



Semarak International Journal of Material Research

Journal homepage:
<https://semarakilmu.my/index.php/sijmr/index>
ISSN: 3083-8908



Mechanical and Microstructure Properties of Porous Geopolymer Concrete Based on Umeanyar Slate Stone Powder

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ARTICLE INFO

Article history:

Received 1 December 2025

Received in revised form 14 January 2026

Accepted 2 February 2026

Available online 18 February 2026

Keywords:

Slate stone powder; compressive strength; split tensile strength; microstructure; porous geopolymer concrete

ABSTRACT

The growth of city areas has led to a reduction in places where rainwater and other water sources can be collected, largely due to the expanding surfaces covered in concrete. One potential answer to this issue is the use of permeable concrete. To minimize the amount of cement used in permeable concrete, this study explores the application of geopolymer materials in creating porous geopolymer concrete. The geopolymer binder utilized consists of slate stone powder waste sourced from Umeanyar Bali, along with an alkali activator (NaOH and Na₂SiO₃). Various proportions of geopolymer binder were tested to assess the mechanical features and microstructure of the porous geopolymer concrete. All samples were evaluated at the ages of 7 days and 28 days. The mechanical properties assessed include tests for compressive strength, splitting tensile strength, porosity, and permeability according to ACI 522 R10. Simultaneously, the microstructure analysis used X-ray Diffraction (XRD). The peak results for compressive strength reached 13.67 MPa, splitting tensile strength was 1.87 MPa, porosity measured at 18.67%, and permeability was recorded at 8.58 mm/s. These mechanical testing outcomes fulfill the standards outlined in the regulations and can serve as an environmentally friendly construction material.

1. Introduction

The development of urban settlements has resulted in a reduction in rainwater and other water source catchment areas due to the increasing area covered by pavement. One effort to reduce rainwater surface runoff and increase infiltration into the soil is the use of porous concrete technology. Porous concrete is a uncommon sort of concrete made from a blend of coarse total, portland cement, water, and the nearness or nonappearance of fine total [1]. Portland cement, as one of the constituent elements of porous concrete requires, a large amount of energy in its production, because the process involves heating at temperatures reaching 1500°C [2-10]. The essential components of cement comprise of limestone (CaCO), silica sand or clay (SiO and AlO and

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press oxide (FeO). These crude materials at that point go through a warming and calcination prepare until carbon dioxide (CO₂) gas is discharged, which is one of the fundamental donors to nursery gas outflows in the environment. In recent years, total global cement production has reached 4 billion tons annually, which indicates that around 4 billion tons of CO₂ gas is released into the atmosphere every year [11-15]. Since these noteworthy CO₂ gas outflows have a negative affect on the environment, one moderation step that can be taken is to diminish the utilize of cement in the concrete-making handle.

A Geopolymer binder is a type of geosynthetic binder that utilizes precursors (raw materials) other than cement and is added with an alkali activator. The concept of geopolymer was to begin with presented by Davidovits in 1978, who found the presence of polymerization authoritative between soluble base activator and fundamental materials comprising of fly fiery remains and rice husk cinder [5]. Research on geopolymers continues to develop with the utilize of fly ash with the addition of several other precursor materials, such as polypropylene fiber, pumice soil, and silica fume [12,16,17].

A few considers on porous geopolymer concrete have been conducted utilizing fly ash and GGBS (Ground Granulated Blast Furnace Slag) as precursors [18-21]. However, no studies have used Umeanyar slate stone ash as a precursor, a local Balinese material. This study will use slate stone ash waste as a precursor material in porous geopolymer concrete innovations, plus an alkali activator. The chemical composition of slate stone ash consists of SiO₂ (49%), AlO (11%), Fe₂O (22.35%), CaO (11.2%), and other metals amounting to 6.5% [5]. From the processing of this stone crushing industry, stone ash is produced at around 25% - 30% of the volume of slate stone processed. Piles of this stone ash are very abundant around industrial locations and are allowed to pile up or even form mountains so that they can disturb the nearby environment (Figure 3). With a chemical composition of silica and alumina >50%, slate ash waste can be utilized as a substitute for fine total and filler in typical concrete [13,22]. In addition, this slate stone ash waste has the potential to be used as a precursor in geopolymer binders [4,5,14,23]. For the next stage, this research will develop the use of Umeanyar slate stone ash waste as a geopolymer binder in porous geopolymer concrete towards sustainable green construction materials.

2. Methodology

2.1 Materials

Umeanyar slate stone powder (USSP) was used as the raw material (Fig.1). Figure 2 and Table 1 present the microstructure of USSP. X-ray diffraction (XRD) analysis and microstructure of USSP are available in previous research [5]. A combination of sodium hydroxide (NH) and sodium silicate (NS) was chosen as the alkali activator. A 12 molar NH arrangement was arranged by dissolving 95–98% immaculate NH in refined water one day some time recently blending. The coarse aggregate used was crushed stone with a maximum nominal size of 12 mm and a silt content of less than 1%, as required by SNI [24].



Fig. 1. Umeanyar slate stone powder (USSP)

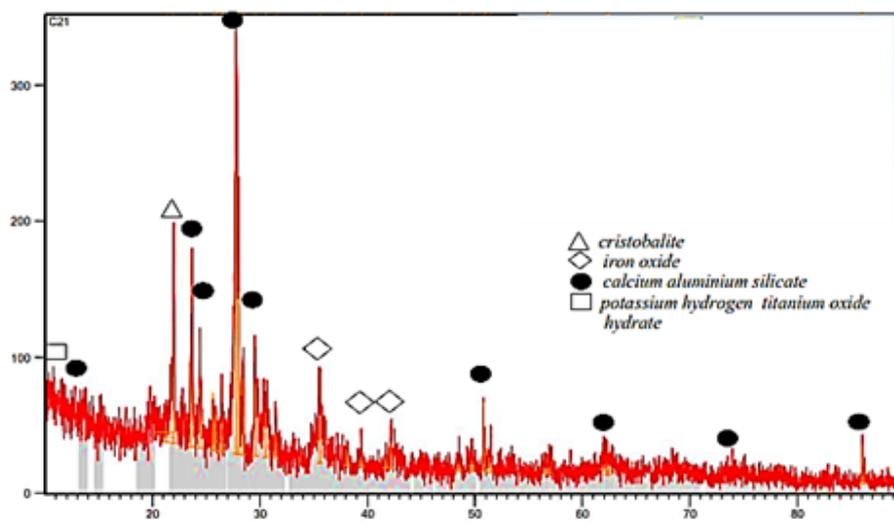


Fig. 2. XRD of Umeanyar slate stone powder (USSP)

Table 1

XRF of Umeanyar slatestone powder (USSP)

Compound	Percentage (%)
Al ₂ O ₃	11,00
SiO ₂	49,00
K ₂ O	3,37
CaO	11,20
TiO ₂	2,06
V ₂ O ₅	0,03
MnO	0,55
Fe ₂ O ₃	22,35
CuO	0,14
ZnO	0,04
Rb ₂ O	0,04
SrO	0,17
ZrO ₂	0,12
BaO	0,20
Re ₂ O ₇	0,04

2.2 Methods and Preparation

The molarities of the binder, air/binder, alkali/binder, and NH solution were 450-650 kg/m, 2.0, and 12 M, respectively, in all mix designs. The volumetric technique served as the foundation for the

design of the concrete mix. The ideal NS/NH solution was determined to be 2.0 in this investigation based on prior studies [20,25]. The mix designs and specimen labels are displayed in Table 2.

Table 2
 Mix design (kg/m³)

Code	Coarse agregate	Binder	NS/NH
B1	1475	450	2.0
B2	1475	500	2.0
B3	1475	550	2.0
B4	1475	600	2.0
B5	1475	650	2.0

The binder and aggregate were pre-mixed for three minutes to accomplish a homogeneous blend. The NH and NS arrangements were blended for 30 minutes some time recently being included. New concrete was set in round and hollow molds with a breadth of 10 cm and a tallness of 20 cm for physical and mechanical property testing. Each example was arranged by pouring the blend into three layers and tamping 25 times. In this ponder, after molding, the examples were set in an broiler at 70°C for one day to accomplish a tall degree of geopolymerization. After 24 hours, the examples were evacuated and cured at room temperature until the 7- and 28-day test ages.

3. Results and Discussion

3.1 Density Test

The density values of porous geopolymer concrete for various binder amounts are shown in Figures 3, Figure 4, and Table 3. As the amount of binder material goes up, the density keeps increasing all the time. Density also increases steadily with age, from 7 days to 28 days. To find out the density or theoretical content weight of the test object, you can divide its weight by its volume [26]. The density of the porous geopolymer concrete sample can be calculated using Equation 1:

$$W_p = \frac{W_r}{V}$$

(1)

by:

Wp = density (g/cm³)

Wr = weight of test object (g)

V = volume of the test object (cm³)

The samples were tested at 7 days and 28 days old, and the results are shown in Figure 3 and Table 3. Based on the data in Table 3, a graph showing the density of the porous geopolymer concrete at 7 days and 28 days was created (Figure 4).

The density value increases due to the increasing porous geopolymer concrete content. This occurs in sample B5, which has the highest amount of porous geopolymer concrete compared to B1-B4 (Table 2). Increasing the amount of solid material can contribute to a high volumetric weight in porous geopolymer concrete. Age also affects the density value. The density goes down as the age increases from 7 to 28 days because the polymerization bonds become more perfect and the porous geopolymer concrete is getting drier. Similar opinions were also expressed by other researchers, such as in their research [18].



Fig. 3. Density test

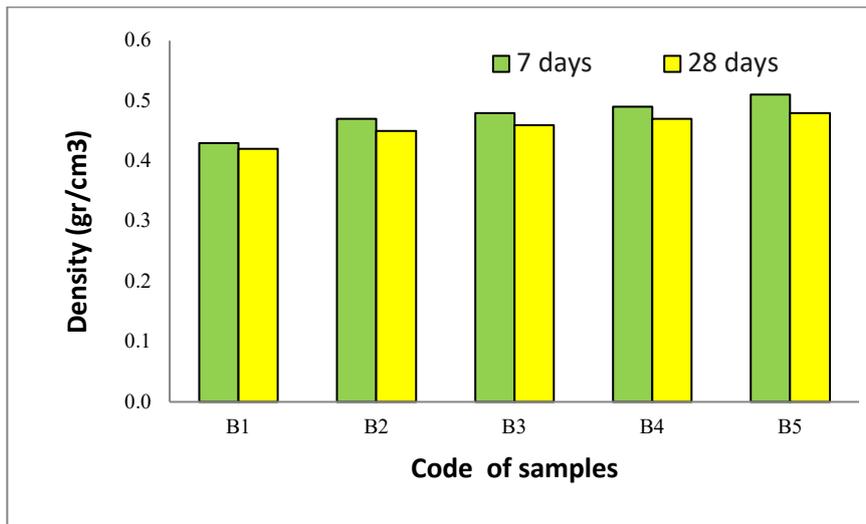


Fig. 4. Density results of porous geopolymer concrete

Table 3

Density results of porous geopolymer concrete

Code	7 days (gr/cm ³)	28 days (gr/cm ³)
B1	0.43	0.42
B2	0.47	0.45
B3	0.48	0.46
B4	0.49	0.47
B5	0.51	0.48

3.2 Compressive Strength and Split Tensile Strength

The Indonesian National Standard (SNI) standards were followed in determining the test specimens' compressive strength [27]. For compression testing, thirty cylindrical samples with a diameter of 100 mm and a height of 200 mm were created for various mixtures using different amounts of binder. Thirty cylindrical samples, each with a diameter of 150 mm and a height of 300 mm, were used to test the splitting tensile strength test, which was carried out in accordance with SNI protocols. The specimens were removed from the oven and left to cure at room temperature for a whole day to gain enough strength. To check the mechanical properties after 7 and 28 days, three specimens were tested on average for each mix.

Compressive strength is the amount of force applied over an area that breaks the test material when it is pushed together by a machine. To do the test, the sample is placed inside the machine with its flat side on the top plate. The machine is started, and it applies pressure until the material breaks. This test helps find out how strong the material is when it is fully hardened by using the

machine until it breaks completely [30]. The compressive strength value of porous concrete according to ACI 522R-10 is between 2.8 – 28 MPa. According to SNI [28], the compressive strength of concrete can be calculated using Equation 2 like this:

$$\sigma = \frac{P}{A}$$

(2)

by:

σ = compressive strength (N/mm² or MPa)

P = ultimate load (N)

A = cross-sectional area (mm²)

The samples were tested at 7 and 28 days old, and the results are shown in Figure 5 and Table 3. Using the data from Table 3, a graph showing the compressive strength of geopolymer concrete at 7 and 28 days was created (Figure 6).



Fig. 5. Compressive strength test

Table 3

Compressive strength results of porous geopolymer concrete

Code	7 days (MPa)	28 days (MPa)
B1	7.86	11.79
B2	7.92	11.87
B3	8.78	11.97
B4	9.33	12.82
B5	9.89	13.67

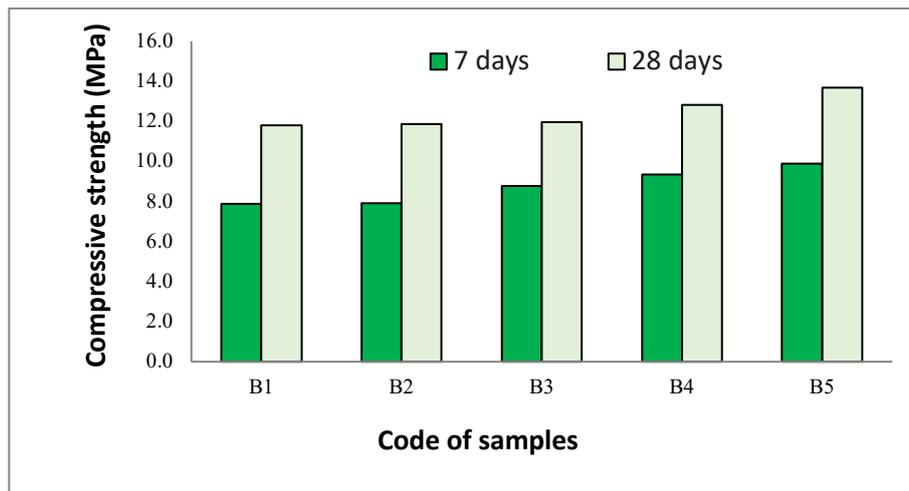


Fig. 6. Compressive strength results of porous geopolymer concrete

When you use more geopolymer binder, it changes the compressive strength of porous geopolymer concrete. A higher amount of binder makes the structure of the binder tighter, which helps hold the aggregate better. This leads to higher compressive strength in porous geopolymer concrete. Also, the age of the concrete affects the compressive strength — the longer it ages, the higher the compressive strength becomes., the greater its increase strength. When the sample is 28 days old, the polymerization bond in the binder is more perfect, and this causes the compressive strength to increase. Among the B1 to B5 samples, sample B5 has the highest compressive strength value, namely 13.67 MPa, and meets the ACI 522R-10 porous concrete requirements, which are above 2.8 MPa. Sample B5 has the highest binder content compared to samples B1-B4. Other researchers also produce higher compressive strength along with the increasing content of geopolymer binder in the porous geopolymer concrete mixture [29].



Fig. 7. Split tensile strength test

The split tensile strength test is done to find the maximum tensile strength a sample can handle. The sample is in the shape of a cylinder. During the test, tensile stress is applied indirectly to the cylinder. The cylinder is placed between two plates and then compressed, which creates tensile stress inside the material. The result of the test can be found by using Equation 3 as follows:

$$f_{ct} = \frac{2P}{\pi.L.D}$$

(3)

by:

f_{ct} = split tensile strength (MPa)

P = maximum test load (N)

L = length of test specimen (mm)

D = diameter of test specimen (mm)

The samples were tested when they were 7 days and 28 days old, and the results are shown in Figure 7 and Table 5. Based on the calculations in Table 5, a graph was created showing the split tensile strength of porous geopolymer concrete at 7 days and 28 days (Figure 8).

Table 5
 Split tensile strength results of porous geopolymer concrete

Code	7 days (MPa)	28 days (MPa)
B1	0.92	1.39
B2	0.99	1.52
B3	1.06	1.61
B4	1.08	1.66
B5	1.12	1.87

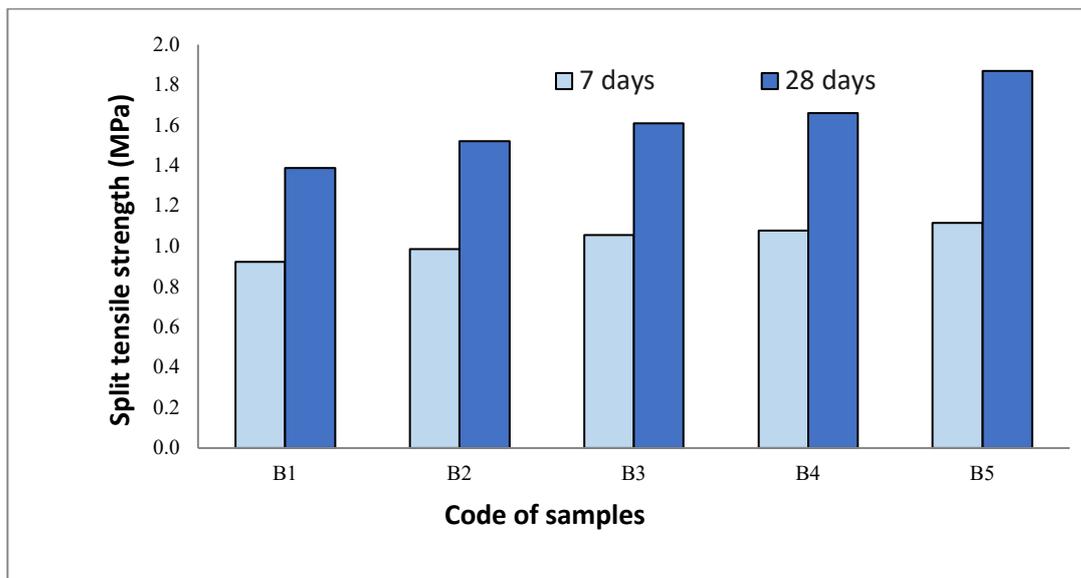


Fig. 8. Split tensile strength results of porous geopolymer concrete

The split tensile strength of porous geopolymer concrete changes based on how much geopolymer binder is used. As more geopolymer binder is added, the split tensile strength goes up. When there is more silica in the geopolymer binder, the split tensile strength becomes stronger. Other studies also show that adding more binder leads to higher split tensile strength [30]. Split tensile strength also increases with the age of the concrete. At 28 days, the average split tensile strength of porous geopolymer concrete is higher than that of 7 days. This is because at 28 days, the polymerization bond that occurs in the geopolymer binder is more perfect, thus increasing the split tensile strength of porous geopolymer concrete.

3.3 Porosity

Porosity is a way to measure how much empty space there is inside a material, and here it refers to the geopolymer binder. According to ASTM [31], the porosity test is done by finding the difference in weight between a sample that has been soaked in water after being heated and the same sample when it's dry. This difference is then shown as a percentage of the dry weight of the sample. The porosity value of porous concrete according to ACI 522R-10 is between 15% -35%. To determine the porosity value, use the formula in Equation 4.

$$P = \frac{B-A}{B-C} \times 100\%$$

(4)

by:

P = total porosity (%)

A = oven-dry weight of the test specimen (g)

B = weight of the test specimen in SSD condition (g)

C = weight of the test specimen in water (g)

The porosity test results for the test specimens at 7 days and 28 days are shown in Figure 9 and Table 6. Based on the calculations in Table 6, a graph is created, which is displayed in Figure 10.



Fig. 9. Porosity test

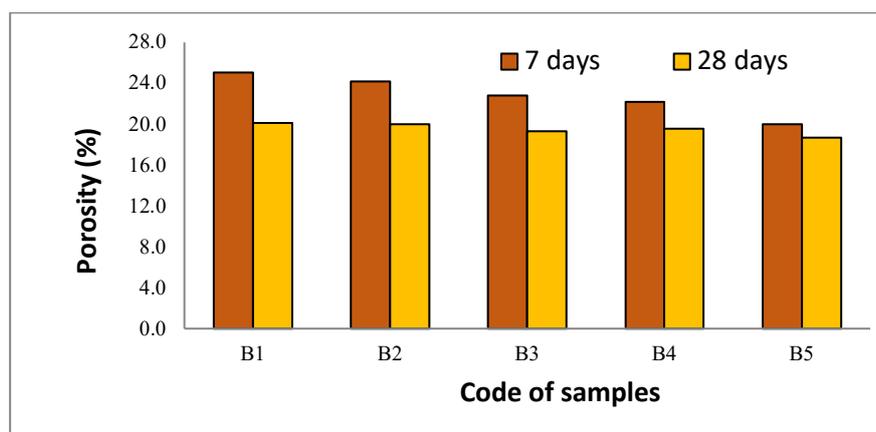


Fig. 10. Porosity results of porous geopolymer concrete

Table 6
Porosity results of porous geopolymer concrete

Code	7 days (%)	28 days (%)
B1	25.07	20.14
B2	24.15	19.98
B3	22.83	19.33
B4	22.19	19.56
B5	20.01	18.67

Figure 10 shows that with increasing binder amount, the porosity value decreases. Likewise, with the age factor, the porosity value will decrease with age. Porous concrete with increasing binder amount and age will have increasingly dense cavities or pores, so that the porosity value decreases. However, even though the porosity value decreases, this porous concrete has an increase in compressive strength and splitting tensile strength values because its density increases [32]. From samples B1-B5, the resulting porosity value still meets the requirements for porous concrete according to ACI 522R-10, which is between 15% -35%.

3.4 Permeability

Permeability is the ease with which liquids or gases pass through concrete [4]. The permeability of porous concrete refers to the ability of concrete to allow liquids to flow through the cavities contained within it. Permeability values are usually expressed in cm/s. According to ACI 522R-10, testing is carried out using the Falling Head Permeability method with permeability values ranging from 81-730 l/min/m or 1.44 mm/s-12.2 mm/s. Falling Head Permeability is a method used to measure water permeability by measuring the time required for water to flow through the sample until the remaining water is in equilibrium between the water in the sample and the inlet pipe (drain pipe), the sample is covered in a latex membrane to prevent water from flowing along the side of the sample and the ability of the concrete to transmit water into the ground in pavement applications. The permeability equation using the falling head method is shown in Equation 5 as follows:

$$K = 2,303 \frac{\alpha L}{A \Delta t} \log \frac{h_0}{h_1}$$

(5)

by:

K = permeability (mm/s)

L = thickness of the test specimen (mm)

α = area of the measuring cylinder (mm²)

A = area of the test specimen cylinder (mm²)

h₀ = initial water level of the measuring cylinder (mm)

h₁ = final water level of the measuring cylinder (mm)

Δt = measurement time interval (s)

The falling head method permeability test is conducted using the following steps:

- The porous concrete specimen is placed under the pipe, bound with a rubber layer to prevent leakage.
- The pipe is filled with water to a specified height (h₀), and the specimen is saturated.

- c. The water stop valve is opened until a height difference of approximately 150 mm is achieved. The stop valve is closed, and the time for the water to fall is recorded.



Fig. 11. Permeability test

The results of the permeability test of the test specimens at the ages of 7 days and 28 days can be seen in Figure 11 and Table 6. From the calculation results in Table 7, a graph is obtained as shown in Figure 12.

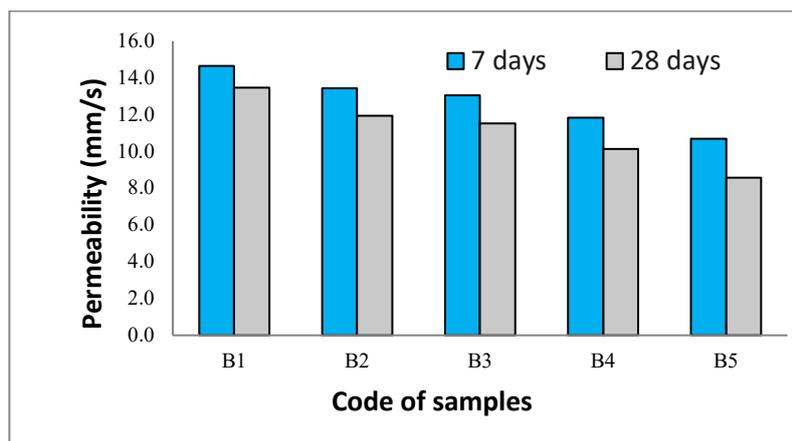


Fig. 12. Permeability results of porous geopolymer concrete

Table 7

Permeability results of porous geopolymer concrete

Code	7 days (mm/s)	28 days (mm/s)
B1	14.66	13.47
B2	13.44	11.95
B3	13.04	11.54
B4	11.84	10.13
B5	10.69	8.58

In this permeability test study, it was found that increasing the amount of geopolymer binder can reduce the permeability value. Likewise, with increasing age of the concrete, the permeability value decreases. At 28 days, sample B1 did not meet the requirements for porous concrete (>12.2 mm/s). Only samples B2-B5 met the requirements for porous concrete, indicating that the samples were able to flow water according to ACI 522R-10 regulations (1.44 mm/s -12.2 mm/s). However, although the permeability value decreased with increasing amount of binder, this was inversely

proportional to the results of the compressive strength test. The same thing was also found in studies conducted by other researchers previously [32].

3.5 XRD (X-Ray Diffraction)

XRD is a tool used to study the crystal structure and size of solid materials. When materials with crystals are examined using XRD, they create unique patterns called peaks. This method helps find out what unknown substances are in a solid by comparing the patterns with data from a database called the Powder Diffraction File, which is managed by the International Center for Diffraction Data. XRD testing of porous geopolymer concrete samples was carried out at the Labotopia Laboratory in Bandung, with the results in Fig. 13 to 22 for the ages of 7 and 28 days.

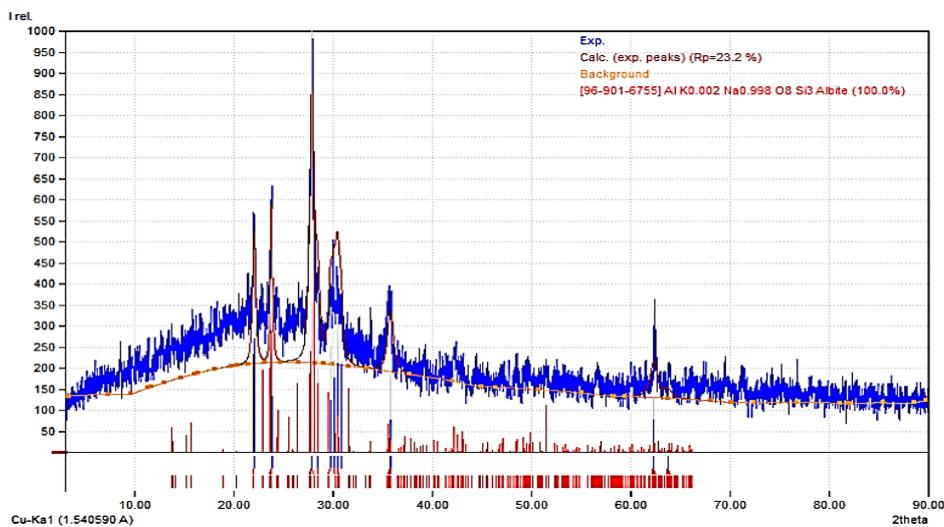


Fig. 13. XRD of sample B1 (7 days)

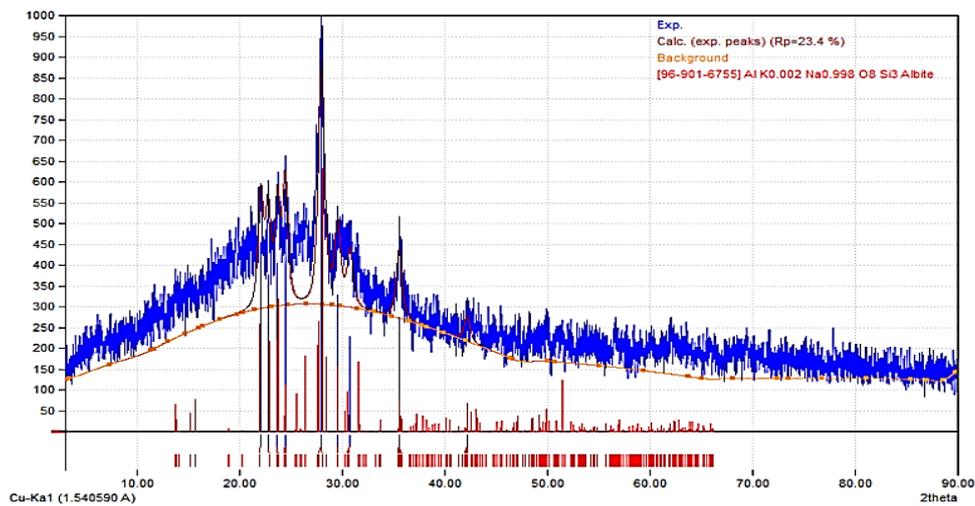


Fig. 14. XRD of sample B2 (7 days)

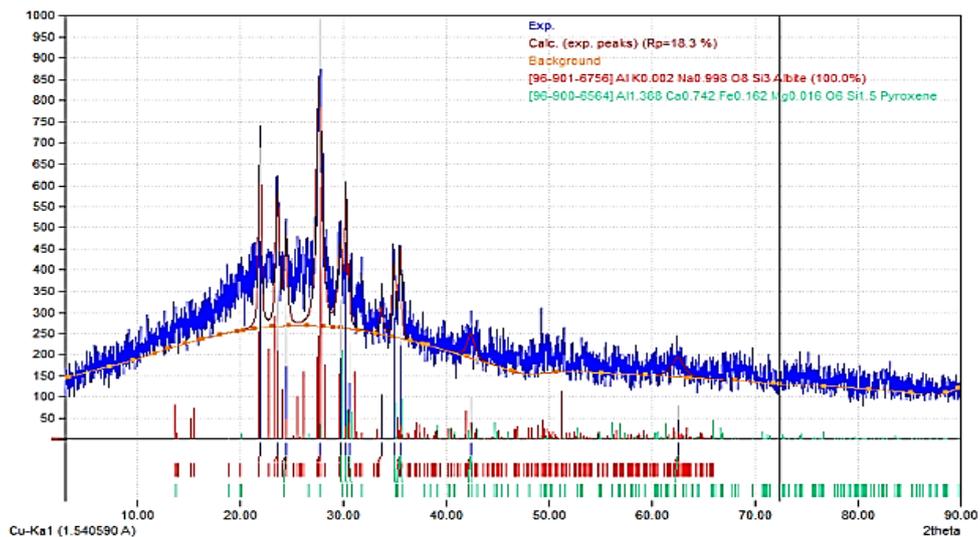


Fig. 15. XRD of sample B3 (7 days)

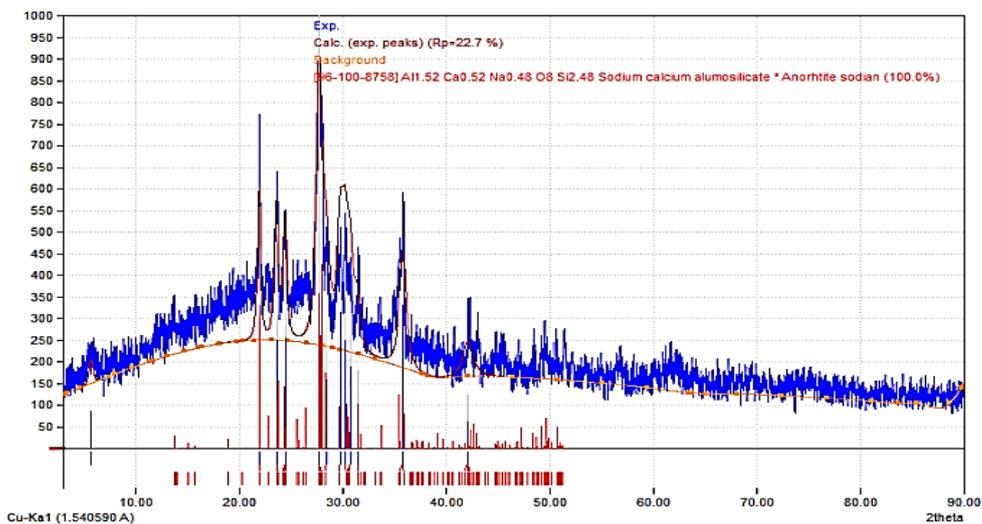


Fig. 16. XRD of sample B4 (7 days)

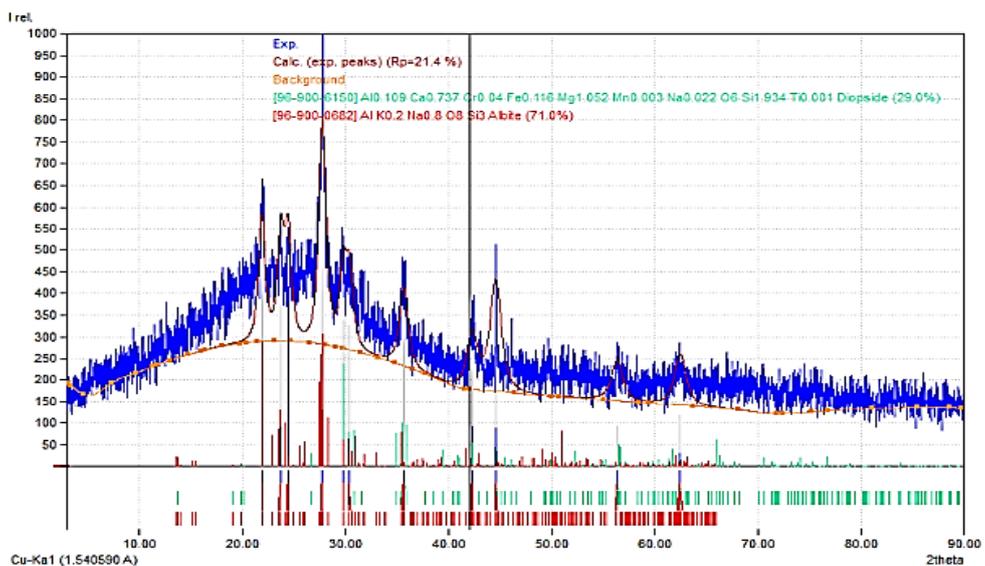


Fig. 17. XRD of sample B5 (7 days)

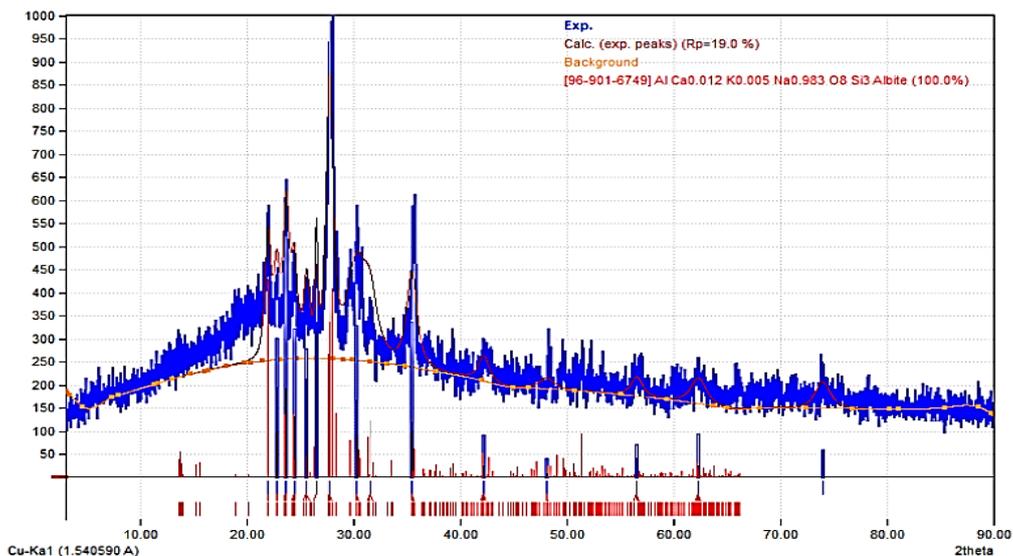


Fig. 18. XRD of sample B1 (28 days)

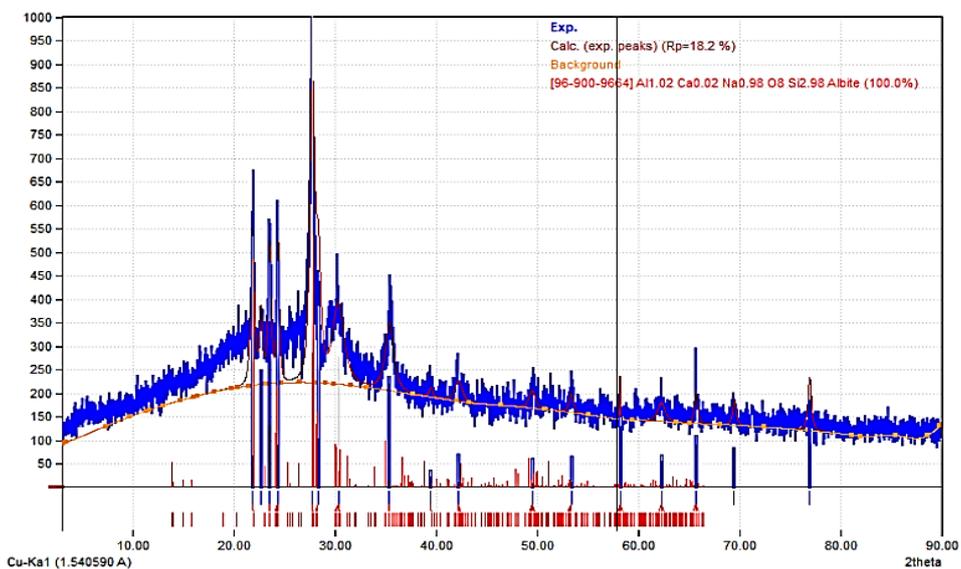


Fig. 19. XRD of sample B2 (28 days)

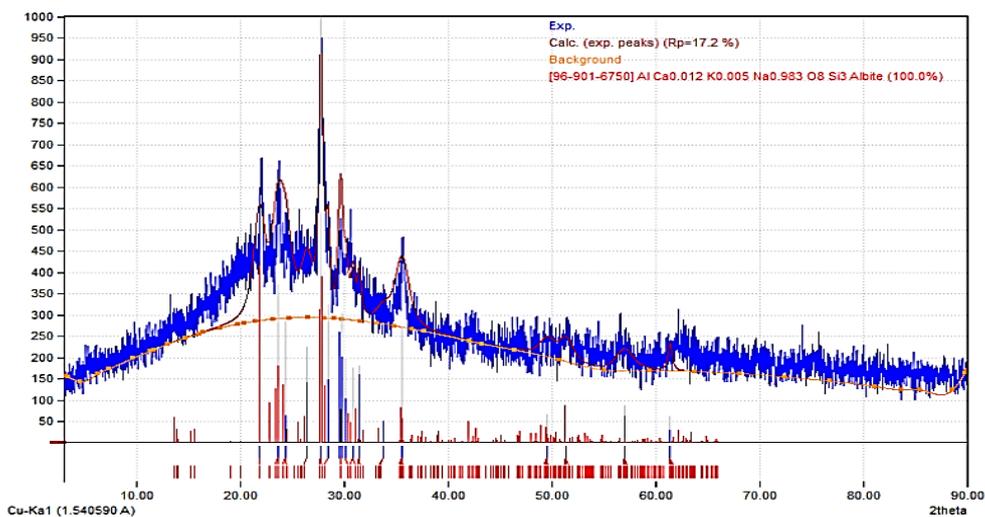


Fig. 20. XRD of sample B3 (28 days)

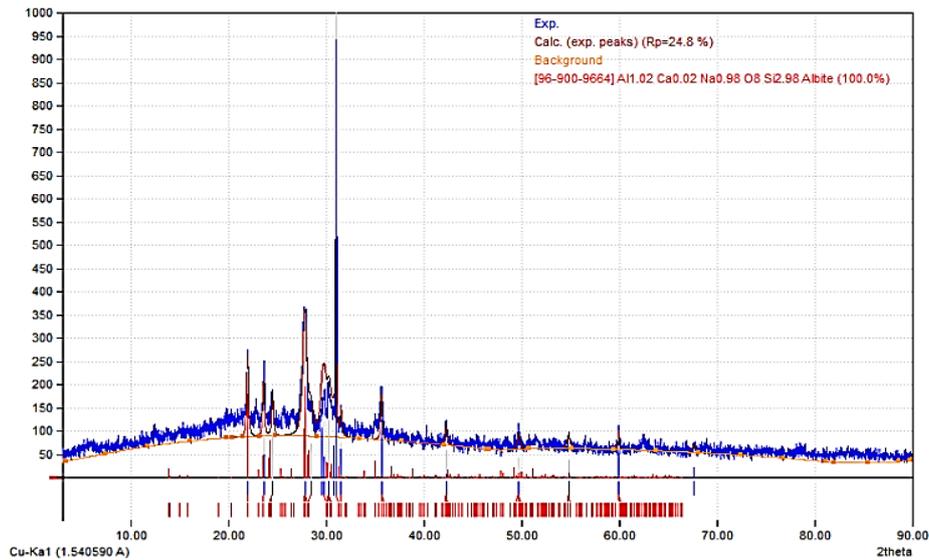


Fig. 21. XRD of sample B4 (28 days)

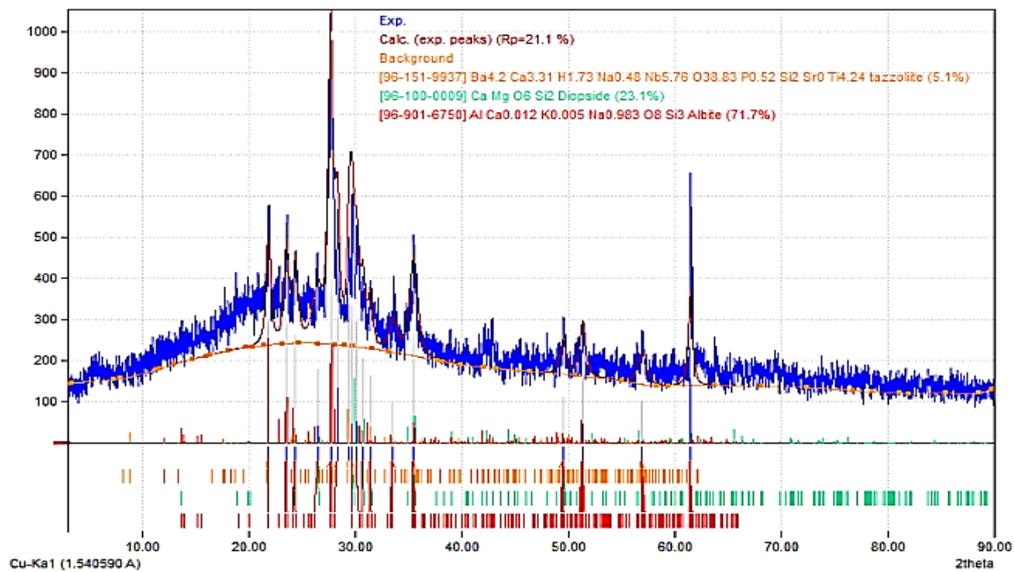


Fig. 22. XRD of sample B5 (28 days)

The results of XRD analysis on porous geopolymer concrete samples at the age of 7 days are shown in Figures 13 to 17, while at the age of 28 days are shown in Figures 18 to 22. The highest peak (angle 2θ) between 20° - 30° shows the highest mineral content in each sample. At the age of 7 days, samples B1-B4 contain 100% Albite compounds, while in sample B5, there is a decrease in Albite content to 71.0% and the emergence of a new compound Diopside by 29%. This shows that sample B5 has a more amorphous geopolymer structure and has a wider intensity peak. At the age of 28 days, the XRD test results are shown in Figures 13 to 17. For samples B1-B4 at the age of 28 days, 100% Albite minerals are still dominant, which indicates that the crystalline phase is more dominant in the mixture. Meanwhile, in sample B5, there are Tazzolite (5.1%), Diopside (23.1%), and Albite (71.7%). The B5 sample mixture has the highest geopolymer binder content, so it can increase the geopolymerization reaction and produce higher compressive strength compared to samples B1-B4. This has also been proven in previous research. In that study, porous geopolymer concrete samples contained albite, quartz, and other minerals [32-34].

4. Conclusions

The research conducted yielded several results from tests on the physical, mechanical, and microstructural properties of porous geopolymer concrete using Umemanyar slat stone ash as a precursor:

- Density increases due to the higher geopolymer binder content. Increasing the amount of solids contributes to a higher bulk density in porous geopolymer concrete. Age also influences the bulk density. The bulk density decreases with age, from 7 to 28 days, as the polymerization bond becomes more complete and the porous geopolymer concrete dries out.
- Porous concrete with increasing binder content and age will have increasingly dense voids or pores, resulting in a decrease in porosity. For samples B1-B5, the resulting porosity values still meet the requirements for porous concrete according to ACI 522R-10, which is between 15% and 35%.
- Permeability tests showed that sample B1 did not meet the requirements for porous concrete (>12.2 mm/s). Only samples B2-B5 met the requirements for porous concrete, indicating that they were water permeable according to ACI 522R-10 regulations (1.44 mm/s - 12.2 mm/s).
- Increasing the amount of geopolymer binder affected the compressive strength of porous geopolymer concrete. Of the samples B1-B5, sample B5 had the highest compressive strength of 13.67 MPa, meeting the ACI 522R-10 requirements of porous concrete, which is above 2.8 MPa.
- As the amount of geopolymer binder increases, the splitting tensile strength of the geopolymer also increases. The higher the silica content in the geopolymer binder, the higher the resulting splitting tensile strength.
- Microstructure testing (XRD) was also conducted in this study. At 7 (seven) days, samples B1-B4 contained 100% Albite, while in sample B5, the Albite content decreased to 71.0% and the new compound Diopside appeared at 29%. At 28 (twenty-eight) days, the XRD test results are shown in Figures 13 to 17. For samples B1-B4 at 28 days, 100% Albite was still dominant, indicating a more dominant crystalline phase in the mixture. Meanwhile, sample B5 contained Tazzolite (5.1%), Diopside (23.1%), and Albite (71.7%).

Acknowledgement

The author and team would like to express their gratitude for the assistance and support from the parties who have helped during this research, especially at the Civil Engineering Laboratory of Universitas Ngurah Rai, the Mechanical Engineering Laboratory of Udayana University, the Bali Provincial Public Works Department Testing Center, and Labotopia Bandung.

References

- [1] Handana, M. A. P., Syahrizal, R. Karolina, M. W. A. Srg, and B. Banjai. "Application of Pervious Concrete Principles on U-Ditch Covers in Overcoming Puddles." In *International Conference on Emerging Smart Cities*, pp. 3-12. Singapore: Springer Nature Singapore, 2022. https://doi.org/10.1007/978-981-99-1111-0_1
- [2] Wajima, Takaaki, and Say Buntan. "Conversion of Waste Stone-Fine Slurry into Geopolymer Cement with Addition of Coal Fly Ash." *GEOMATE Journal* 20, no. 78 (2021): 44-49. <https://doi.org/10.21660/2021.78.Gx133>
- [3] Sakamoto, Kazuki, and Takaaki Wajima. "Preparation of geopolymer cement from simulated lunar rock sand using alkali fusion." *GEOMATE Journal* 18, no. 70 (2020): 62-67. <https://doi.org/10.21660/2020.70.9162>
- [4] Astariani, N. K., I. M. A. K. Salain, I. N. Sutarja, and I. B. R. Widiarsa. "Setting time of geopolymer binder based on Umeanyar slate stone powder." In *IOP Conference Series: Earth and Environmental Science*, vol. 871, no. 1, p. 012002. IOP Publishing, 2021. <https://doi.org/10.1088/1755-1315/871/1/012002>

- [5] Astariani, Ni Kadek, I. M. A. K. Salain, I. Nyoman Sutarja, and Ida Bagus Rai Widiarsa. "Mechanical properties and microstructure of geopolymer binder based on umeanyar slatestone powder." *Civil Engineering and Architecture* 9, no. 6 (2021): 1698-1716. <https://doi.org/10.13189/cea.2021.090604>
- [6] Mboya, Hieronimi A., Karoli N. Njau, Alex L. Mrema, and Cecil K. King'onde. "Influence of scoria and pumice on key performance indicators of Portland cement concrete." *Construction and Building Materials* 197 (2019): 444-453. <https://doi.org/10.1016/j.conbuildmat.2018.11.228>
- [7] Dakhli, Zakaria, Khaled Chaffar, and Zoubeir Lafhaj. "The effect of phase change materials on the physical, thermal and mechanical properties of cement." *Science* 1, no. 27 (2019): 1-11. <https://doi.org/10.3390/sci1010027>
- [8] Naghizadeh, A., and S. O. Ekolu. "Pozzolanic materials and waste products for formulation of geopolymer cements in developing countries: a review." (2017).
- [9] Bello, Afeez Adefemi, J. A. Ige, and Grace Ibironke Ibitoye. "Geotechnical Properties of Lateritic Soil Stabilized with Cement-Bamboo Leaf Ash Admixture." *International Journal of Applied Engineering Research* 9, no. 21 (2014): 9655-9665.
- [10] Rustendi, Iwan, Eddy Poerwodihardjo, and Citra Pradipta Hudoyo. "Utilization of iron sand waste and bottom ash as alternate concrete-making materials." *Civil Engineering and Architecture* 8, no. 4 (2020): 549-556. <https://doi.org/10.13189/cea.2020.080419>
- [11] Sutarja, I. Nyoman, Ni Kadek Astariani, and Ngurah Sedana Putra. "The Utilization of Bungkulan Pumice Soil as Geopolymer Binder." *Civil Engineering and Architecture* 13 (2025): 2518-2530. <https://doi.org/10.13189/cea.2025.131324>
- [12] Ellis, Leah D., Andres F. Badel, Miki L. Chiang, Richard J-Y. Park, and Yet-Ming Chiang. "Toward electrochemical synthesis of cement—An electrolyzer-based process for decarbonating CaCO₃ while producing useful gas streams." *Proceedings of the National Academy of Sciences* 117, no. 23 (2020): 12584-12591. <https://doi.org/10.1073/pnas.1821673116>
- [13] Astariani, Ni Kadek, I. Gusti Made Sudika, and I. Wayan Balik Budiarta. "Mechanical properties and microstructure of concrete using Umeanyar slate stone powder as a filler." In *AIP Conference Proceedings*, vol. 3110, no. 1, p. 020038. AIP Publishing LLC, 2024. <https://doi.org/10.1063/5.0204961>
- [14] N. K. Astariani, I. G. M. Sudika, I. G. N. E. Partama, P. D. H. Ardana, and N. P. O. Ayuningtyas, "the Effect of Activator Ratio and Concentration Molarity on Setting Time of Geopolymer Binder With Umeanyar Slate Stone Powder Precursor," *ARNP J. Eng. Appl. Sci.*, vol. 20, no. 5, pp. 257–264, 2025. <https://doi.org/10.59018/032538>
- [15] Rizk, Ashraf, Essam Kishar, D. A. Ahmed, and Mohamed Kohail. "Preparation and Characterization of Low Cost Geopolymer Cement." *Journal of Scientific Research in Science* 36, no. 1 (2019): 36-48. <https://doi.org/10.21608/jsrs.2019.30996>
- [16] Rastri Utami, Felisitas Aprilia, Andreas Triwiyono, Ni Komang Ayu Agustini, and Indra Perdana. "Thermal conductivity of geopolymer with polypropylene fiber." In *IOP Conference Series: Materials Science and Engineering*, vol. 742, no. 1, p. 012031. IOP Publishing, 2020. <https://doi.org/10.1088/1757-899X/742/1/012031>
- [17] Sampe, Fanriyanto, Andreas Triwiyono, Ni Komang Ayu Agustini, and Indra Perdana. "Thermal properties of geopolymers with silica fume." In *IOP Conference Series: Materials Science and Engineering*, vol. 742, no. 1, p. 012032. IOP Publishing, 2020. <https://doi.org/10.1088/1757-899X/742/1/012032>
- [18] Lv, Yajun, Yiming Chen, Wei Dai, He Yang, Linhua Jiang, Keliang Li, and Weizhun Jin. "Preparation and properties of porous concrete based on geopolymer of red mud and yellow river sediment." *Materials* 17, no. 4 (2024): 923. <https://doi.org/10.3390/ma17040923>
- [19] Andrade, Alexis, Tito Castillo, Marcel Paredes, Ester Gimenez-Carbo, and Víctor García. "Geopolymer Designed with Pumice Stone from Ecuador." *Civil Engineering and Architecture* 10, no. 5 (2022): 1864-1880. <https://doi.org/10.13189/cea.2022.100513>
- [20] Uma Magesvari, M., P. Muthaiyan, S. Yugasini, and M. Ammaiappan. "Experimental studies on pervious geopolymer concrete." In *IOP Conference Series: Materials Science and Engineering*, vol. 989, no. 1, p. 012032. IOP Publishing, 2020. <https://doi.org/10.1088/1757-899X/989/1/012032>
- [21] Azimi, Zahir, and Vahab Toufigh. "Influence of blast furnace slag on pore structure and transport characteristics in low-calcium fly-ash-based geopolymer concrete." *Sustainability* 15, no. 18 (2023): 13348. <https://doi.org/10.3390/su151813348>
- [22] Astariani, Ni Kadek, I. Gusti Ngurah Eka Partama, and I. Wayan Eka Ariantika. "Pengaruh pemanfaatan limbah batu pipih umeanyar sebagai substitusi sebagian agregat halus terhadap kuat tekan dan kuat tarik belah beton." *PADURAKSA: Jurnal Teknik Sipil Universitas Warmadewa* 13, no. 2 (2024): 105-111. <https://doi.org/10.22225/pd.13.2.9949.105-111>
- [23] Astariani, Ni Kadek, I. M. A. K. Salain, I. N. Sutarja, and I. B. R. Widiarsa. "E effect alkin e activator ratio on porosity geopolymer binder based umeanyar slate stone powder." *International Journal of Engineering and Emerging Technology*. 6 (2021): 1-5. <https://doi.org/10.1088/1755-1315/871/1/012002>

- [24] Badan Standardisasi Nasional, "Tata Cara Pembuatan Rencana Campuran Beton Normal. SNI 03-2834-2000," *Badan Stand. Nas.*, pp. 1–34, 2000.
- [25] Arafa, Salaheddin Abdulsalam, Ahmad Zurisman Mohd Ali, Siti Nazahiyah Rahmat, and Yee Loon Lee. "Optimum mix for pervious geopolymer concrete (GEOCRETE) based on water permeability and compressive strength." In *MATEC Web of Conferences*, vol. 103, p. 01024. EDP Sciences, 2017. <https://doi.org/10.1051/mateconf/201710301024>
- [26] Solouki, Abbas, Giovanni Viscomi, Riccardo Lamperti, and Piergiorgio Tataranni. "Quarry waste as precursors in geopolymers for civil engineering applications: A decade in review." *Materials* 13, no. 14 (2020): 3146. <https://doi.org/10.3390/ma13143146>
- [27] Indonesia, Standar Nasional, and B. S. Nasional. "Tata cara pemilihan campuran untuk beton normal, beton berat dan beton massa." *Panitian Teknis* (2012): 91-01.
- [28] SNI 2049:2015, "SNI Semen Portland," p. 147, 2015.
- [29] Nguyen-Tuan, Trung, Tung Pham-Thanh, and Phuong Nguyen-Viet. "Experimental study on mechanical and hydraulic properties of porous geopolymer concrete." *GEOMATE Journal* 19, no. 74 (2020): 66-74. <https://doi.org/10.21660/2020.74.41280>
- [30] Faza, Yanwar, Andrie Harmaji, Veni Takarini, Zulia Hasratiningsih, and Arief Cahyanto. "Synthesis of porous metakaolin geopolymer as bone substitute materials." *Key Engineering Materials* 829 (2020): 182-187. <https://doi.org/10.4028/www.scientific.net/KEM.829.182>
- [31] ASTM C642-06, "ASTM C 642," in *Standar Test Method for Density, Absorption, and Voids in Hardened Concrete*, 2008, pp. 11–13.
- [32] Anwar, Faiz Habib, Hilal El-Hassan, Mohamed Hamouda, Abdulkader El-Mir, and Kim Hung Mo. "Performance evaluation of pervious geopolymer concrete incorporating recycled concrete aggregate." *International Journal of Sustainable Engineering* 17, no. 1 (2024): 908-925. <https://doi.org/10.1080/19397038.2024.2417003>
- [33] Madai, Ferenc, Ferenc Kristaly, and Gabor Mucsi. "Microstructure, mineralogy and physical properties of ground fly ash based geopolymers." *Ceramics–Silikáty* 59, no. 1 (2015): 70-79.
- [34] Ralli, Zoi G., and Stavroula J. Pantazopoulou. "State of the art on geopolymer concrete." *International Journal of Structural Integrity* 12, no. 4 (2021): 511-533. <https://doi.org/10.1108/IJSI-05-2020-0050>