2.00 and 2.40 and $Na_2SiO_3/NaOH=2.5$.

Therefore, this research focuses on the effect of sodium hydroxide in alkaline solution molarity on compressive strength of geopolymer porous concrete at $Na_2SiO_3/NaOH=2.5$. The porous geopolymer concrete's physical and mechanical properties were investigated. The information gathered will aid in the future usage of fly ash-based geopolymer in the creation of porous concrete, reducing cement consumption and reducing environmental concerns.

## MATERIALS AND METHODOLOGY

In this study, coarse aggregates of sizes 5 mm to 10 mm were used to produce the porous concrete as shown in Figure 1. Before mixing the concrete, the physical or mineralogical properties of the aggregates are determined to produce a suitable mix. Shape, texture, size gradation, moisture content, and specific gravity are examples of aggregate properties. This is to ensure that the strength, workability and toughness of the porous concrete are determined by these properties along with the water and cementitious material ratio. For this research, the properties of aggregates are determined by conducting the water absorption test, Los Angeles abrasion test, flakiness and elongation index test and Aggregate Crushing Value (ACV) test. The aggregates' physical properties are shown in Table 1.

As shown in Figure 2, the fly ash (FA) was obtained from Mukah power plant station in Mukah district of Sarawak, Malaysia. The chemical composition of the FA used in this study is shown in Table 2. A solution of sodium hydroxide (NaOH) and sodium silicate was used as the alkaline activator ($Na_2SiO_3$).

**Figure 1.** Aggregates

**Table 1.** Aggregates Properties

| Aggregate size (mm) | Water absorption (%) | Flakiness Index (%) | Elongation Index (%) | ACV Value (%) | Abrasion value (%) |
|---|---|---|---|---|---|
| 5 – 10 | 0.5 | 14.3 | 30.6 | 18.67 | 75.34 |

**Table 2.** Fly ash sample chemical composition

| **Elements** | **Fly As Mukah, Sarawak (%)** |
|---|---|
| $SiO_2$ | 45.33 |
| $Al_2O_3$ | 18.11 |
| $Fe_2O_3$ | 8.89 |
| CaO | 12.42 |
| $TiO_2$ | 0.67 |
| $K_2O$ | 1.86 |
| $SO_3$ | 1.69 |
| MgO | 5.77 |
| $TiO_2$ | 0.67 |
| $P_2O_5$ | 0.20 |
| Na2O | 4.89 |
| SrO | 0.17 |
| BaO | 0.00 |

**Figure 2.** Fly ash

## Geopolymer Porous Concrete Mix Proportions, Mixing and Casting

The NaOH in pellets form was dissolved in 1000 ml of distilled water to produce NaOH solution. The process of dissolving sodium hydroxide is involving some heat. The concentration of NaOH was used in this study is 12M, 14M and 16M. The ratio of sodium silicate ($Na_2SiO_3$) to sodium hydroxide (NaOH) was constant at 2.5. The ratio of alkaline solution to FA was 0.5 to form a geopolymer binder which is used to bind the aggregates. The ratio of geopolymer binder to coarse aggregate was fixed to 1:3 to form the geopolymer porous concrete. The mix proportions of normal porous concrete and geopolymer porous concrete are shown in Table 3. There were a total of 24 (twenty four) specimens were casted in this study.

The geopolymer porous concrete was done in a concrete workshop. FA was mixed with NaOH for 5 min in a pan type mixer. Coarse aggregate was then incorporated and mixed for 5 more minutes. This was followed by the addition of $Na_2SiO_3$ with a final mixing of 1 min. After being mixed, the GPC was placed into cylinder moulds with size of 100 mm in diameter and 200 mm in height. The mixed is poured into three layers and was compacted with 25 blows for each layer using steel compaction weight as shown in Figure 3. The specimens were wrapped with a thin plastic sheet to minimize moisture loss and allowed to stand for 1 h at 25°C as shown in Figure 4. The GPC specimens were demoulded as shown in Figure 5 and was then cured at 60°C for 48 h in the oven and stored in the concrete workshop at room temperature until 28 days of age.

**Table 3.** Mix proportions of porous concrete

| **Specimens** | **OPC (kg/m$^3$)** | **FA (kg/m$^3$)** | **Water to cement ratio** | **Alkaline Activator (AA)** | | **AA to FA ratio** | **Binder to aggregate ratio** | **Normal Aggregate (kg/m$^3$)** | **Number of specimens** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | NaOH concentration (Molarity, M) | $Na_2SiO_3$ to NaOH ratio | | | | 7 days | 28 days |
| PC | 380.97 | - | 0.5 | - | - | - | 1:3 | 1336.73 | 3 | 3 |
| GPC1 | - | 403.05 | - | 12 | 2.5 | 0.5 | 1:3 | 1336.73 | 3 | 3 |
| GPC2 | - | 403.05 | - | 14 | 2.5 | 0.5 | 1:3 | 1336.73 | 3 | 3 |
| GPC3 | - | 403.05 | - | 16 | 2.5 | 0.5 | 1:3 | 1336.73 | 3 | 3 |
| | Total number of specimens | | | | | | | | 24 | |

**Figure 3.** Mix of porous concrete compacted with compaction weight

**Figure 4.** The mould is covered with thin plastic sheet wrap to prevent moisture loss

**Figure 5.** Geopolymer porous concrete specimens

## Testing Detail

### Porosity and Water Permeability

The porosity of porous concrete is conducted referred to ASTM C1754/C1754-12 [14]. The samples are weighed before it was immersed in the water. The weight of dry specimens is recorded and weighed again after it is immersed in the water for 30 minutes. The porosity of porous concrete can be determined by using the Eq. (1).

$$P = (1 - \frac{W_2 - W_1}{V \cdot \rho_w}) \times 100 \tag{1}$$

Where,
P = Porosity of porous concrete (%)
$W_1$ = Weight of porous concrete (kg)
$W_2$ = Weight of the water saturated specimen (kg)
$\rho_1$ = Density of water (kg/$m^3$)
$V$ = Volume of the specimen ($m^3$)

After the porosity test, the cylindrical specimens were inserted into the PVC pipe and tightened with round clamps. The water permeability of GPC was tested using the constant head method [15], [16]. The experimental setup is shown in Figure 3. The permeability test was performed when a uniform flow was achieved. The coefficients of water permeability (k) were the average of three samples and were calculated according to Darcy's law as shown in Equation 2:

$$K = \frac{QL}{HAt} \tag{2}$$

Where,
K = the coefficient of water permeability (cm/s)
Q = the quantity of water collected ($cm^3$) over time t (s)
L = the length of specimen (cm)
H = the water head (cm)
A = the cross-sectional area of specimen (cm2)

## Compressive Strength

Figure 7 shows the compressive strength tests [17] performed at 7 and 28 days of life. Sulfur capping compound was applied to both ends of compression test cylinders. The strengths listed were the average of three tests.

**Figure 7.** Compressive Strength Test

## Microstructure Observation

Scanning electron microscopy (SEM) is used to study the bonding of geopolymer with aggregates, as shown in Figure 8 below. Particles for magnification are selected based on their size and surface roughness of aggregates. Since the physical properties of aggregates can affect the performance of porous geopolymer concrete, they need to be studied. The porosity of the aggregate and the bonding of the geopolymer binder between the aggregates can be clearly seen under the microscope.

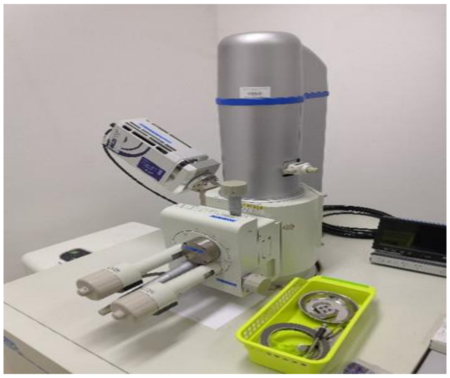


**Figure 8.** Scanning Electron Microscopy (SEM)

## RESULTS AND DISCUSSION

### Porosity

The results of the porosity and water permeability coefficients of GPC are summarized in Table 3. Based on the Table 4 and Figure 9, the GPC 16M has the highest percentage of porosity among the three GPC samples. GPC 16M has the highest porosity of 22.64% and GPC 12M has the smallest porosity of 16.21%. GPC 12M and GPC 14M has achieved the porosity ranged stated by Rangelov *et al.* [18] which the porosity ranged from 10.2% to 21.0 % for small porous concrete. GPC 16M has exceeds the porosity limit stated by Rangelov *et al.* [18]. By referring to the research by Huang [19], it is acceptable that the porosity ranged from 20% to 30%. The mix that is made from geopolymer binder could still achieve the porosity and acceptable range of permeability rate. The presence of sodium silicate in a mixture tends to produce porous geopolymer concrete with large pore sizes. GPC 16M has higher alkaline content so it has higher porosity than porous geopolymer concrete with low alkaline like GPC 12M and GPC 14M. If the alkaline solution added to the mixture is higher, the water absorption also increases. The low porosity of GPC 12M is still in the range. The typical range of porosity of porous concrete lies in the range 18% to 30%. The low porosity might occur due to the interconnected voids between the particles.

**Table 4.** Porosity and water permeability coefficient of GPC

| Specimen | Porosity (%) | Water Permeability Rate (mm/s) |
|---|---|---|
| Control Mix | 25.88 | 25.10 |
| GPC 12 M | 16.21 | 19.02 |
| GPC 14 M | 18.89 | 16.98 |
| GPC 16 M | 22.64 | 18.77 |

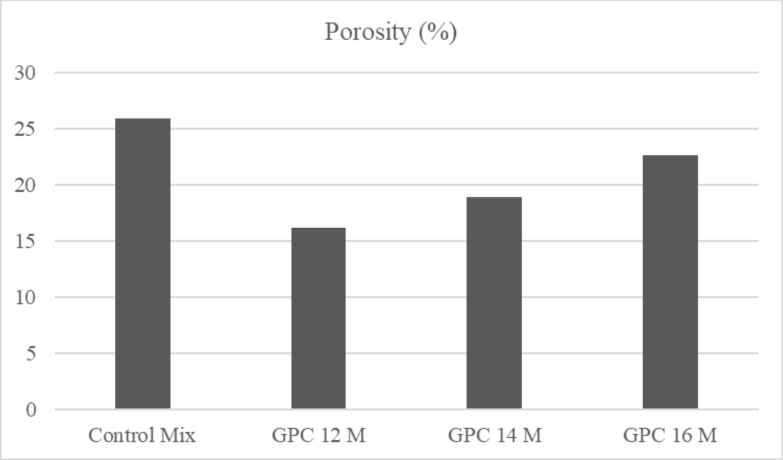


**Figure 9.** Porosity of Porous Concrete

### Water Permeability

The falling head method is used to determine the water permeability of porous geopolymer concrete. The purpose of the water permeability test is to determine the water permeability coefficients, K. Before the compressive strength test, the water permeability of porous geopolymer concrete is tested. Three porous concrete specimens for each molarity were chosen to conduct the test and the water permeability mean is calculated. There are three different interval time which is 200 mm to 150 mm, 200 to 100 mm and 200 mm to 50 mm.

Based on Figure 10, GPC 12M has the highest water permeability rate while GPC 14M has the lowest water permeability rate. The permeability has relation with compacting method. The water permeability rate of GPC 12M, GPC 14M and GPC 16M are almost the same due to the viscosity of the alkaline solution. A higher concentration of NaOH will increase the viscosity [20]. The alkaline solution has a higher viscosity than normal water. The control mix managed to achieved 25.10 mm/s of water permeability rate. During the mixing of the geopolymer paste, the geopolymer paste became very stiff and dry with the increase of time.

Other than that, the compaction method affects the water permeability rate of all the GPC samples. Due to the compaction, the interconnected voids became smaller and the space between the aggregates and the binder decreased. Moreover, the small voids will prevent the channel of water to flow through the voids of porous concrete. The binder to aggregates ratio used in this research is 1:3 shows that a large amount of binder is used. Large amount of binder content can cause the voids filled with the binder. It is preferable to have high water permeability rate of porous concrete that can allow the movement of water especially during a heavy rain occurs to prevent flood. Huang [19] stated that the acceptable permeability range of porous concrete implies between 10 mm/s to 20 mm/s which acceptable enough for construction of drainage layer. In previous research conducted by Joshi & Dave [21], the water permeability of the porous concrete is generally 2 to 30 mm/s. In addition, the mixture of GPC itself can lead to a reduction of permeability with adding the binder to aggregates ratio.

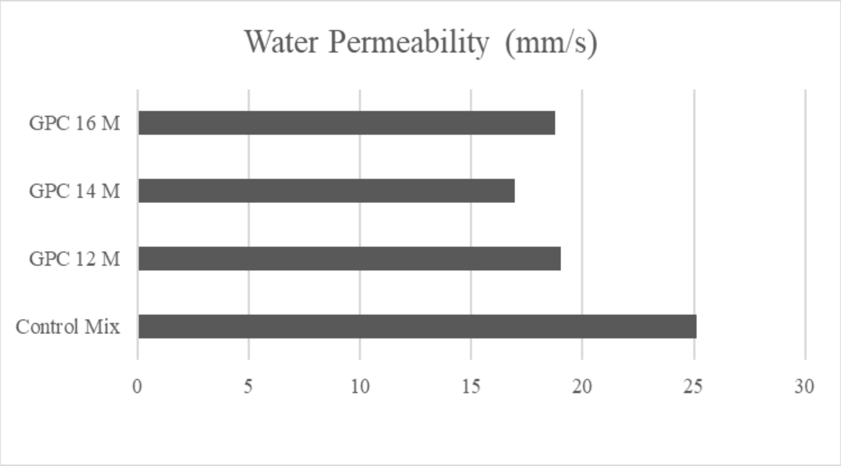


**Figure 10.** Water Permeability of Porous Concrete

## Compressive strength

Compressive strength testing is used to determine the strength of concrete by casting specimens and testing them under a compressive force. Three specimens were prepared from GPC 12M, GPC 14M and GPC 16M to investigate the effect of sodium hydroxide concentration on compressive strength. The test is conducted after 7 days and 28 days age of concrete. The average compressive strength was computed from these samples. For further research, the crushed samples were taken for microscopic analysis. The experimental results of compressive strength for each sample for 7-days and 28-days are shown in the Table 5, Table 6, Figure 11 and Figure 12. The density of porous concrete is shown in Table 7.

For 7 days and 28 days, the control mix and GPC 16M show nearly identical strength values. The strength of the binder and the correct binding of the aggregates and the binder determine the compressive strength of porous geopolymer concrete. A higher concentration of sodium hydroxide increases the solution's viscosity. It is observed that the porous concrete containing geopolymer binder of fly ash were found to be more consistent and the flow ability was reduced.

The specimens with a high concentration of sodium hydroxide produced higher compressive strength. This is due the fly ash alkali activation increased. The dissolution of fly ash is helped by the presence of sodium hydroxide. A higher concentration of sodium hydroxide can lead to the formation of binder that can increase the compressive strength.

From Table 5 and Table 6, it can be seen that the compressive strength of the geopolymer porous concrete is lower than that of the normal porous concrete. This is because the geopolymer porous concrete needs to be cured in a water bath at a constant temperature for at least 6 to 24 hours after demolding. This can increase the strength of the geopolymer binder made of fly ash, because anything containing fly ash can accelerate the strength increase. Muhammad [22] mentioned in his study that curing temperature and duration are important to achieve higher compressive strength. He found that the best curing temperature for geopolymer concrete is 80°C. The study conducted by Canpolat and Naik [23] confirmed that the curing temperature should not exceed 80°C because it may have a negative effect on the properties of the geopolymer. After the specimens have been heat cured for 24 hours, they are then cured under ambient conditions. After the normal curing process, the geopolymer porous concrete is removed and stored at room temperature until the day of testing.

The geopolymer porous concrete and normal porous concrete has the same ratio of mixture. The flat aggregates and flaky aggregates as shown in Figure 13 is the example that will cause lower compact ability and can results higher range of breakage. Difference in aggregates shape results to poor performance and reduced the strength of the concrete. The flat and flaky aggregates seems to refrain the other aggregates to pack together or interlocking each other. The presence of voids will leads to the failure of the concrete and prevent the porous concrete to achieve a maximum compressive strength. It is recommended that the porous concrete mix have a high packing density. Figure 14 below shows the diagram of maximum packing of aggregates. High packing density can minimized the amount of binder or paste that needed to fill the voids. Moreover, the presence of gap between the aggregates makes the particles to collide with each other because there are no particle interlocking action [24].

**Table 5.** Compressive strength test results of 7-days specimens

| **Specimen** | **Sample** | **Compressive Strength (N/mm²)** 7 days Strength (N/mm²) | **Compressive Strength (N/mm²)** Average Strength (N/mm²) |
|---|---|---|---|
| Control Mix | 1 | 8.5 | 8.4 |
| | 2 | 8.6 | |
| | 3 | 8.2 | |
| GPC 12 M | 1 | 6.1 | 6.3 |
| | 2 | 6.5 | |
| | 3 | 6.3 | |
| GPC 14 M | 1 | 6.2 | 6.9 |
| | 2 | 6.7 | |
| | 3 | 8.0 | |
| GPC 16 M | 1 | 7.1 | 7.4 |
| | 2 | 8.2 | |
| | 3 | 7.0 | |

**Table 6.** Compressive strength test results of 28-days specimens

| **Specimen** | **Sample** | **Compressive Strength (N/mm²)** 28 days Strength (N/mm²) | **Compressive Strength (N/mm²)** Average Strength (N/mm²) |
|---|---|---|---|
| Control Mix | 1 | 10.8 | 9.8 |
| | 2 | 8.6 | |
| | 3 | 9.9 | |
| GPC 12 M | 1 | 7.4 | 7.3 |
| | 2 | 7.5 | |
| | 3 | 7.0 | |
| GPC 14 M | 1 | 8.0 | 7.6 |
| | 2 | 7.6 | |
| | 3 | 7.3 | |
| GPC 16 M | 1 | 8.4 | 8.0 |
| | 2 | 8.2 | |
| | 3 | 7.9 | |

**Table 7.** Density of porous concrete

| **Specimen** | **Average Weight (kg)** | **Density (kg/m³)** |
|---|---|---|
| Control Mix | 2.620 | 1667.94 |
| GPC 12M | 3.020 | 1922.59 |
| GPC 14M | 2.493 | 1587.09 |
| GPC 16M | 2.567 | 1634.20 |

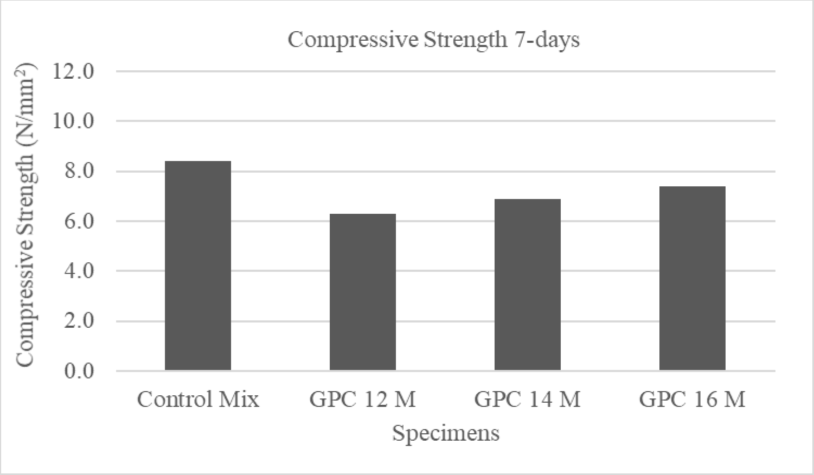


**Figure 11.** Compressive strength of porous concrete chart at 7 days

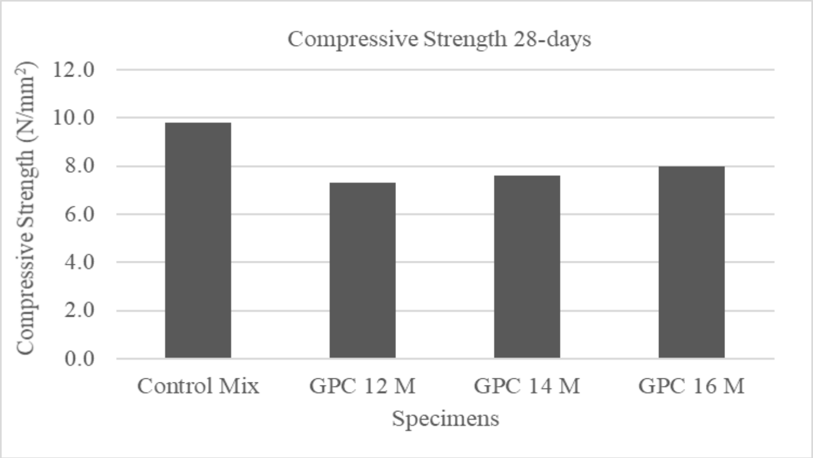
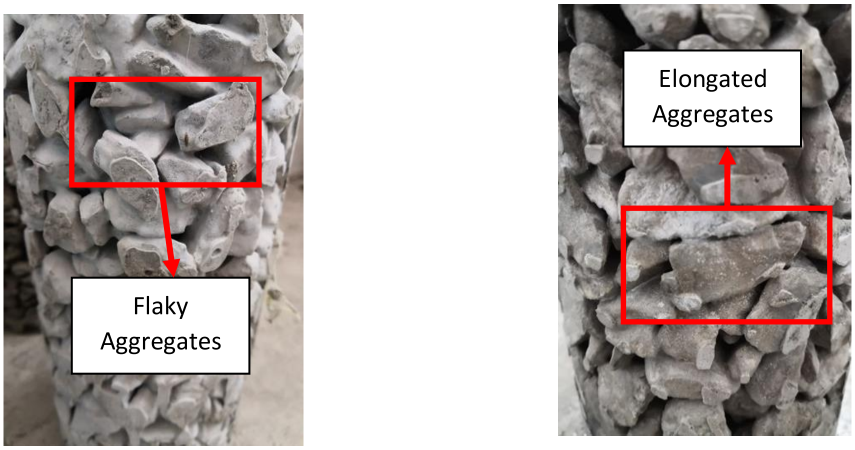


**Figure 12.** Compressive strength of porous concrete chart at 28 days



(a) (b)

**Figure 13.** (a) Normal porous concrete with voids and presence of flaky aggregates; (b) Geopolymer porous concrete with voids and presence of elongated aggregates

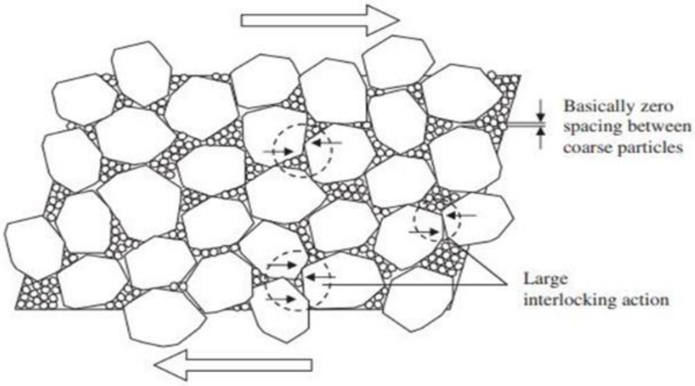


**Figure 14** SEM Micrograph of Geopolymer Binder Bonding with Aggregate [24]

## Microstructure

The highest compressive strength result of the concrete sample was taken at the age of 28 days for a microstructure of normal porous concrete and porous concrete containing geopolymer binder of fly ash. The samples for microstructure are taken from the crushed samples. The result of SEM test for both specimens can be seen from Figure 16 to 17 below.

## Normal Porous Concrete

Based on the Figure 15 below, the surface of the aggregates is very smooth. The smooth surface indicates that the bonding between the cement paste and the aggregates is poor. The poor bonding of cement paste and the aggregates can results in lower compressive strength. Poor bonding between aggregate and cement paste may also be caused by a low ratio of binder to aggregate.

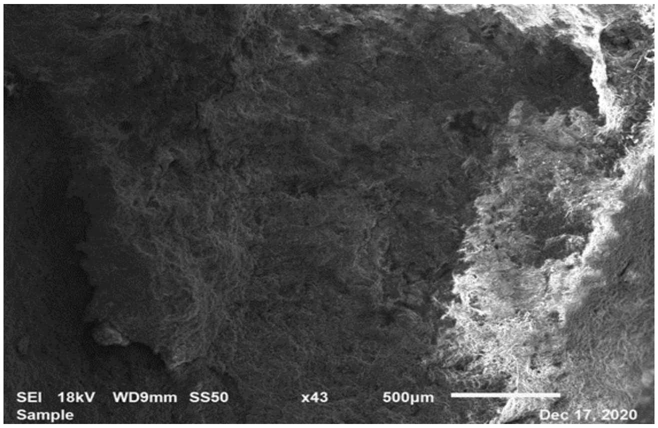


**Figure 15.** SEM Micrograph of Cement Paste Bonding with Aggregate

## Geopolymer Porous Concrete

The bonding between the geopolymer paste and the aggregates also can be defined as smooth because the geopolymer has viscous and cohesive paste. The enhanced dissolution of the fly ash particles and the alkaline compound has created a bond between the two elements. From the review on the SEM observation in Figure 16, the texture of the geopolymer paste containing fly ash was denser and compact.

The microstructure of geopolymer binder of fly ash is presented in Figure 17 below. The microstructure of the geopolymer binder of fly ash has the similar characteristics from similar observations as M. Olivia [25]. The occurrence of microcracks in the microstructure could be the result of mechanical damage during the sample preparation for SEM. The perfect sphere of fly ash indicates the unreacted fly ash. The unreacted alkali might be due to the dissolution of the fly ash that is very slow because it should be hardened in an ambient heat curing and not room temperature curing.

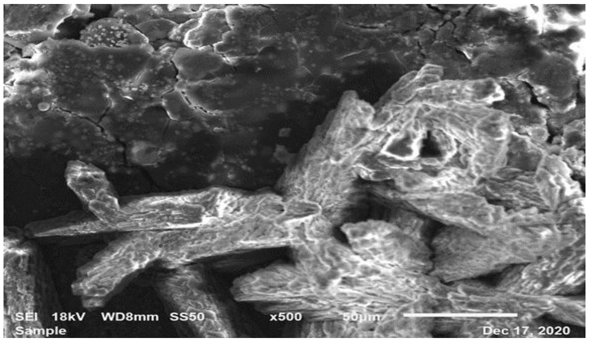


**Figure 16.** SEM Micrograph of Geopolymer Binder Bonding with Aggregate

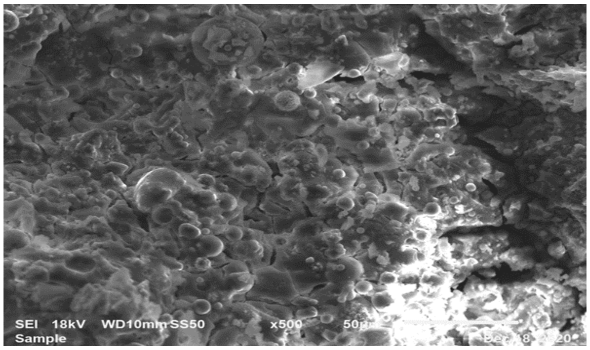


**Figure 17.** SEM Micrograph of Geopolymer Binder of Geopolymer Porous Concrete

## CONCLUSION

The effect of sodium hydroxide molarity on the compressive strength of GPC was studied experimentally. Specimens were prepared in three different sodium hydroxide molarities. The following are the main conclusions of the study:

(a) The compressive strength of geopolymer porous concrete is increased by increasing the molarity of the sodium hydroxide solution. However, the compressive strength of the geopolymer porous concrete produced is lower than that of typical porous concrete.
(b) The compressive strength of both normal porous concrete and geopolymer porous concrete varies from 5.8 MPa to 13.80 MPa, which is acceptable for road pavement construction.
(c) The water permeability rate of the GPC samples is within the acceptable range between 2 mm/s and 30 mm/s.
(d) The porosity of the GPC samples is within the acceptable values for porous concrete. The lowest porosity of GPC at 12 M NaOH could be due to the fact that the bond between the aggregates does not allow water to pass through and the geopolymer porous concrete is filled with too much binder.
(e) The shape of the aggregates is important to prevent the formation of cavities. Flaky and elongated aggregates can affect the quality of compaction because they prevent good interlocking between aggregates. When the aggregates are properly compacted, there are no voids.

The use of geopolymer porous concrete is considered acceptable in the construction industry because it can reduce by years the disposal of fly ash, which requires high costs and large areas of land. The geopolymer porous concrete is made with cement-free binder. It is also important to minimize the use of ordinary Portland cement (OPC) in construction because OPC tends to release an excessive amount of carbon dioxide into the atmosphere and increase the greenhouse effect. Therefore, the use of geopolymers containing fly ash is energy-saving and environmentally friendly.

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