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THE EFFECT OF AGGREGATE GRADATION VARIATION ON MECHANICAL PERFORMANCE AND POROSITY OF POROUS GEOPOLYMER CONCRETE

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ABSTRACT

Porous geopolymer concrete has gained attention as a sustainable and environmentally friendly alternative to conventional Portland cement-based concrete, utilizing industrial waste such as fly ash. This study investigates the effect of aggregate gradation variations on the mechanical properties, porosity, and sustainability of fly ash-based porous geopolymer concrete. The experimental method was employed, utilizing fly ash as the primary binder, sodium hydroxide (NaOH) as the activator, and coarse aggregates of varying sizes (3/8", 1/2", and 3/4"). The concrete samples were tested for compressive strength and porosity at 7, 14, and 28 days following ASTM standards. The results indicate that aggregate gradation significantly influences the mechanical properties, porosity, and sustainability of geopolymer concrete. Smaller aggregate sizes (3/8") produced higher compressive strength (5.42 MPa at 28 days) but lower porosity, while larger aggregates (3/4") increased porosity but reduced compressive strength. Additionally, the study confirms that geopolymer concrete using fly ash as a binder meets the standard requirements for setting time, specific gravity, and durability. These findings contribute to optimizing porous geopolymer concrete for sustainable construction applications, particularly in drainage and permeable pavement systems, promoting waste utilization and environmental sustainability.

Keyword: *Porous geopolymer concrete, fly ash, , porosity, waste, sustainability*

1. INTRODUCTION

Porous geopolymer concrete has emerged as an innovative solution in the sustainable construction industry, serving as an environmentally friendly alternative to conventional Portland cement-based concrete. This type of concrete is designed with a porous structure that allows water to pass through, making it an ideal solution for drainage applications, sustainable pavements, and stormwater runoff mitigation. The use of fly ash as the primary binder in porous geopolymer concrete offers significant environmental benefits by reducing carbon footprints and repurposing industrial waste in a sustainable manner. Fly ash, a byproduct of coal combustion in steam power plants, is abundantly available and often poses environmental challenges if not properly utilized[1].

In the context of sustainability, porous geopolymer concrete offers significant advantages over conventional concrete in terms of resource efficiency and carbon emission reduction. The production of geopolymer using fly ash can reduce carbon emissions by up to 80% compared to Portland cement, making it a more environmentally friendly alternative[2]. Additionally, other studies have shown that the use of porous concrete can extend the lifecycle of infrastructure and mitigate the urban heat island

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effect by enhancing surface permeability. Therefore, it is crucial to gain a deeper understanding of the factors influencing the characteristics of porous geopolymer concrete.

One of the key factors influencing the mechanical properties and porosity of porous geopolymer concrete is the aggregate gradation used in the mixture. Smaller aggregate sizes tend to produce concrete with higher density, which enhances compressive strength but reduces porosity levels[3]. Conversely, larger aggregates create a more porous structure, which can enhance drainage capacity but at the cost of mechanical strength. Other studies have shown that variations in aggregate gradation significantly affect the permeability and durability of porous concrete[5]. Therefore, this study aims to further investigate the effect of aggregate gradation variations on the mechanical properties and porosity of fly ash-based porous geopolymer concrete.

Previous studies have explored various aspects of porous geopolymer concrete; however, several research gaps still need further investigation. For instance, the optimization of the aggregate-to-geopolymer paste ratio has been shown to significantly influence the strength of concrete, but the specific impact of different aggregate sizes has not been thoroughly examined[6]. Similarly, a study conducted by Kevern et al. (2012) found that porous concrete with uniform aggregate gradation exhibited lower compressive strength compared to mixed gradation. However, inconsistencies remain in the results obtained from different types of fly ash[7].

Moreover, other studies have revealed that the activator solution plays a crucial role in controlling the geopolymerization reaction. However, there has been no specific research examining the combination of activator solution with different aggregate gradations[8], geopolymer concrete for blocks [9], characteristics of geopolymer artificial aggregates [10], geopolymer mortar [11][12], laminate concrete between geopolymer and conventional[13].

In practice, porous geopolymer concrete has been widely used in civil engineering and environmental applications, especially in urban areas prone to flooding. A study conducted by Chindaprasirt et al. (2010) showed that the use of porous concrete in urban drainage systems can reduce surface runoff by up to 60%[14]. In addition, other studies have shown that porous concrete has better resistance to freeze-thaw cycles compared to conventional concrete[15]. However, although many studies have been conducted on porous geopolymer concrete, no study has systematically examined the relationship between aggregate gradation variations, mechanical strength, and porosity in one comprehensive study.

The urgency of this research lies in the need for construction material solutions that are not only strong but also sustainable and environmentally friendly. With the increasing production of industrial waste such as fly ash, the use of this material in construction can be an important step in achieving sustainable development. In addition, the novelty of this research is a comprehensive analysis of the effects of aggregate gradation variations on the mechanical performance and porosity of porous geopolymer concrete, which has not been widely studied in previous studies. By understanding this relationship, this research is expected to make a significant contribution to the development of sustainable construction materials.

2. RESEARCH METHOD

The method used in this study is an experimental method aimed at analyzing the effect of aggregate gradation variations on the compressive strength and porosity of porous geopolymer concrete. The main materials used in this study include fly ash sourced from the Tanjung Jati B power plant as the primary binder, coarse aggregates with gradations of 3/8", 1/2", and 3/4", and sodium hydroxide (NaOH) solution with a molarity of 12M as an activator in the geopolymerization process. Water is used to mix the activator solution and ensure an optimal reaction.

The mix design for porous geopolymer concrete in this study uses a ratio of geopolymer paste to aggregate of 1:3, with a water-to-binder ratio (FAS) of 0.3%. The sample preparation process begins with mixing fly ash and NaOH solution to form geopolymer paste, which is then combined with coarse

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aggregates according to the specified gradation variations. The mixture is stirred until homogeneous before being poured into cylindrical molds with a diameter of 10 cm and a height of 20 cm. Subsequently, the casting and compaction process is carried out using a vibration method to ensure uniform aggregate distribution. After casting, the specimens are kept in molds for 24 hours, then demolded and conditioned at room temperature for 7, 14, and 28 days without water curing, as geopolymer concrete does not require hydration like conventional concrete.

The tests conducted in this study include compressive strength and porosity tests. The compressive strength test is performed using a compression testing machine following the ASTM C39/C39M-18 standard, with testing conducted at 7, 14, and 28 days for each aggregate gradation variation. Each variation is tested with 3 samples, and the results are expressed in MPa. Additionally, the porosity test is conducted according to the ASTM C1754/C1754M-12 standard to determine the percentage of voids in porous geopolymer concrete. This test is also conducted with each variation tested using 3 samples. Through this method, the study provides insights into how aggregate gradation variations affect the mechanical properties and porosity of porous geopolymer concrete, serving as a foundation for developing more optimal materials for sustainable construction applications.

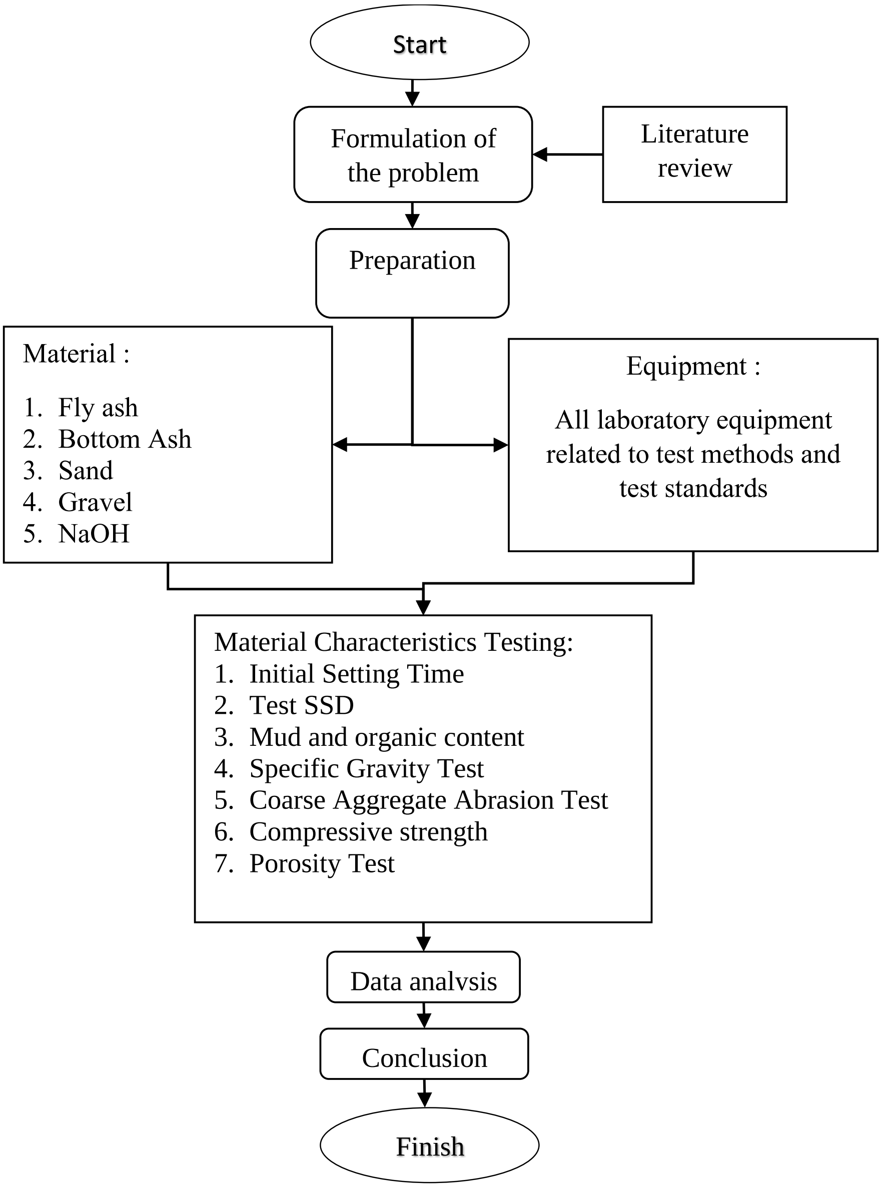

Figure 1. Research Flow Diagram

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3. RESULTS AND DISCUSSION

3.1 Initial Setting Time Test of Fly Ash

Table 1. Initial Setting Time Test Results

No.	Time Reduction (Minutes)	Needle Penetration (mm)	Room Temperature (°C)
1	15	41	27.5
2	30	41	27.6
3	45	41	28.0
4	60	41	27.9
5	75	39	28.0
6	90	39	28.0
7	105	30	27.8
8	120	20	27.7

The test results indicate that the setting time of fly ash occurs within 112,5 minutes. This result complies with the requirements of SNI 15-2049-2004, which stipulate a minimum setting time of 45 minutes and a maximum of 375 minutes.

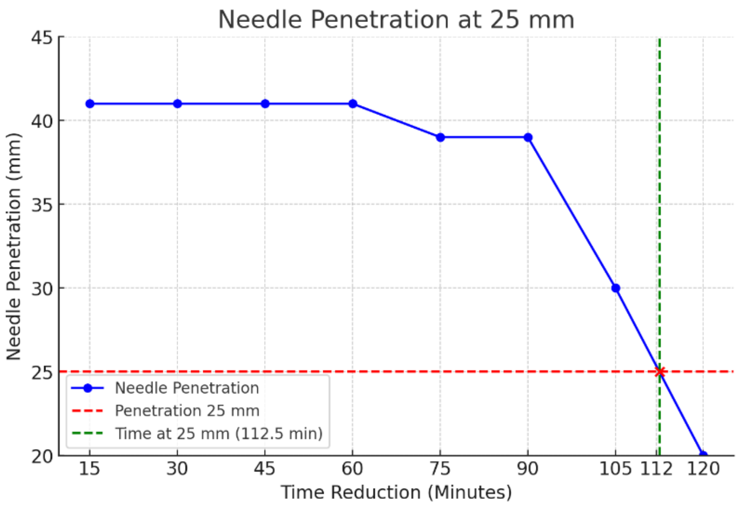

Figure 2. Initial Setting Time Test Graph

3.2 Saturated Surface Dry (SSD) Test

The SSD test determines whether fly ash is in a saturated surface-dry condition, which is crucial for accurate mix proportioning in concrete. The test results indicate that the fly ash is in a wet condition, meaning it retains moisture and needs to be dried before use. Excess moisture in fly ash can affect water-cement ratio calculations, potentially altering the workability and strength of the concrete mix. To ensure proper mix design, drying should be performed until the material reaches an SSD state, where the surface is dry but the internal moisture remains unchanged. This prevents variations in water content that could impact setting time and mechanical properties of the hardened concrete.

3.3 Mud and Organic Content Test

The presence of mud or fine impurities in fly ash can hinder the bond between cement paste and aggregates, potentially weakening the concrete structure. In this study, the fly ash exhibited an average mud content of 0%, significantly lower than the maximum permissible limit of 5% set by industry standards. These results indicate that the fly ash is free from excessive contaminants, ensuring its suitability for high-quality concrete production.

3.4 Specific Gravity Test of Fly Ash

The specific gravity test determines the density of fly ash relative to water, which is essential for mix proportioning in concrete.

Table 2. Specific Gravity Test Results of Fly Ash

Fly Ash Code	Pycnometer (W1) (g)	Pycnometer + Water (W2) (g)	Pycnometer + Fly Ash (W3) (g)	Pycnometer + Fly Ash + Water (W4) (g)	Water Temperature (°C)	Temperature Factor (W5)	Specific Gravity (GS)
FA-01	37	135	64	150	28	0.998	2.1
FA-02	37	135	70	155	28	0.998	2.3
FA-03	37	135	68	153	28	0.998	2.2

Source: Result Analysis, 2024.

The average specific gravity of fly ash obtained from the test is 2.2, which falls within the SNI 03-1969-1990 standard range of 1.9 – 2.55. Specific gravity is a key parameter in determining the workability and density of concrete. A value of 2.2 indicates that the fly ash has an appropriate density for use in cementitious materials, ensuring good particle packing and contribution to the overall strength of the concrete mix. Additionally, the results confirm that the tested fly ash is within the expected range for Class F or Class C fly ash, which typically falls between 2.0 and 2.6, depending on composition.

3.5 Coarse Aggregate Abrasion Test

The abrasion test evaluates the durability and wear resistance of coarse aggregates, which is crucial for their performance in concrete and pavement applications.

Table 3. Coarse Aggregate Abrasion Test Results

Sample	Initial Weight (A) (g)	Retained Weight on Sieve No. 12 (B) (g)	Weight Loss (A - B) (g)	Abrasion Value (%)
CA-01	5000	3751	1249	24.98
CA-02	5000	3680	1320	26.40
Average	**5000**	**3715.5**	**1284.5**	**25.69**

Source: Result Analysis, 2024.

The test results indicate that the coarse aggregate abrasion values are 24.98% and 26.40%, with an average of 25.69%. This value is well within the maximum allowable limit of 40% as specified by SNI 03-1971-1990, confirming that the tested aggregates have good resistance to wear and degradation.

3.6 Compressive Strength Test

The compressive strength test was conducted on **porous geopolymer concrete** using different aggregate gradations.

Table 4. Gradation 3/8"

Age (days)	Sample	Weight (g)	Surface Area (m²)	Compressive Load (kN)	Cylinder Strength (Kg/cm²)	σm (MPa)	Average (MPa)
7	X1	3280	78.5	29.1	37.07	3.71	**3.83**
	X2	3114	78.5	32.2	41.02	4.10	
	X3	3050	78.5	30.4	38.73	3.87	
14	Y1	3150	78.5	34.2	43.69	4.37	**4.52**

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Age (days)	Sample	Weight (g)	Surface Area (m²)	Compressive Load (kN)	Cylinder Strength (Kg/cm²)	σm (MPa)	Average (MPa)
	Y2	3205	78.5	36.0	45.99	4.60	
	Y3	3120	78.5	35.5	45.31	4.53	
28	Z1	3421	78.5	40.5	56.69	5.67	**5.42**
	Z2	3290	78.5	41.8	58.98	5.90	
	Z3	3350	78.5	39.9	53.91	5.29	

Source: Result Analysis, 2024.

The compressive strength of the geopolymer concrete increased steadily over time, starting at 3.83 MPa on day 7, rising to 4.52 MPa by day 14, and reaching 5.42 MPa at 28 days. The most significant strength gain occurred between 7 and 14 days, indicating an active geopolymerization process. By 28 days, the material had achieved near-optimal strength, demonstrating improved bonding and densification over time. This trend highlights the effectiveness of geopolymer concrete in developing structural integrity through prolonged curing.

Table 5. Gradation 1/2"

Age (days)	Sample	Weight (g)	Surface Area (m²)	Compressive Load (kN)	Cylinder Strength (Kg/cm²)	σm (MPa)	Average (MPa)
7	X4	3205	78.5	25.9	32.98	3.29	3.44
	X5	3120	78.5	28.5	36.32	3.63	
	X6	3180	78.5	27.0	34.39	3.44	
14	Y4	3165	78.5	32.2	41.18	4.12	4.32
	Y5	3220	78.5	34.0	43.46	4.35	
	Y6	3195	78.5	33.5	42.83	4.28	
28	Z4	3300	78.5	38.7	51.78	5.18	5.01
	Z5	3255	78.5	36.9	49.37	4.94	
	Z6	3280	78.5	39.2	52.45	5.24	

Source: Result Analysis, 2024.

The compressive strength of the geopolymer concrete exhibited a consistent increase over time, with an average strength of 3.44 MPa at 7 days, 4.32 MPa at 14 days, and 5.01 MPa at 28 days. The most significant strength gain occurred between 7 and 14 days, highlighting the continued geopolymerization reaction and matrix densification. By 28 days, the material had achieved substantial strength, confirming its suitability for structural applications where long-term durability and load-bearing capacity are required.

Table 6. Gradation 3/4"

Age (days)	Sample	Weight (g)	Surface Area (m²)	Compressive Load (kN)	Cylinder Strength (Kg/cm²)	σm (MPa)	Average (MPa)
7	X7	3100	78.5	22.3	28.41	2.84	**2.96**
	X8	3050	78.5	24.5	31.22	3.12	
	X9	3085	78.5	23.8	30.32	3.03	
14	Y7	3125	78.5	28.9	37.02	3.70	**3.84**
	Y8	3180	78.5	30.5	39.07	3.91	
	Y9	3150	78.5	29.8	38.15	3.82	
28	Z7	3250	78.5	33.5	44.84	4.48	**4.35**
	Z8	3180	78.5	35.1	47.00	4.70	
	Z9	3205	78.5	34.2	45.82	4.58	

Source: Result Analysis, 2024.

The compressive strength of the geopolymer concrete followed a progressive increase over time, starting at 2.96 MPa at 7 days, rising to 3.84 MPa at 14 days, and reaching 4.35 MPa at 28 days. The strength gain between 7 and 14 days was more pronounced, indicating active geopolymerization and matrix

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development. By 28 days, the material had achieved substantial strength, confirming its viability for applications where moderate compressive strength and durability are required.

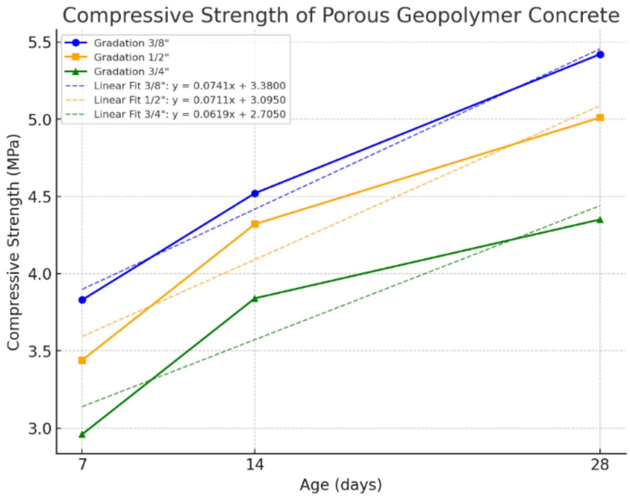

Figure 3. Compressive Strength

Effect of Aggregate Size, The compressive strength results indicate that the 3/8" gradation achieved the highest strength, with an average of 5.12 MPa at 28 days. The 1/2" gradation followed with 4.10 MPa, while the 3/4" gradation had the lowest value at 3.45 MPa. This confirms that smaller aggregate particles contribute to higher compressive strength, as they enhance particle packing density and improve geopolymer bonding, leading to a more compact microstructure.

Strength Development Trends, The compressive strength values show a significant increase from 7 to 14 days, followed by a more gradual rise up to 28 days. The 3/8" gradation exhibits the highest early strength gain, indicating a more effective initial geopolymerization process. This suggests that finer aggregate distribution facilitates a better reaction between fly ash and the alkaline activator, accelerating strength development.

Practical Implications, Given its superior strength performance, the 3/8" gradation is recommended for structural applications requiring higher durability and load-bearing capacity. Meanwhile, the 3/4" gradation, with lower strength, may be more suitable for applications where higher permeability, reduced weight, or improved drainage properties are desired, such as in pervious pavements or lightweight concrete structures.

3.7 Porosity Test Results of Porous Geopolymer Concrete

The porosity test, conducted according to ASTM C1754/C1754M-12. Three aggregate gradations were tested: 3/8" (0.95 cm), 1/2" (1.27 cm), and 3/4" (1.9 cm).

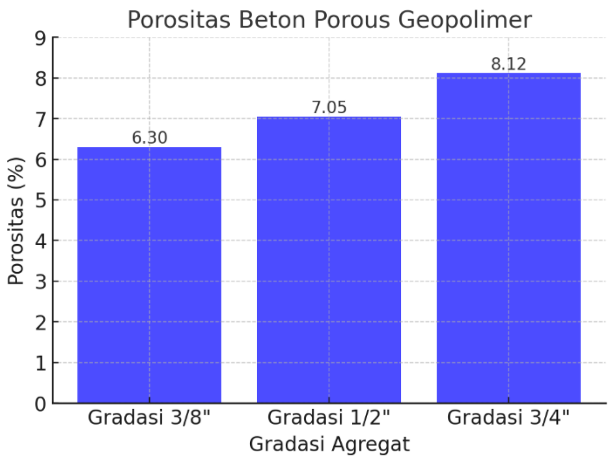

Figure 4. Porosity Test Results

The results indicate that porosity increases as aggregate size increases. The 3/8" gradation exhibits the lowest porosity at 6.30%, followed by the 1/2" gradation at 7.05%, while the 3/4" gradation has the highest porosity at 8.12%.

This trend suggests that larger aggregate sizes create more void space between particles, leading to higher overall porosity in the concrete mix. Conversely, smaller aggregates provide a denser packing, reducing the number of voids. This aligns with the principle that concrete containing coarser aggregates tends to have more air voids and larger pores, which can impact its mechanical properties and permeability.

4. CONCLUSION

This study shows that variations in aggregate gradation have a significant effect on the compressive strength and porosity of fly ash-based porous geopolymer concrete. Smaller aggregate gradation (3/8") produces the highest compressive strength of 5.42 MPa at 28 days, while the 3/4" gradation has the highest porosity at 8.12%, which is useful for permeable applications but reduces mechanical strength. The use of fly ash as a cementitious material contributes to the journey by reducing carbon emissions and utilizing industrial waste. Porous geopolymer concrete with optimal aggregate gradation can be a sustainable material solution for road pavements and ecological systems, showing a balance between strength and porosity.

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