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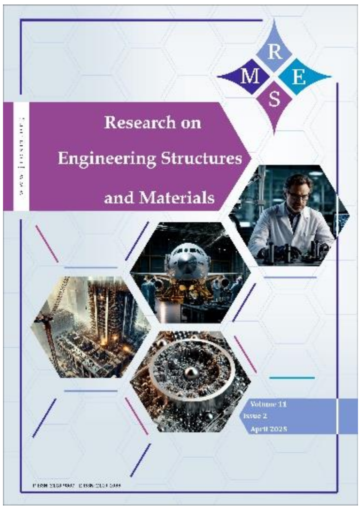

Compressive and tensile strength of fly ash based lightweight geopolymer concrete with variation of Na_2SiO_3 and NaOH using expanded polystyrene

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Research Article

Compressive and tensile strength of fly ash based lightweight geopolymer concrete with variation of Na_2SiO_3 and NaOH using expanded polystyrene

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Abstract

Conventional concrete production contributes significantly to global CO2 emissions, encouraging a sustainable alternative material. Geopolymer concrete, exceptionally lightweight geopolymer concrete (LWGC), an innovative approach, offers a promising solution by utilizing industrial by-products like fly ash while reducing environmental impact. However, optimizing alkali activator ratios remains a critical challenge in developing LWGC with adequate mechanical properties for structural applications. This study investigates the effect of varying sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH) ratios on the properties of LWGC synthesized from fly ash and expanded polystyrene (EPS). Three different Na_2SiO_3/NaOH ratios (1.5, 2.0, and 2.5) were examined to evaluate their effects on fresh and hardened concrete properties. Fresh concrete properties were assessed through setting time and slump flow tests, while hardened concrete was evaluated for density, compressive strength, and splitting tensile strength at 14, and 28 days. Results demonstrated that increasing the Na_2SiO_3/NaOH ratio decreased workability but enhanced mechanical properties, with the 2.5 ratio achieving the highest 28-day compressive strength (22.85 MPa) and splitting tensile strength (1.43 MPa). All LWGC variations exhibited densities between 1080-1250 kg/m^3, qualifying them as lightweight concrete according to ASTM C125 standards. Polynomial regression analysis revealed a non-linear positive correlation between activator ratio and mechanical strength development. This research demonstrates that fly ash-based LWGC with EPS aggregate can be effectively engineered by optimizing the alkali activator ratio, providing sustainable construction materials with mechanical properties suitable for structural applications while contributing to circular economy principles through waste utilization properties.

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1. Introduction

The production of Portland cement contributes significantly to global CO_2 emissions, accounting for approximately 7-8% of anthropogenic CO_2 releases [1]. Conventional concrete, a remarkable building material composite, comprises 12% cement, 8% water, and 80% aggregate. Annually, global production includes 1.6 billion tons of cement, nearly 10 billion tons of sand and rock, plus 1 billion tons of water. With total consumption reaching 12.6 billion tons of raw materials yearly, the concrete industry stands as the world's largest consumer of natural resources[2]. Cement, one of the most widely utilized materials for construction, plays a crucial role as the primary binder in

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concrete [3]. However, developing sustainable construction materials has become a critical focus in recent years due to the increasing demand for friendly and high-performance building materials [4]. Geopolymer concrete has emerged as a promising alternative to traditional Portland cement-based concrete. Concrete technology innovation was also developed so that concrete has a lighter specific gravity because standard concrete has a reasonably high weight and reduces the dead load of concrete in buildings [5,6]. Lightweight concrete (LW) has a lighter specific gravity than conventional concrete [7,8]. LW is a suitable replacement for normal concrete, especially in applications prioritizing weight reduction and insulation [9].

Among the sustainable concrete innovations, Geopolymer concrete (GC) is primarily composed of industrial by-products such as fly ash and offers several advantages, including lower carbon emissions, enhanced durability, and better chemical resistance [10]. Geopolymers, formed by polymerizing organic and inorganic materials, can be made from recycled silica-rich sources [11]. Fly ash, a waste product from coal-fired power plants is a pozzolanic material that reacts with alkali activators to form a binding matrix in geopolymer systems. Commonly classified as waste, fly ash is a material generated by burning or combustion. These industrial by-products mitigate the environmental impact of waste disposal and reduce the carbon footprint associated with cement production [12,13,14]. As a sustainable and composite material activated by alkaline substances, geopolymer concrete (GC) offers the construction industry a valuable tool for reducing carbon footprint by providing lower-carbon alternatives to traditional cement [15]. When combined with appropriate alkaline activators, typically sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH), fly ash can form strong cementitious materials through geo-polymerization reactions.

The combination of lightweight concrete and geopolymer concrete has led to the development of lightweight geopolymer concrete (LWGC), representing an advancement in sustainable material design. Expanded Polystyrene (EPS), known for its ultra-lightweight properties and excellent thermal insulation characteristics, has been used as a lightweight concrete aggregate [16]. EPS offers reduced density, improved workability, and enhanced thermal performance. It also presents a sustainable solution for EPS disposal, addressing environmental concerns [17]. However, EPS incorporation offers benefits such as reduced density, improved workability, and enhanced thermal performance while presenting a sustainable solution for EPS disposal.

Geopolymers with a combination of lightweight concrete have been limitedly investigated (18). Previous studies have investigated various aspects of fly ash-based geopolymer concrete and lightweight concrete separately. LWGC presents a promising solution for creating environmentally friendly concrete that combines the advantages of lightweight materials with enhanced performance. Its reduced mass helps address structural load issues, thereby lessening the strain on building foundations while maintaining durability and strength [19]. Studies have shown that incorporating EPS can reduce density and improve thermal insulation but may affect mechanical properties and durability, a study [20] show the result in tha density range 1321-1912 kg/m3.

The optimization of the $Na_2SiO_3/NaOH$ ratio in lightweight geopolymer concrete remains a critical area requiring further investigation, particularly regarding the combined effects of activator ratio variation and EPS incorporation. This study investigates the influence of various $Na_2SiO_3/NaOH$ ratios on the compressive and tensile strength of fly ash-based lightweight geopolymer concrete containing expanded polystyrene with fresh material properties. The research aims to optimize the alkaline activator composition to achieve desirable mechanical properties while maintaining the lightweight characteristics of the concrete. The findings will contribute to developing sustainable construction materials that combine reduced environmental impact, lightweight properties, and adequate structural performance.

1.1. Research Significance

More studies exploring various material properties in LWGC have been investigated and published. However, the potential of LWGC using EPS as lightweight aggregate, particularly regarding its mechanical properties and mix design optimization, has not yet been thoroughly investigated and requires further research. This study aimed to acknowledge and evaluate the LWGC using EPS, focusing on mechanical, compressive, and tensile strength properties. The research concerns construction issues and uses fly ash as the primary material in geopolymer concrete, one alternative to traditional Portland cement and a way to reduce emissions.

The study investigated optimizing alkaline activator ratios, Na_2SiO_3, and NaOH variation from 1.5, 2.0, and 2.5 to optimize the polymerization process. This study also determines the optimal balance between alkali activator ratios for enhanced mechanical properties, targeting compressive strength above 17 Mpa and split tensile strength exceeding 1.5 Mpa for structural applications. It also includes detailed mechanical property analysis to mix design parameters and concrete performance.

This study's unique factor is its focus on incorporating Expanded Polystyrene (EPS) as a lightweight aggregate of 25% by concrete volume. The justification of 25% is based on concrete trial as substitution of fine aggregate and related study The analysis of particle size influence was performed using a substitution level of 25%, carefully selected to facilitate clear observation of the interactive dynamics between sand and plastic components [21]. EPS provides an innovative solution to reduce concrete density while maintaining structural integrity through mixed proportions and curing conditions [22]. This study fills a knowledge gap in lightweight applications and supports the management of EPS recycling waste.

LWGC offers potential cost reduction in construction through waste materials and enables significant material behavior, which leads to more efficient structural design and application in elements. This research also provides a structure for future sustainable construction material research. An investigation of concrete mechanical properties, integrated with the reuse of waste materials, provides a structure to improve LWGC. Future research may optimize lightweight geopolymer concrete formulations, particularly in long-term durability, thermal resistance, and microstructural analysis.

2. Materials and Methods

The production of LWGC is shown in Fig. 1. Production begins with fly ash as a precursor mixed with sand and EPS. The alkali activator is Sodium Hydroxide, and Sodium Silicate is added in variation ratios of 1.5, 2.0, and 2.5. All materials are mixed through the LWGC mix design and cured in an oven at 60^0C for 24 hours to produce LWGC.

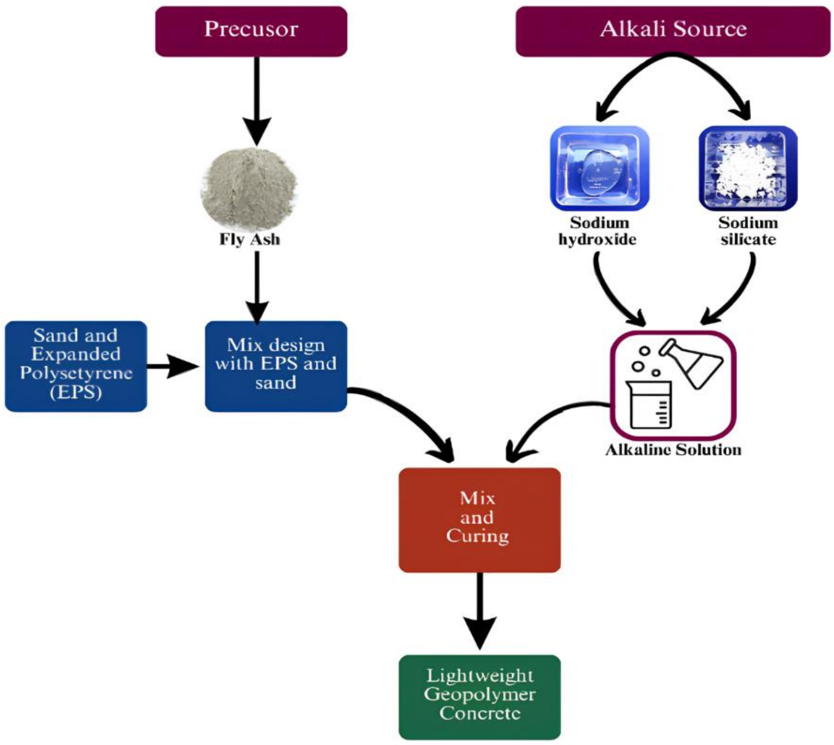

Fig. 1. An overview lightweight geopolymer concrete productions

2.1. Fly Ash

The fly ash utilized in this research was sourced from Pupuk Sriwidjaja Palembang Company and subjected to analysis using XRF (X-ray fluorescence), XRD (X-ray diffraction), and SEM (Scanning Electron Microscopy) techniques to know the class and characteristic [14]. Fly ash, also called pulverized fuel ash, is a by-product of thermal power plants composed of fine particles. Fly ash's properties will change depending on the source and composition of coal [13]. Fly ash is the main solid waste from coal combustion in power stations [23]. Table 1 presents the chemical composition (XRF) of the fly ash, while Figures 2 and 3 show the results of SEM and XRD, respectively.

Scanning Electron Microscopy (SEM), an electron microscope technique that creates images by scanning a sample's surface with a focused electron beam, was used to examine the fly ash [24]. As the electron beam interacts with the sample, emitted or reflected electrons are detected, amplified, and displayed as shades of gray on a monitor, thus forming the image [14]. As shown in Fig. 3 (3000x magnification), the SEM revealed that most fly ash particles exhibit a spherical morphology, facilitating their rapid reaction with other components during geopolymer mixture production. The particle size distribution is broad, ranging from approximately 0.3 μm to over 5 μm in diameter, as estimated from the 10 μm scale bar.

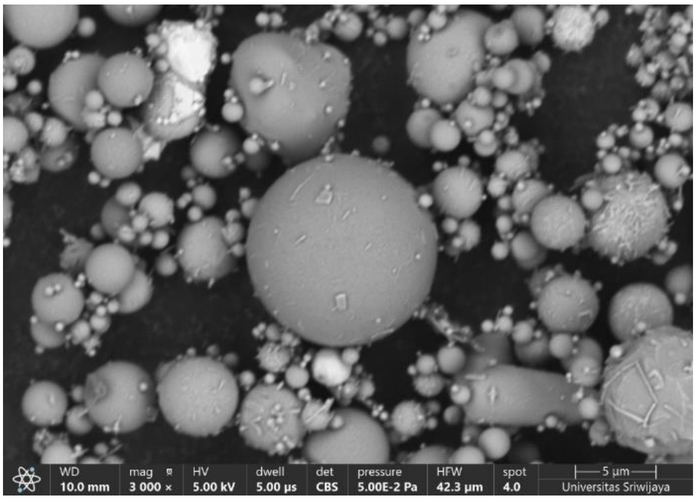

Fig. 2. SEM of fly ash

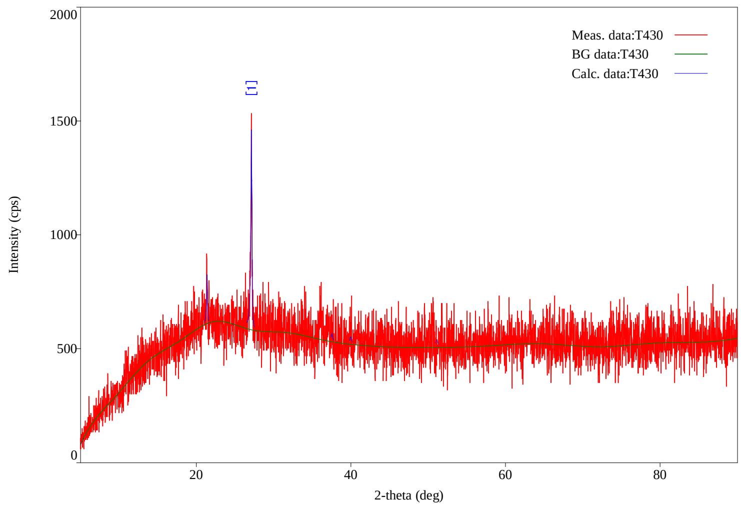

Fig. 3. XRD of fly ash

Table 1. XRF (chemical composition) fly ash

Component	% in mass
SiO_2	50,531 ± 0,180%
Al_2O_3	22,944 ± 0,142%
Fe_2O_3	11,298 ± 0,041%
CaO	4,927 ± 0,027%
Na_2O	4,472 ± 0,268%
MgO	1,853 ± 0,088%
SO_3	1,526 ± 0,022%
K_2O	1,369 ± 0,020%
TiO_2	0,837 ± 0,011%
P_2O_5	0,174 ± 0,020%
Mn_3O_4	0,070 ± 0,004%

X-ray fluorescence (XRF) analysis is attempted to identify the chemical composition of fly ash. The material process works by exposing to high-energy X-rays and measuring the characteristic secondary X-rays emitted by the elements present, enabling both qualitative and quantitative elemental analysis [25]. According to the ASTM 618 standard [26], fly ash can be classified as type F because it contains $SiO_2 + Al_2O_3 + Fe_2O_3 \geq 70\%$ and low CaO content (typically <10%).

X-ray diffraction (XRD) analysis was conducted on the fly ash to assess its crystalline content, as a high degree of crystallinity can hinder its reactivity in material casting processes. XRD aims to determine the crystal system, lattice parameters, atomic arrangement, structure type, orientation, and grain size [27]. The XRD analysis, as illustrated in Fig. 3, reveals a broad, amorphous hump with a relatively small, sharp peak at approximately 27.12^{o} with an intensity of 1486.56 cps. The relatively low intensity of the crystalline peak demonstrates that the fly ash used in this study possesses a predominantly amorphous structure, which is favourable for geopolymerization. These microstructural characteristics directly influence mechanical performance through multiple mechanisms: the spherical morphology enhances workability and improves compaction; the varied particle sizes create an efficient packing effect that increases matrix density; and the high reactive silica and alumina content participates in pozzolanic reactions with cement hydration products to form additional C-S-H gel that fills capillary pores. As a result, concrete incorporating this fly ash exhibits improved mechanical properties, including enhanced compressive strength development (particularly long-term) and better resistance to aggressive agents, demonstrating the apparent correlation between the observed microstructure and enhanced mechanical performance in cementitious systems.

2.2. Alkali Activator

Sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) were used as alkali activators [28]. The activator consists of NaOH and silica, where silica acts as a strong acid that reacts with the strong base. Na_2SiO_3 speeds up the polymerization process. Simultaneously, NaOH 14M interacts with the Si and Al in the fly ash, forming strong polymer bonds. This combination is used to prepare the alkaline activator [29].

2.3. Fine Aggregate

Tanjung Raja sand, ranging from 4.75 mm to 0.075 mm in size, was used as fine aggregates for the investigation. The sand was used in saturated surface dry (SSD) conditions, where internal pores are water-filled, but the surface is dry [30]. The fine aggregate's fine modulus is 2.545, within the recommended range (usually 2.3-3.1) for good fine aggregate [31]. Based on the standard color test with an organic plate, the samples are in color number two. These results indicate that fine aggregates have relatively low organic content and will not interfere with the cement hydration process or concrete strength [32]. These fine aggregates can be used in concrete construction without the need for additional processing [33].

2.4. Expanded Polystyrene

Expanded polystyrene (EPS) is a versatile material widely used in various industries, including construction, packaging, and aquaculture. Despite its utility, EPS poses significant environmental and health challenges due to its persistence and potential toxicity. This response explores the multifaceted aspects of EPS, including its environmental impact, applications, and recycling methods. The EPS size used in this study was ranging 3-4 mm.

EPS is valued for its low thermal conductivity and cost-effectiveness in construction as an insulation material. Innovations such as EPS-alumina aerogel composites enhance its fire resistance and mechanical properties, making it suitable for practical applications [34]. Due to its recyclability, expanded polystyrene (EPS) is a common choice as the insulation core in structural insulated panels. This rigid and tough polymeric foam features a closed-cell structure [35].

2.5. Admixture

Admixture is a material other than water, aggregate, and hydraulic cement mixed with concrete or mortar added before or during mixing. Admixtures modify the properties and characteristics of concrete, for example, to improve its workability or for other purposes, namely, energy savings [36]. The admixture used in this study is a superplasticizer type F. It helps the workability of the LWGC mixture and accelerates the binding time [37].

2.6. Design Mix Proportion and Experimental Methodology

This study investigates fresh material properties, compressive strength, and tensile strength of LWGC using EPS. The materials used in this study are Fly ash as a primary binder, fine aggregate, EPS as Lightweight aggregate replacement, and alkali activator consisting of a combination of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH). The target density of LWGC developed on less than. The alkali activator to binder ratio was maintained at 0.3 for all mixtures. Three different $Na_2SiO_3/NaOH$ ratios were investigated: 1.5, 2.0, and 2.5. The solution was prepared 24 hours before being mixed with pellets in distilled water to a 14 M concentration. EPS beads were used to replace 25% of the total concrete volume target. The LWGC concrete mixtures shown in Table 2LWGC are characterized by their compressive strength (CS) and Split Tensile Strength (STS), which are prepared at 14 days and 28 days. CS and STS were tested on a compression testing machine (CTM). The specimen was cast like a $50mm \times 50mm \times 50mm$ cube or a $150\ mm \times 300\ mm$ length cylinder.

Table 2. LWGC concrete mixtures for $1m^3$ volume of concrete

Materials	Specimen Shape	Specimen size (mm)	Number of Specimens
	LWGC_1.5	LWGC_2.0	LWGC_2.5
Fly Ash (kg)	692	692	692
Fine Aggregate (kg)	540	540	540
EPS	10.8	10.8	10.8
AA/B	0.3	0.3	0.3
Ratio AA	1.5	2.0	2.5
Alkali Activator (AA) (Kg)	207.6	207.6	207.6
Mol NaOH (M)	14	14	14
Superplasticizer (kg)	14.5	14.5	14.5

This study investigates fresh material properties, compressive strength, and tensile strength of LWGC using EPS. The materials used in this study are Fly ash as a primary binder, fine aggregate, EPS as Lightweight aggregate replacement, and alkali activator consisting of a combination of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH). The target density of LWGC developed on less than 1800 kg/m^3. The alkali activator to binder ratio was maintained at 0.3 for all mixtures. Three different $Na_2SiO_3/NaOH$ ratios were investigated are 1.5, 2.0, and 2.5. $NaOH$ The solution was prepared 24 hours before being mixed with NaOH pellets in distilled water to a 14 M concentration. EPS beads were used to replace 25% of the total concrete volume. Fig. 4

shows the mixing process of LWGC. The LWGC concrete mixtures for $1m^3$ volume of concrete shown in Table 2.

Fig. 4. Mixing process of LWGC

2.7. Proportions of Test Specimens

LWGC is characterized by its compressive strength (CS) and Split Tensile Strength (STS), which are prepared at 7 days and 28 days. CS and STS were tested on a compression testing machine (CTM). The specimen was cast like a $50mm \times 50mm \times 50mm$ cube or a $150\ mm\ \times 300\ mm$ length cylinder. The number of specimens and tests is shown in Table 3.

Table 3. The number of specimens and tests

Mix Design	Specimen Shape	Specimen size (mm)	Number of Specimens	Purpose
LWGC_1.5	Cube	$50 \times 50 \times 50$	6	Compressive Strength (CS)
LWGC_1.5	Cylinder	150×300	6	Split Tensile Strength (STS)
LWGC_2.0	Cube	$50 \times 50 \times 50$	6	Compressive Strength (CS)
LWGC_2.0	Cylinder	150×300	6	Split Tensile Strength (STS)
LWGC_2.5	Cube	$50 \times 50 \times 50$	6	Compressive Strength (CS)
LWGC_2.5	Cylinder	150×300	6	Split Tensile Strength (STS)

2.8. Process of Casting and Curing

The mold used for this casting is steel cubic $50mm \times 50mm \times 50mm$ dimensions for compressive strength and cylindrical molds of $150\ mm\ \times 300\ mm$ height for splitting tensile strength testing. All molds used are thoroughly cleaned and coated with oil to facilitate easy demolding. Sodium hydroxide 14 M concentration was prepared 24 hours before mixing with sodium silicate.

First, Weigh the lightweight geopolymer concrete material according to the mix design. Then, Dissolve the solid with distilled water according to the planned molarity of 14 M. Then, mix the solutions until they are evenly distributed according to the planned ratio to become an alkali activator solution. Put fly ash and fine aggregate into the mixer at gear speed 1 for 3 minutes with the addition of superplasticizer little by little until evenly mixed. After that, Mix the alkali activator solution into the mixer, then stir with gear 2 for 3 minutes. Mix the weighed EPS (Expanded Polystyrene) into the mixer, then stir with gear 1 for about 2 minutes until everything is evenly distributed. Fig. 5 show many LWGC's specimen after casting.

Test the fresh concrete properties, such as slump flow and setting time testing. Then, put the test object into a $150\ mm\ \times 300\ mm$ cylinder mold and a $50mm \times 50mm$ cube mold. After the concrete object is molded for 24 hours, the mold is opened. Then, the specimens are cured in an oven at 60^0c for 24 hours are shown in Fig. 6. After initial curing in an oven at 60°C for 24 hours, the specimens were transferred to a room with controlled relative humidity of 65±5% at room temperature (23±2°C) until the designated testing age. This process is important to ensure that the geo-polymerization process continues in a controlled manner, preventing overly rapid drying that could cause micro-cracking.

Fig. 5. Many LWGC's specimens

Fig. 6. Curing in oven LWGC's specimen

3. Result and Discussion

3.1. Setting Time

From the research results, the time setting is shown in Fig. 7. The graph compares the initial time (initial time) and the final time (final time) for three LWGC variations, namely LWGC_1.5, LWGC_2.0, and LWGC_2.5.

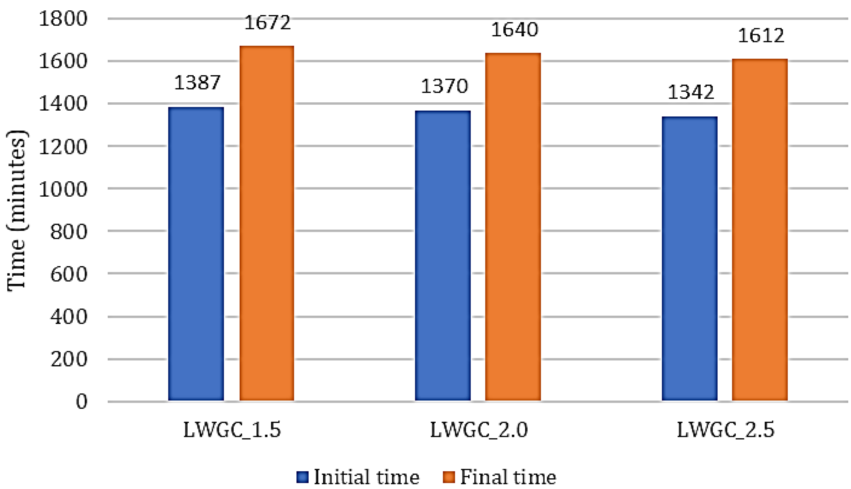

Fig. 7. Setting time LWGC

Time is measured in minutes. The third variation shows a consistent pattern where the initial time ranges from around 1200 minutes and the Final time ranges from around 1500 minutes. The difference between initial and final times is relatively the same for all variations. These results show that the Na_2SiO_3/NaOH ratio has no significant effect. However, LWGC_1.5 takes longer than other variations. This is because the higher proportion of NaOH in the mixture affects the reaction kinetics, so it has a more intensive geo-polymerization reaction [38].

3.2. Slump Flow Test

The workability of the LWGC mixture was measured using slump flow testing by ASTM C1611. The results of the slump flow test for the three mixture variations are shown in Figure 8. The highest slump flow value was obtained in LWGC_1.5 of 22.78 cm, while LWGC_2.0 and LWGC_2.5 reached 21.5 cm and 20.40 cm, respectively. There is a tendency for the slump flow value to decrease with the increase in the Na_2SiO_3/NaOH ratio in the mixture. This decrease in workability can be attributed to the characteristics of sodium silicate (Na_2SiO_3), which has a higher viscosity than sodium hydroxide (NaOH). When the proportion of Na_2SiO_3/ increases in the mixture, the viscosity of the geopolymer paste also increases, resulting in a decrease in the flowability of the mixture. However, all mixture variations still show adequate levels of workability for the casting and compaction process of LWGC with EPS aggregates. The difference in slump value occurs due to different geo-polymerization reactions where different Na_2SiO_3/NaOH ratios affect the rate of aluminosilicate gel formation and polymerization process [37]. The mixture with a lower Na_2SiO_3/NaOH ratio (LWGC_1.5) has a higher NaOH concentration, contributing to increased workability due to the more fluid nature of NaOH.

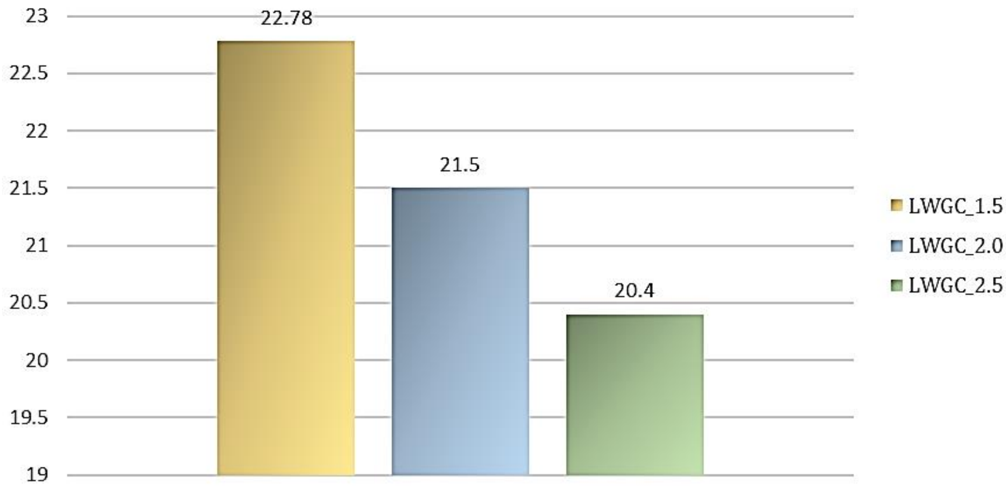

Fig. 8. Slump flow LWGC

3.3. Density

Density testing was conducted to evaluate the effect of Na_2SiO_3/NaOH ratio variations on the specific gravity of LWGC. The density test results presented in Figure 9 show an increase in density values along with an increase in the Na_2SiO_3/NaOH ratio. LWGC_1.5 has the lowest density of 1080 kg/m^3, while LWGC_2.0 and LWGC_2.5 each reached 1217.07 kg/m^3 and 1249.87 kg/m^3. This density increase is related to forming a denser geopolymer matrix structure at a higher Na_2SiO_3/NaOH ratio. Sodium silicate (Na_2SiO_3) plays an important role in forming aluminosilicate gel and the polymerization process, where increasing its proportion produces a more compact structure. Despite the variation in density, all mixtures still meet the criteria for lightweight concrete [31], which requires a maximum specific gravity of 1900 kg/m^3. Using EPS aggregates as a substitute for conventional aggregates contributes significantly to achieving the target specific gravity of lightweight concrete. At the same time, variations in the Na_2SiO_3/NaOH ratio have a more subtle effect on the final density of LWGC [34].

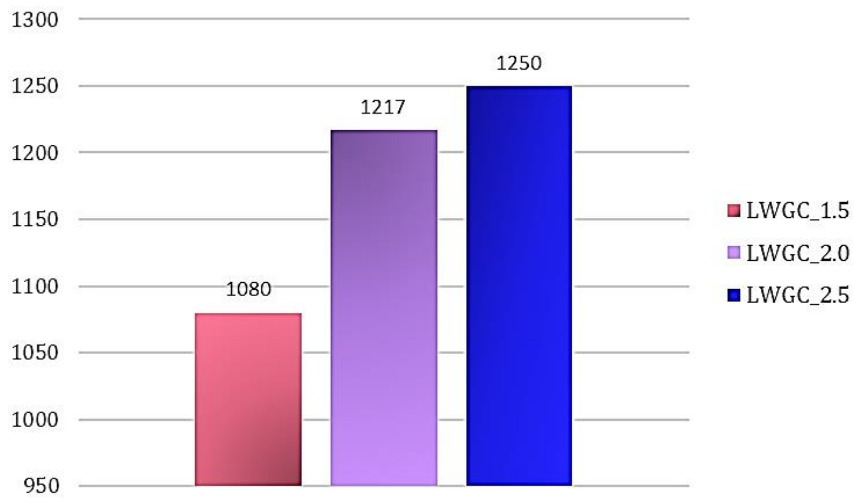

Fig. 9. Density of LWGC

3.4. Compressive Strength

The compressive strength of LWGC was tested at 14 and 28 days to evaluate the effect of varying the Na_2SiO_3/NaOH ratio on the development of concrete compressive strength. As shown in Fig. 10, there is a consistent increase in compressive strength along with the increase in the Na_2SiO_3/NaOH ratio and the age of the concrete. In the 14-day test, LWGC_1.5 achieved a compressive strength of 15.52 MPa, LWGC_2.0 was 17.46 MPa, and LWGC_2.5 obtained the highest value of 21.02 MPa. A similar pattern was seen in the 28-day test with an increase in compressive strength to 16.87 MPa, 18.98 MPa, and 22.85 MPa for LWGC_1.5, LWGC_2.0, and LWGC_2.5, respectively. This increase in compressive strength occurs due to the role of sodium silicate (Na_2SiO_3) in forming the geopolymer structure. Higher Na_2SiO_3/NaOH ratios resulted in a denser geopolymer matrix and a more regular microscopic structure, contributing to the increase in compressive strength. In addition, increasing the concrete age from 14 to 28 days provided more time for the geo-polymerization process, increasing compressive strength by about 10-15% across all mix variations. Despite using EPS aggregates with relatively low strength, the test results showed that LWGC could still achieve adequate compressive strength for lightweight structural applications. LWGC_2.5 showed the best performance with a compressive strength of 22.85 MPa at 28 days, indicating that higher Na_2SiO_3/NaOH ratios resulted in more optimal geopolymer matrix bonding [39].

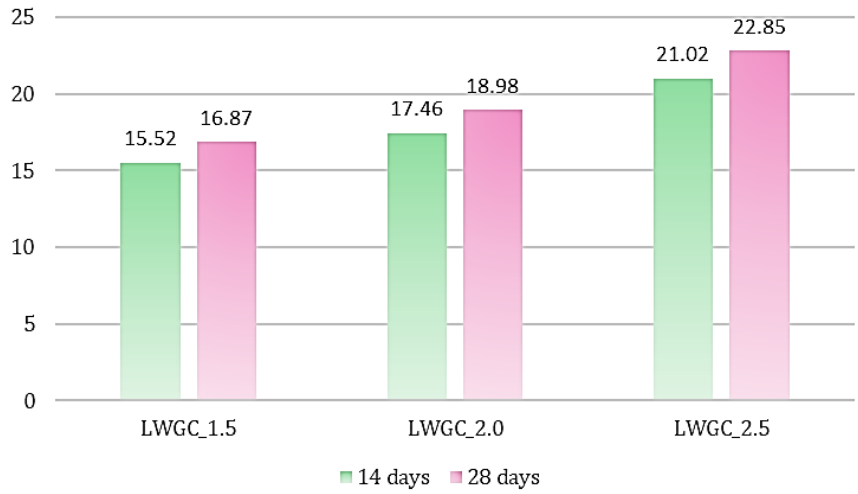

Fig. 10. Compressive strength

3.5. Split Tensile Strength

Splitting tensile strength was tested on cylindrical specimens at 28 days. The results of the splitting tensile strength test are shown in Figure 11. The splitting tensile strength values vary depending on the molarity, and $Na_2SiO_3/NaOH$ ratio used in the mixture. LWGC_1.5 showed the lowest splitting tensile strength, which was 1.23 MPa. Increasing the Alkali activator ratio to LWGC_2.0 resulted in a higher splitting tensile strength of 1.31 MPa. The highest splitting tensile strength was achieved by LWGC_2.5, reaching 1.43 MPa. These results indicate that increasing the molarity and NaOH generally increases the splitting tensile strength of fly ash-based lightweight geopolymer concrete. Higher molarity likely causes a more efficient geo-polymerization process, resulting in a denser and stronger matrix, improving the tensile performance of concrete. The increase in splitting tensile strength, along with increasing variations in alkali activator, indicates the important role of alkali activation in developing the mechanical properties of this lightweight geopolymer concrete [40].

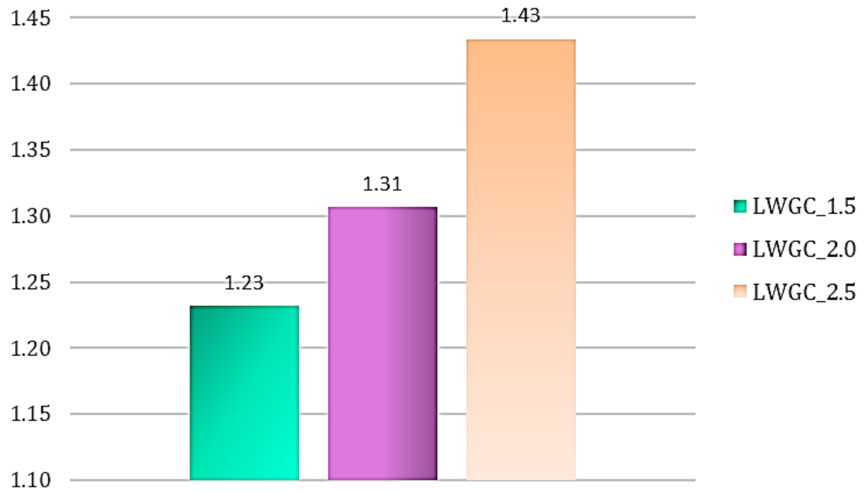

Fig. 11. Split Tensile strength

3.6. Effect of $Na_2SiO_3/NaOH$ Ratio

The results in fig. 12 showed a significant relationship between the alkali activator ratio ($Na_2SiO_3/NaOH$) and the mechanical strength of geopolymer concrete. Based on second-degree polynomial regression analysis, a powerful correlation was obtained between the activator ratio and both compressive strength and splitting tensile strength, indicated by the R^2 value of 1 for both parameters (R^2 = 1 for compressive strength and R^2 = 1 for splitting tensile strength). The compressive strength of geopolymer concrete increased polynomially with increasing activator ratio, following the equation $y = 3.5181x^2 - 8.0961x + 21.098$. The curve pattern indicates that within the tested activator ratio range (1.5 to 2.5), the compressive strength experiences an accelerating rate of increase as the activator ratio increases. The resulting compressive strength varied from 16.87 MPa to 22.85 MPa in this activator ratio range. Correspondingly, the splitting tensile strength also increased polynomially, as the equation $y = 0.1041x^2 - 0.2143x + 1.319$. Although the increase is more moderate than the compressive strength, the polynomial curve reveals that the splitting tensile strength increases at higher activator ratios. The splitting tensile strength values ranged from 1.23 MPa to 1.43 MPa across the tested ratio range.

The polynomial growth trend in both parameters indicates that the geo-polymerization reaction is optimal within the studied activator ratio range and suggests a non-linear effect of the activator ratio on mechanical strength. This may be attributed to the complexity of the geo-polymerization reaction involving the formation of aluminosilicate networks influenced by alkali activator concentration. This polynomial model provides a more comprehensive understanding of material behavior than a simple linear model, with the perfect R^2 value (R^2 = 1) demonstrating that this model is highly accurate in predicting the mechanical strength of geopolymer concrete across various alkali activator ratios. The activator ratio 2.5 gave the best results for both strength parameters, and the absence of an optimum point indicates the potential for further strength increases at higher ratios. This strong correlation also indicates the reliability of the mix design in producing consistent strength, with a ratio of increase in compressive strength to splitting tensile strength [39].

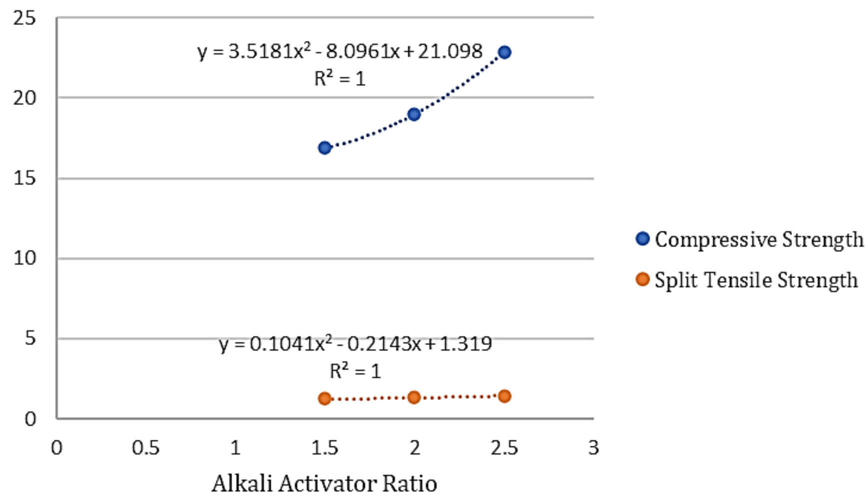

Fig. 12. Effect of $Na_2SiO_3/NaOH$ Ratio

3.7. Future Research

After the research, LWGC has good mechanical properties of compressive and tensile strength and has the potential to be developed. Adding EPS as a lightweight aggregate, replacing ordinary aggregate, and variations in alkali activators provide significant improvements in properties. However, to maximize the potential of this material, several areas of further research can be explored. Future research can focus on further optimization of the mixture composition to improve mechanical performance and durability by further exploring different $Na_2SiO_3/NaOH$ ratios to find the most effective combination in promoting the geo-polymerization reaction and the effect of EPS size variations. Investigating rupture strength for prisms and mechanical testing for 90 days can for next studies. To better understand the underlying mechanisms of lightweight geopolymer concrete behavior, microstructural characterization with techniques such as SEM/EDX and its durability testing are essential. Further research can focus on developing customized mix designs for specific structural applications, such as wall panels, deep beams, building blocks, or precast elements.

4. Conclusions

From the experimental study on the mechanical behavior of LWGC in terms of compressive strength, tensile strength, and fresh material properties using three different alkali activators in concrete, respectively. The following conclusions are drawn:

- The variation in the $Na_2SiO_3/NaOH$ ratio affects the physical and mechanical properties of fly ash-based LWGC with EPS aggregate. LWGC_2.5 shows the best mechanical strength performance, LWGC_2.5, with the highest sodium silicate proportion, exhibits superior mechanical strength characteristics due to the formation of more compact and well-developed alumina-silicate gel networks. While LWGC_1.5 has the highest workability, its higher NaOH concentration, demonstrates superior workability characteristics as the higher alkalinity facilitates faster initial dissolution of fly ash particles, creating a more fluid mixture initially.
- The setting time does not show significant differences between variations, but LWGC_1.5 requires a longer setting time because the higher NaOH concentration results in a more intensive geo-polymerization reaction.

- The slump flow value decreases as the $Na_2SiO_3/NaOH$ ratio increases, with the highest value of 22.78 cm in LWGC_1.5 and the lowest of 20.40 cm in LWGC_2.5. This is due to the higher viscosity of Na_2SiO_3 compared to NaOH.
- The density of LWGC increases with the increase in the $Na_2SiO_3/NaOH$ ratio, ranging from 1080 to 1250 kg/m^3. All variations meet the requirements of lightweight concrete according to ASTMC.125
- The compressive strength of LWGC increases with the increase in the $Na_2SiO_3/NaOH$ ratio and the age of the concrete. At 28 days, LWGC_2.5 achieved the highest compressive strength, 22.85 MPa, followed by LWGC_2.0 (18.98 MPa) and LWGC_1.5 (16.87 MPa).
- The splitting tensile strength at the age of 28 days showed a similar pattern to the compressive strength, where LWGC_2.5 reached the highest value of 1.43 MPa, while LWGC_2.0 and LWGC_1.5 reached 1.31 MPa and 1.23 MPa, respectively.
- The polynomial regression models with perfect R^2 values of 1 for both compressive and splitting tensile strength demonstrate that the mechanical properties of geopolymer concrete increase non-linearly with increasing alkali activator ratio within the tested range (1.5 to 2.5)
- The LWGC has good mechanical behavior and provides sustainable construction materials.
- The implementation of Lightweight Geopolymer Concrete (LWGC) in actual construction projects offers significant advantages, particularly in reducing dead loads on structures

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