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Properties of Fly Ash-Slag-Based Geopolymer Concrete with Low Molarity Sodium Hydroxide

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Abstract

Most geopolymer concrete is produced using low-calcium fly ash and cured at high drying temperatures. Additionally, the activator is prepared with a sodium hydroxide (SH) solution of high molarity. This research proposes using a low molarity SH solution to produce fly ash-slag-based geopolymer concrete cured at room temperature. The properties to be investigated include workability, water absorption, and compressive strength. The influence of mixture composition, i.e., slag content, sodium silicate to sodium hydroxide (SS/SH) ratio, and alkaline activator to binder (Al/Bi) ratio on those properties is of interest. The slag substituted fly ash at 10, 20, 30, 40, and 50% replacement levels. The SS/SH ratio is 1.0, 1.5, and 2.0, with the SH molarity determined at 2M. The Al/Bi ratio is 0.40, 0.45, and 0.50. The results show that a higher percentage of slag reduces slump and water absorption but increases the compressive strength of the geopolymer concrete. The mixtures suitable for use are at the percentages of slag 20, 30, and 40%. An increase in the SS/SH ratio decreases the slump and water absorption. Geopolymer concrete with an SS/SH ratio of 1.5 gives maximum compressive strength compared to the other ratios. Increasing the ratio of Al/Bi increases the workability of geopolymer concrete. At an Al/Bi ratio of 0.45, the compressive strength is maximum and the water absorption is minimum. The recommended mix design in terms of workability, water absorption, and compressive strength of geopolymer concrete is a mixture with slag contents of 20, 30, and 40%, a SS/SH ratio of 1.0 and 1.5, and an Al/Bi ratio of 0.45 and 0.50.

Keywords: Low Molarity Sodium Hydroxide; Workability; Water Absorption; Compressive Strength; Slag; Geopolymer Concrete.

1. Introduction

Sustainability is a major issue in the design and construction of buildings. Therefore, the development of new construction materials must consider the impact caused by materials during production, the construction process, and the service life of the building on the environment. The most significant environmental impact in the case of concrete is the carbon dioxide (CO_2) emissions, primarily due to the CO_2 emissions from cement production [1]. The production of 1 cubic meter of concrete gives CO_2 emissions of 354 kg CO_2-eq, of which 269 kg CO_2-eq (76%) came from cement production [2]. Subsequently, an alternative binder is needed to substitute cement to create more sustainable concrete. One such example is a geopolymer.

Geopolymer concrete is a cement-free concrete where the binder is obtained from the reaction between a precursor and an alkaline activator solution. The precursor is a material with high silica (SiO2) and alumina (Al2O3) content, such as silica fume, fly ash, or ground granulated blast furnace slag (GGBS). The alkaline activator solution can be sodium

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hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate (Na_2SiO_3), or potassium silicate (K_2SiO_3). The precursor and alkaline reaction form a geopolymer paste that bind aggregates and other materials through a polymerization process [3]. Unlike OPC concrete, matrix formation and strength development in geopolymer concrete rely on alumino-silicate polycondensation [4]. Geopolymer concrete has good engineering properties [3] and can be considered a sustainable material due to its low carbon footprint and low energy consumption [5]. Davidovits [6] shows that geopolymer cement produces 80–90% fewer carbon emissions than OPC. Another group of researchers shows that using fly ash and slag waste as a partial or total cement substitution in geopolymer mortar reduces the carbon footprint by more than 100% [7]. Both slag and fly ash are by-products of other processes, and their use can also improve the characteristics of concrete [8].

Fly ash and slag are low-cost materials compared to silica fume and alccofine [9]. Hence, these materials can be the choice for preparing the precursor in geopolymer concrete. Fly ash will react with alkaline solutions to form a Sodium-Alumino-Silicate-Hydrate (N-A-S-H) gel that binds fine and coarse aggregates [10, 11]. Much research works on fly ash-based geopolymer concrete was carried out mainly using low-calcium fly ash [12–14]. The disadvantage of using low-calcium fly ash is the requirement of high drying temperatures for curing, which limits cast-in-place applications [15]. So, the development of geopolymer concrete cured at ambient temperature is currently growing. GGBS, often called slag, can be a key to such development. Slag is a non-metallic product resulting from the residue of blast furnace combustion in the manufacture of refined iron in granular form [15]. This granular material contains CaO, MgO, SiO_2, and Al_2O_3 [16]. The addition of slag to fly ash-based geopolymer mortar, even in small amounts, can omit the necessity of high-temperature curing [17]. It is because the activation of GGBS, which contains high amounts of calcium oxide (CaO), produces Calcium Silicate Hydrate (C-S-H) gel, which increases strength and reduces setting time even when cured at ambient temperature [18]. Other studies have found that a higher substitution of fly ash with slag improves geopolymer concrete's microstructure and mechanical properties. This can be attributed to the increase in Calcium-Alumino-Silicate-Hydrate (C-A-S-H) gel, as the main product of geopolymerization, which has a denser microstructure [11, 17, 19, 20].

In addition to being cured at ambient temperature, the geopolymer concrete also requires certain properties in its fresh state so it can be easily mixed, handled, transported, placed, and compacted. Such properties may be judged by their workability. Unlike OPC, geopolymer concrete tends to have a sticky characteristic due to the presence of silicates, which subsequently results in a lower workability. Geopolymer concrete can be categorized as having low workability if its slump value is below 50 mm. In comparison, slump values between 50-89 mm and more than 90 mm are classified as medium and high workability, respectively [21]. Using slag to substitute fly ash causes a decrease in slump, and the influence is more evident at higher slag content [22, 23]. The lowest slump was obtained with a mixture of 100% slag [24]. In addition to increasing the compressive strength, the higher fly ash substitution by slag can reduce the water absorption, porosity, and sorptivity of concrete [11, 22, 25, 26]. The decrease in water absorption can be attributed to the chemical reactions that occur in the binder. Slag inclusion results in the formation C-A-S-H gels, which are denser than N-A-S-H type gels [27].

Apart from the type of binder used, other variables affect the properties of geopolymer concrete, including the type, concentration, and ratio of the alkaline activator, the Al/Bi ratio, the curing temperature, the curing time, and the SiO_2/Al_2O_3 ratio in the binder. Furthermore, these parameters cannot alone affect the properties of geopolymer concrete [9]. The type of alkaline activator that is most often used is a combination of sodium hydroxide (SH) and sodium silicate (SS), because of the characteristics of the chemical compounds they contain [28]. Another reason is that sodium-based compounds are more widely available, and their cost is lower than that of potassium-based compounds [29]. Of the two types of alkaline activators, SH concentration is one of the variables that has been widely studied. Moreover, most of the research uses SH solutions with moderate to high molarity [15, 17, 23, 28-33]. However, there is still no agreement regarding the optimal SH molarity for geopolymer concrete/mortar mixtures.

An environmental issue could be another consideration in determining the SH molarity. Many studies indicate that the most significant CO_2 emissions in the process of making geopolymer concrete/mortar are from the production process of alkaline activator solution [1, 2, 9, 34, 35]. In addition, using a high molarity of SH has an adverse effect because it is corrosive, exothermic, and less economical. So, Upadhyay et al. [9] recommended using SH concentrations of less than 8M. This research proposes using low molarity of SH solution to produce fly ash-slag-based geopolymer concrete that can be cured at room temperature. The molarity of the SH solution is 2M, which is much lower than suggested by Upadhyay et al. [9]. The properties to be investigated are workability, water absorption, and compressive strength. Meanwhile, the variables to be studied include the effect of slag content, sodium silicate to sodium hydroxide (SS/SH) ratio, and alkaline activator to binder (Al/Bi) ratio. The results will be useful in determining the mixtures of environmentally friendly geopolymer concrete that can be easily applied in construction without compromising its essential properties.

The following section describes the experimental works in detail, covering all the research stages. An overview of the workflow is given first, followed by a description of the raw materials used for producing the geopolymer concrete and their properties, the mix design of the geopolymer concrete, the mixing procedure, the curing method, and finally, testing the specimens. Section 3 discusses the experimental results regarding the effect of using low concentrations of SH (2M) on fly-ash-based geopolymer concrete properties, including workability, water absorption, and compressive strength. Moreover, this section is divided into three sub-sections according to the variables investigated, i.e., slag content as a substitute for fly ash, SS/SH ratio, and Al/Bi ratio. Finally, section 4 conveys the main findings of this research as conclusions.

2. Materials and Methods

2.1. Research Flow

This research consists of several stages. The experimental works start with preparing the materials used in the experiment, determining the mixture composition of the geopolymer concrete, casting, demolding, and curing the specimens, and then testing the specimens. The data obtained from the experimental works are then analyzed to convey the conclusions. Figure 1 illustrates the workflow of this research.

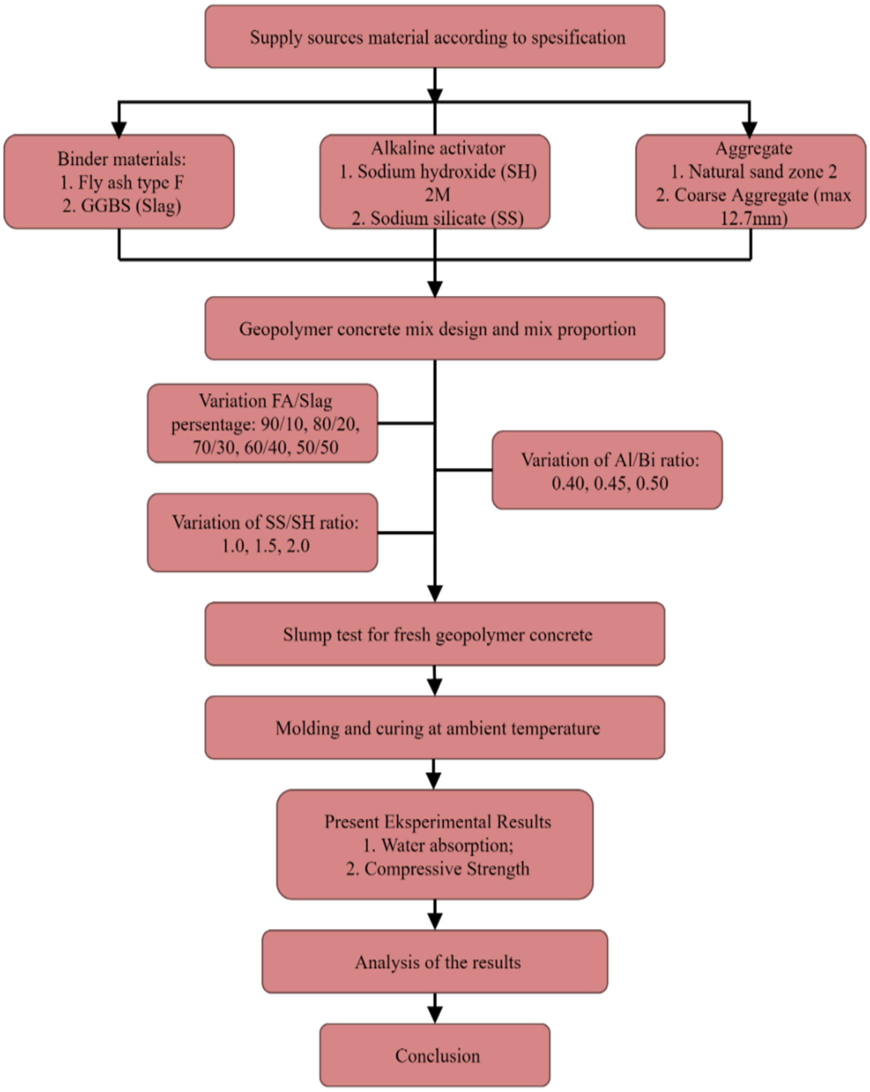


Figure 1. Research flowchart

2.2. Materials

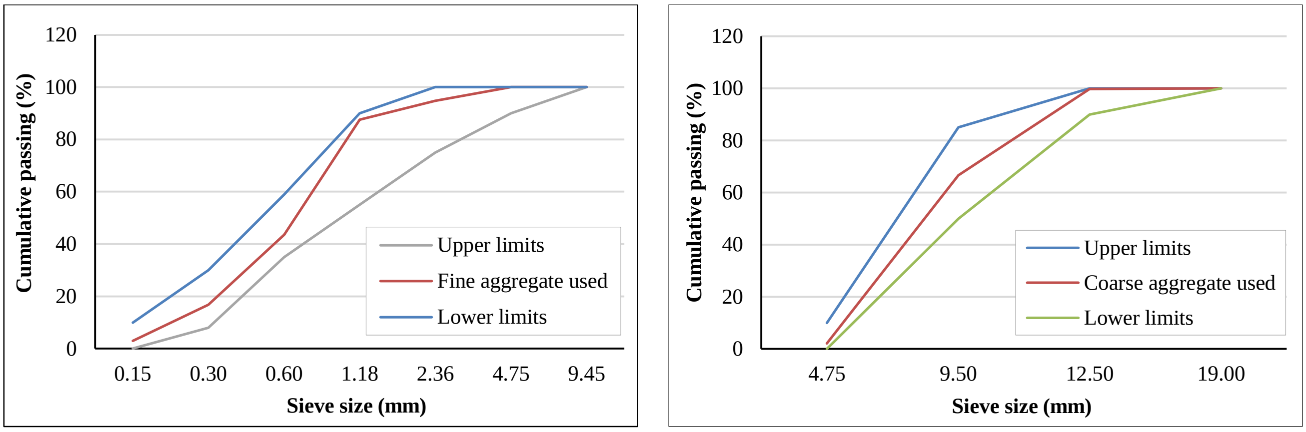
The primary aluminosilicate source used in the manufacture of specimens in this study was class F fly ash, according to ASTM C618, obtained from power plants PLTU Tanjung Jati B, Jepara, Indonesia. The slag used as a partial replacement for fly ash was obtained from PT. Krakatau Semen Indonesia, Cilegon, West Java, Indonesia. Fly ash to be used as a binder must pass through sieve no. 200 with a diameter of 75 μm. The chemical compositions of fly ash and slag were obtained from the X-ray fluorescence (XRF) test, and the results are shown in Table 1. The total SiO_2, Al_2O_3, and Fe_2O_3 content in fly ash is 83.83% (>70%), and calcium oxide content is 8.64% (<10%), so the fly ash belongs to class F. Meanwhile, the slag contains high calcium oxide, which is 62.1%. The fine aggregate is natural sand obtained from Kulonprogo, Yogyakarta, Indonesia, and the coarse aggregate is obtained from PT. Panca Beton, Karanganyar, Central Java, Indonesia, with a maximum aggregate size of 12.7 mm. Figure 2 shows the raw materials for preparing the geopolymer concrete. Based on Figure 3, it can be seen that the fine and coarse aggregate gradations meet the gradation limits, where the fine aggregate gradation falls within zone 2.

Table 1. Chemical composition of class F Fly ash and Slag

Component %	Fly Ash	Slag
SiO_2	41.00	23.50
Al_2O_3	15.00	8.20
Fe_2O_3	26.94	0.95
CaO	8.64	62.10
MgO	0.74	0.30
SO_3	0.50	0.94
K_2O	2.43	0.10
TiO_2	1.71	1.20

(a) (b) (c) (d)

Figure 2. Materials (a) Fine Aggregate, (b) Coarse Aggregate, (c) Fly ash, and (d) Slag



(a) (b)

Figure 3. The grading curve for (a) Fine aggregate; (b) Coarse aggregate

The alkaline activator (Figure 4) used in this research was a mixture of sodium hydroxide (SH) and sodium silicate (SS) solutions. A sodium hydroxide solution was prepared by dissolving a sodium hydroxide pellet of 98% purity in distilled water. The SH solution having a concentration of 2 M was kept constant for all mixtures. The sodium silicate solution used in this study was in the form of a gel with the production code BE-58, which is widely available in chemical stores.

(a) (b)

Figure 4. Alkaline activator (a) Sodium hydroxide, and (b) Sodium silicate

2.3. Mix Proportions, Mixing and Curing

The mixture proportions of nine geopolymer concrete (GPC) used in this study are shown in Table 2. The mix design is based on a normal concrete mix with a design strength of 25 MPa, according to SNI 7656:2012 [36] which is the adoption of modified ACI 211.1-91 [37]. All mixtures have the exact material requirements for sand, coarse aggregate, and binder. The mixed variables include the percentage of slag as a partial replacement for fly ash (based on mass), SS/SH ratio, and Al/Bi ratio. A mixture of GPC1 to GPC5, using the same SS/SH ratio and Al/Bi ratio, was prepared to determine the effect of slag content as a partial replacement of fly ash. A mixture of GPC3, GPC6, and GPC7 was prepared to determine the effect of the SS/SH ratio. Meanwhile, a mixture of GPC3, GPC8, and GPC9 was used to determine the effect of the Al/Bi ratio. The geopolymer concrete mix is determined based on the various components used. For example, S10-1.5-0.45 represents a geopolymer concrete mixture with a slag of 10%, an SS/SH ratio of 1.5, and an Al/Bi ratio of 0.45. No extra water or a superplasticizer is added to the mixture.

Table 2. Details of Mix Proportions

Mix ID	Designation	Concrete Mixture Quantity (Kg/m^3)					
		CA	Sand	Fly ash	Slag	SS	SH
GPC1	S10-1.5-0.45	858	863	360	40	108	72
GPC2	S20-1.5-0.45	858	863	320	80	108	72
GPC3	S30-1.5-0.45	858	863	280	120	108	72
GPC4	S40-1.5-0.45	858	863	240	160	108	72
GPC5	S50-1.5-0.45	858	863	200	200	108	72
GPC6	S30-1.0-0.45	858	863	280	120	90	90
GPC7	S30-2.0-0.45	858	863	280	120	120	60
GPC8	S30-1.5-0.40	858	863	280	120	96	64
GPC9	S30-1.5-0.50	858	863	280	120	120	80

CA: Coarse Aggregate; SS: Sodium Silicate; SH: Sodium Hydroxide.

Mixing of all concrete constituents is carried out mechanically based on the requirements of ASTM C192/C192M-02 [38] regarding to mixing and curing concrete in the laboratory. Both the precursor and alkaline activator were prepared first. In this case, the fly ash and slag were mixed homogenously in a container to obtain a uniform mixture of precursors. The sodium hydroxide solution was prepared 24 hours in advance, and the alkaline activator solution (SS and SH) was mixed 30 minutes before being mixed with other ingredients. After the precursor and alkaline activator were ready, the mixing of geopolymer concrete started with adding sand and coarse aggregate in a mixer and rotating it for 1 minute, then adding a mixture of fly ash and slag and rotating the mixer for another 2 minutes. Finally, an alkaline activator solution of sodium silicate and sodium hydroxide in a specific ratio was added and mixed for 5 minutes to ensure a homogeneous mixture.

Figure 5 shows the mixing process till the specimens were cured. Once the mixing process was complete, the workability of the fresh mixture was determined by slump test. Subsequently, the mixture was poured into cylindrical molds with a diameter of 100 mm and a height of 200 mm. The specimen-making process in the molds was carried out in two layers. Each layer was compacted to achieve a specimen with a minimum pore. After 24 hours, the specimens were removed from the mold and then cured for 28 days. The curing of the specimens was carried out at ambient temperature by storing them in tightly closed plastic bags to avoid excessive moisture loss. Prior to the water absorption test, the cylindrical specimens were cut into cylinders with a diameter of 100 mm and a height of 50 mm.

(a) (b) (c)

Figure 5. Mixing and curing specimen (a) Fresh concrete, (b) Slump test, and (c) Molding and curing

2.4. Testing Specimens

The workability of fresh concrete was tested by slump test, according to ASTM C143/C143M-12 Standard Test Method for Slump of Hydraulic-Cement Concrete. The slump test was carried out immediately after mixing [39]. The water absorption test was conducted in accordance with ASTM 642-97 Standard Test Method for Density, Absorption, and Voids in Hardened Concrete [40]. The compressive strength test (Figure 6) was carried out after 28 days of curing according to ASTM C39/C39M-01 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens [41]. The compressive strength of concrete was tested using a Universal Testing Machine (UTM) with a maximum capacity of 50 tons.

(a) (b) (c)

Figure 6. The compressive strength test: a) Universal Testing Machine, b) Specimen before testing, c) Specimen after testing

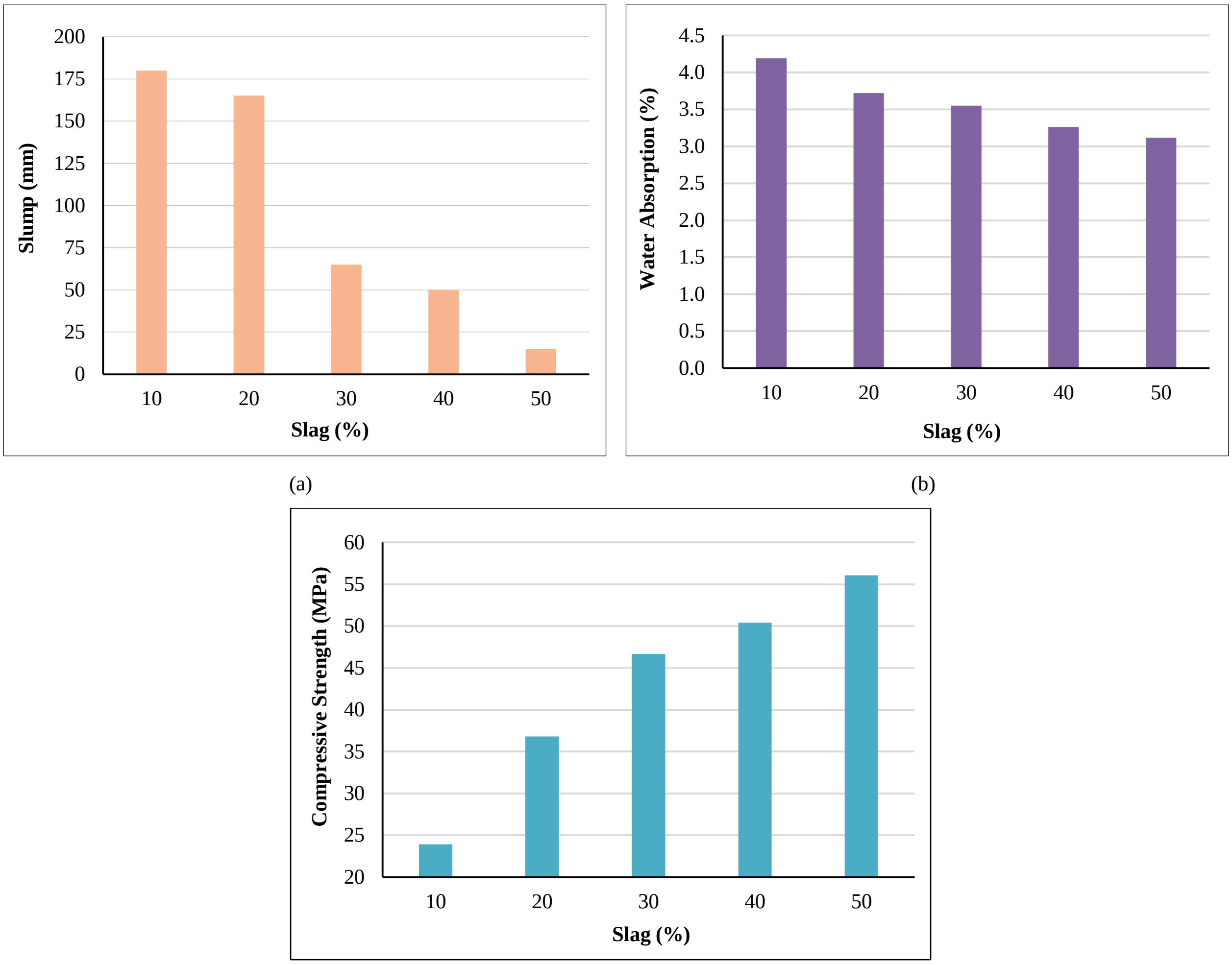
3. Results and Discussion

In this study, nine geopolymer concrete mixtures were made, which were designed to analyze the effect of various parameters on workability, water absorption, and compressive strength of cured concrete at room temperature. The results and discussion will be divided according to the variables investigated, including the effect of slag as a substitute for fly ash, the effect of the ratio of SS/SH, and the effect of the ratio of Al/Bi.

3.1. The Effect of Slag as a Substitute for Fly Ash

The mixtures used to determine the effect of slag as a substitute for fly ash are GPC1, GPC2, GPC3, GPC4, and GPC5, where 10%, 20%, 30%, 40% and 50% of slag are used, respectively. The overall results are shown in Figure 7. Based on Figure 7-a, it can be seen that the slag content of 10% and 20% have slump values of more than 90 mm, so it is classified as highly workable GPC. Geopolymer concrete with 30% and 40% slag content has slump values between 50 mm – 89 mm; it is classified as medium workability. Meanwhile, GPC with a slag content of 50% is classified as geopolymer concrete that has low workability because it has a slump value of less than 50 mm. In addition, it is also seen that the slump value is inversely proportional to the slag content. This means that the more slag used as a partial replacement for fly ash, the lower the slump value. The lower workability of slag-containing concrete is due to the high content of calcium ions dissolved from the slag and its rapid reaction with an alkaline activator and form of calcium silicate hydrate [42]. Fly ash particles have a smooth, spherical surface that helps lubricate the mixture. In contrast to the irregular shape of the slag particles with a rougher surface, it hinders the movement of the mixture [43]. A researcher also stated that the reason for the increase in slump value in the mixture with a high fly ash content was most likely due to the increase in the mobility of the spherical fly ash, in contrast to the irregularly shaped slag particles [24].

The results also show that when the slag content increases in the GPC mixture, the water absorption decreases, and the compressive strength of the concrete increases. As shown in Figure 7-b that the highest water absorption is 4.19% with 10% slag, and the lowest is 3.12% for mix with 50% slag. The maximum compressive strength is 56.076 MPa with 50% slag content, and the lowest is 23.93 MPa when using 10% slag, as shown in Figure 7-c. This condition is caused by an increase in the amount of C-(A)-S-H gel, which leads to the formation of a denser binder matrix and a reduction in the pore volume in the concrete [25]. The decrease in the porosity of concrete in the presence of slag is due to the formation of C-S-H gel through slag activation, which can reduce pores [44]. This is also in line with another study that the increase in slag causes an increase in the formation of C-A-S-H gel, which will reduce the porosity and makes the concrete microstructure denser [45, 46]. In addition, more calcium ions will increase the fly ash dissolution process and form geopolymer gels [22]. This is because the presence of C-A-S-H and C-S-H gel will increase the alkalinity, thereby accelerating the geopolymerization and dissolution of aluminosilicate [47].



(a) (b)

(c)

Figure 7. The relationship between slag as a partial replacement of fly ash with (a) Slump, (b) Water absorption, and (c) Compressive strength of concrete

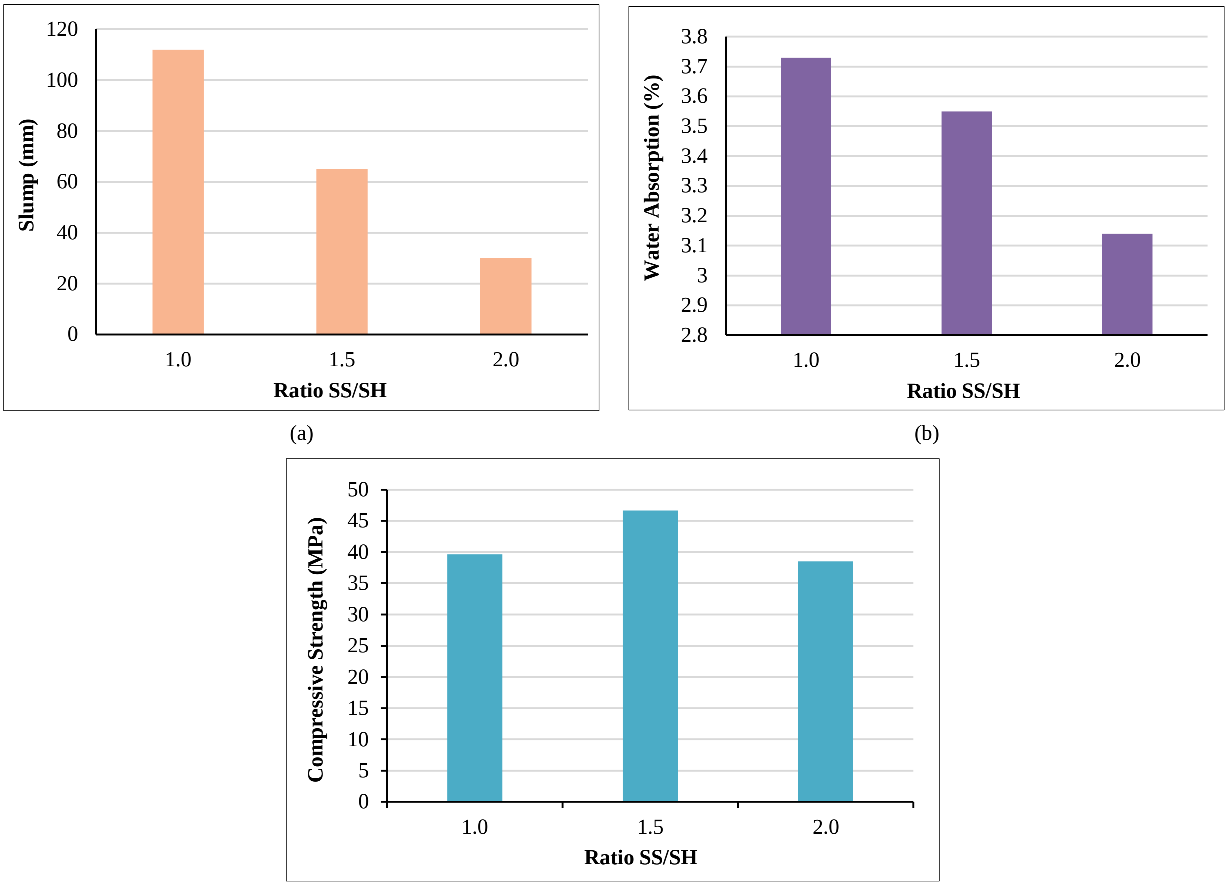
The compressive strength test shows different types of damage between concrete with low and high compressive strength. In low-compressive strength concrete, most cracks occur in the bond between the coarse aggregate and the paste/mortar. Whereas in concrete with high compressive strength, damage occurs due to the breakdown of coarse aggregate. This indicates that the higher the slag content, the stronger and denser the bonds.

Based on the workability and compressive strength of the design concrete, which is 25 MPa, the recommended percentage of slag to be applied is 20%, 30%, and 40%. This is because the 20%, 30%, and 40% slag percentages have high to medium workability. In addition, at these percentages of slag, the compressive strength of the resulting geopolymer concrete is greater than the designed compressive strength.

3.2. The Effect of Sodium Silicate to Sodium Hydroxide Ratio (SS/SH)

The mixtures used to determine the effect of the ratio of sodium silicate to sodium hydroxide (SS/SH) are GPC6, GPC3, and GPC7, where each uses an SS/SH ratio of 1.0, 1.5, and 2.0, respectively. The complete results can be seen in Figure 8.

It can be seen from Figure 8-a, that the slump value decreases with increasing SS/SH ratio. The ratio of SS/SH mainly affects the consistency of the geopolymer mixture. The SS is stickier than SH, so the mixture's viscosity increases with a higher SS/SH ratio. Generally, the slump value of geopolymer concrete decreases with increasing SS content [18, 46]. The SS/SH ratio of 1.0 categorized as high workability with slump values higher than 90 mm, the SS/SH ratio of 1.5 has slump values between 50– 89 mm, so it is categorized as having medium workability. While the SS/SH ratio of 2.0 has a low workability with a slump value of less than 50 mm. The effect of the SS/SH ratio on water absorption is inversely proportional, in which as the SS/SH ratio increases, the water absorption decreases, as shown in Figure 8-b.



(a) (b)

(c)

Figure 8. Relationship of SS/SH ratio with (a) Slump, (b) Water absorption and (c) Compressive strength of concrete

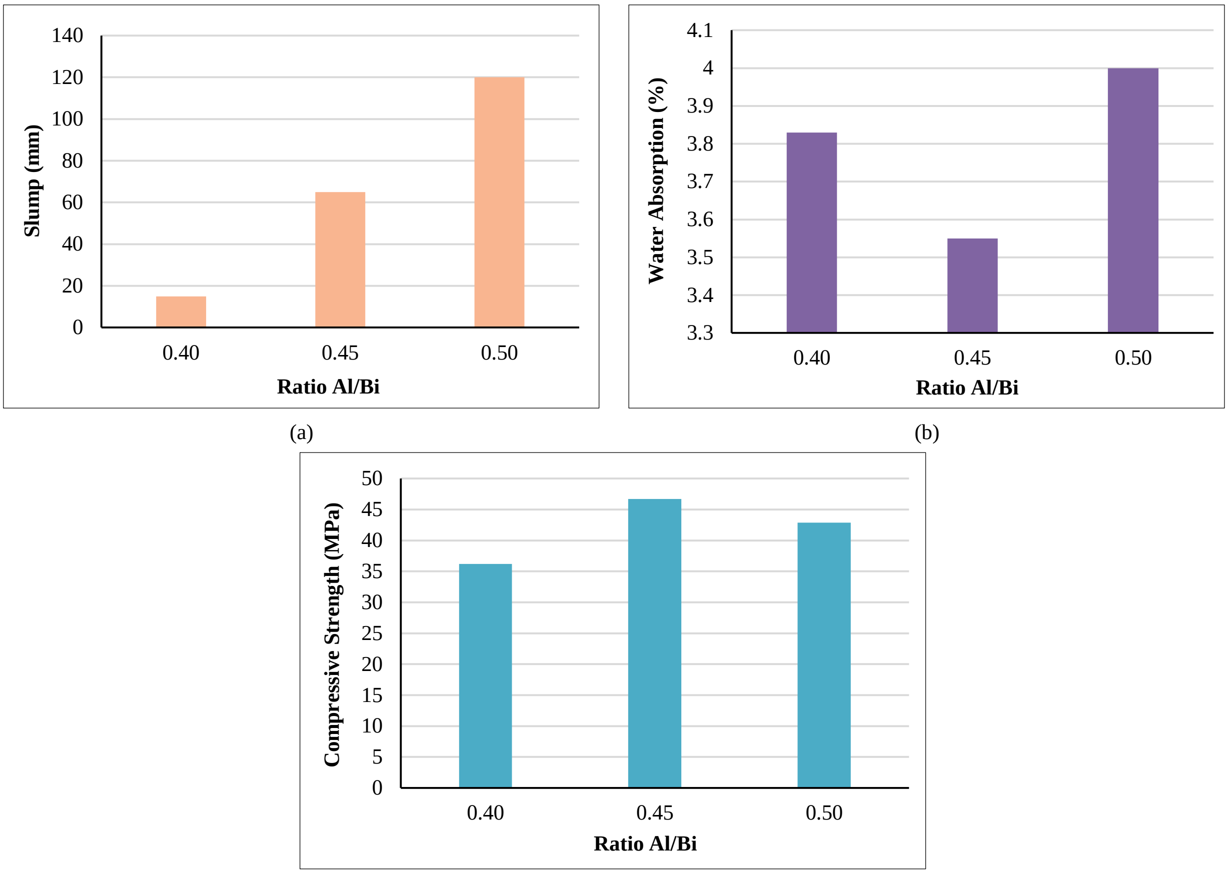
Figure 8-c shows that the optimal SS/SH ratio is 1.5, which produces a maximum compressive strength of 46.667 MPa. The SS/SH ratio of 2.0 produces a lower compressive strength than the ratio of SS/SH 1.5, which is 38.531 MPa or a decrease of 17.43%. This condition also occurs in research conducted by other researchers [18, 46] where the compressive strength decreased when the SS/SH ratio was increased from 1.5 to 2.5. The compressive strength decreases when more silicates are added because the excess sodium silicate inhibits the evaporation process and the formation of the geopolymer matrix. Meanwhile, the compressive strength of the concrete produced at the SS/SH ratio of 1.0 is 39.620 MPa and has decreased by 15.1% when compared to the compressive strength of the SS/SH ratio of 1.5. This is due to the fact that the decrease in silica content causes the polymerized gel to be less dense with poor mechanical properties, resulting in a decrease in the compressive strength of the concrete.

3.3. The Effect of Alkaline Activator to Binder Ratio (Al/Bi)

A mixture of GPC8, GPC3, and GPC9 was used to determine the effect of the ratio of alkaline activator to binder (Al/Bi), with an Al/Bi ratio of 0.40, 0.45 and 0.50, respectively. The overall results can be seen in Figure 9.

Figure 9-a indicates that the slump value increases when the Al/Bi ratio rises. It is because when the ratio of Al/Bi is higher, the content of activator liquid in the mixture is also higher, which subsequently increases the mixture's consistency [18]. This suggests that the content of alkaline activator in the mixture plays a dominant role in the workability of concrete [45]. The Al/Bi ratio of 0.40 has a slump value of less than 50 mm, so it is categorized as low workability. Meanwhile, Al/Bi 0.45 and 0.50 have slump values between 50 mm – 89 mm, so they are categorized as having medium workability.

The relationship between the Al/Bi ratio with water absorption and compressive strength is shown in Figures 9-b and 9-c, respectively. It can be seen that the minimum water absorption and maximum compressive strength are obtained at an Al/Bi ratio of 0.45. At a lower Al/Bi ratio, namely 0.40, the compressive strength is lower because the amount of alkaline activator solution is not sufficient for the geopolymerization reaction. Meanwhile, at an Al/Bi ratio of 0.50, the compressive strength of concrete is also lower. Excessive alkaline activator causes an increase in the amount of water in the mixture, which inhibits the geopolymerization process [48]. The increase in the alkaline activator solution affects the condensation process of the geopolymerization and thereby decreases compressive strength. So it is essential to determine the right amount of alkaline activator to produce a workable geopolymer concrete without compromising the compressive strength [18].



(a) (b) (c)

Figure 9. Relationship of Al/Bi ratio with (a) Slump; (b) Water absorption and (c) Compressive strength

The relationship between the Al/Bi ratio with water absorption and compressive strength is shown in Figures 9-b and 9-c, respectively. It can be seen that the minimum water absorption and maximum compressive strength are obtained at an Al/Bi ratio of 0.45. At a lower Al/Bi ratio, namely 0.40, the compressive strength is lower because the amount of alkaline activator solution is not sufficient for the geopolymerization reaction. Meanwhile, at an Al/Bi ratio of 0.50, the compressive strength of concrete is also lower. Excessive alkaline activator causes an increase in the amount of water in the mixture, which inhibits the geopolymerization process [48]. The increase in the alkaline activator solution affects the condensation process of the geopolymerization and thereby decreases compressive strength. So it is essential to determine the right amount of alkaline activator to produce a workable geopolymer concrete without compromising the compressive strength [18].

4. Conclusions

This paper presents the results of an experimental study conducted to analyze the effect of slag as a partial replacement of FA, the ratio of SS/SH, and the ratio of Al/Bi on the properties of fly ash-slag-based geopolymer concrete. This study's interest is in the geopolymer concrete made using a low molarity SH solution (2 M). Based on the results of the study, it can be concluded that:

- The higher the slag content for fly ash replacement, the lower the slump and water absorption values are; on the other hand, the compressive strength of concrete increases. A mixture with 50% slag content is not workable, so it is necessary to add an admixture to increase the workability. The mixture with a 10% slag content does not meet the design strength because its compressive strength is less than 25 MPa;
- The SS/SH ratio has the same effect on slump and water absorption values; slump and water absorption values decrease when the SS/SH ratio increases. The mixture with an SS/SH ratio of 2.0 is not workable, so it is necessary to add an admixture to increase workability. The maximum compressive strength can be expected in a mixture with an SS/SH ratio of 1.5;
- Increasing the Al/Bi ratio will increase the workability of concrete. Low workability is noted in a mixture with an Al/Bi ratio of 0.4, so an additional admixture is needed if this mixture is to be used. The Al/Bi ratio of 0.45 is the optimum ratio because, in this ratio, maximum compressive strength and minimum water absorption are obtained;

- The recommended mix design for the geopolymer concrete is mixtures with slag contents of 20, 30, and 40%; SS/SH ratios of 1.0 and 1.5; and Al/Bi ratios of 0.45 and 0.50.

Moreover, this study confirms that the low molarity of SH (2M) can be used as an alkaline activator in the production of geopolymer concrete. The resulting properties are comparable to the medium-high molarity of SH. Furthermore, with a smaller mass of NaOH in the SH solution, it gives lower CO_2 emissions. Thus, geopolymer concrete made using low molarity SH is a more environmentally friendly material.

5. Declarations

5.1. Author Contributions

Conceptualization, E.S.S., S.A., and S.A.K.; methodology, E.S.S, S.A., and A.R.M.; software, E.S.S.; validation, E.S.S., S.A., A.R.M., and S.A.K.; formal analysis, E.S.S.; investigation, E.S.S.; resources, E.S.S.; data curation, E.S.S. and S.A.; writing—original draft preparation, E.S.S.; writing—review and editing, E.S.S., S.A., A.R.M., and S.A.K.; visualization, E.S.S.; supervision, S.A.K.; project administration, E.S.S.; funding acquisition, S.A. and S.A.K. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

6. References

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