

## Article

# A Comprehensive Performance Evaluation of GGBS-Based Geopolymer Concrete Activated by a Rice Husk Ash-Synthesised Sodium Silicate Solution and Sodium Hydroxide

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**Abstract:** Commercial sodium hydroxide (NaOH) and sodium silicate (SS) are commonly used as alkaline activators in geopolymer concrete production despite concerns about their availability and associated CO<sub>2</sub> emissions. This study employs an alternative alkaline activator (AA) synthesized from a sodium silicate alternative (SSA) solution derived from rice husk ash (RHA) and a 10 M sodium hydroxide solution. The initial phase established an optimal water-to-binder (W/B) ratio of 0.50, balancing workability and structural performance. Subsequent investigations explored the influence of the alkali/precursor (A/P) ratio on geopolymer concrete properties. A control mix uses ordinary Portland cement (OPC), while ground granulated blast-furnace slag (GGBS)-based geopolymer concrete—GPC mixes (GPC1, GPC2, GPC3, GPC4) vary the A/P ratios (0.2, 0.4, 0.6, 0.8) with a 1:1 ratio of sodium silicate to sodium hydroxide (SS: SH). The engineering performance was evaluated through a slump test, and unconfined compressive strength (UCS) and tensile splitting (TS) tests in accordance with the appropriate standards. The geopolymer mixes, excluding GPC3, offer suitable workability; UCS and TS, though lower than the control mix, peak at an A/P ratio of 0.4. Despite lower mechanical strength than OPC, geopolymers' environmental benefits make them a valuable alternative. GPC2, with a 0.4 A/P ratio and 0.5 W/B (water to binder) ratio, is recommended for balanced workability and structural performance. Future research should focus on enhancing the mechanical properties of geopolymer concrete for sustainable, high-performance mixtures.

**Keywords:** alternative alkaline activator; sodium silicate alternative; rice husk ash; GGBS; geopolymer; unconfined compressive strength; tensile strength; alkali/precursor (A/P) ratio; commercial sodium hydroxide; sodium silicate



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## 1. Introduction

The construction industry contributes significantly to global greenhouse gas emissions and is under increasing pressure to adopt sustainable practices and reduce environmental impact. Cement is an essential binding agent in the construction industry due to the worldwide demand for concrete, a ubiquitous building material. Traditionally, ordinary Portland cement (OPC) has served as the primary binder for concrete. However, OPC is associated with a substantial embodied energy footprint, emitting between 0.66 and 0.82 kg of carbon dioxide (CO<sub>2</sub>-e) per kilogram of production. This makes OPC production a significant contributor, responsible for approximately 5 to 7 percent of the world's anthropogenic CO<sub>2</sub> emissions [1]. This substantial carbon footprint is primarily due to the energy-intensive processes involved in OPC production, including the high-temperature calcination of raw materials and the clinker formation. Moreover, the reliance on finite limestone resources further compounds environmental concerns associated with OPC manufacturing. As the global construction industry continues its rapid expansion, it is imperative to explore more sustainable alternatives to OPC, which are capable of significantly reducing

emissions and mitigating the environmental impact associated with conventional cement production methods. In this context, geopolymer concrete has emerged as a promising alternative to traditional Portland cement-based concrete due to its lower carbon footprint and remarkable mechanical properties. According to research conducted by Turner and Collins [2], geopolymer concrete demonstrates a notable environmental advantage, with CO<sub>2</sub> emissions being approximately 9% lower than Portland cement-based concrete.

In the 1970s, Professor Joseph Davidovits and a team of researchers from France introduced the term “geopolymer” into the scientific discourse. This term was explicitly coined to define a novel class of raw materials resulting from the chemical reaction between aluminosilicate powder and an alkaline solution [3]. This innovative concept marked a significant turning point in materials science, paving the way for the development of geopolymer technology and its applications across various industries. Geopolymers are three-dimensional, inorganic aluminosilicate polymers formed by a chemical reaction [4]. Geopolymer concrete makes use of industrial by-products rich in aluminosilicate sources, such as ground granulated blast furnace slag (GGBS), metakaolin, fly ash, and similar materials, as precursors. These materials react with a highly alkaline activator solution, thereby facilitating waste reduction and the conservation of natural resources [5]. The activation process plays a pivotal role in geopolymerisation, determining the ultimate performance and characteristics of the geopolymer concrete. Commercial sodium hydroxide (NaOH) and sodium silicate (SS) solutions are widely employed activators for geopolymerization [6]. However, it’s essential to acknowledge that the accessibility and cost of these materials can become a notable concern, particularly in regions across the globe. Also, in industrial contexts, the production of sodium silicate typically involves a four-stage process. Initially, a mixture of sodium carbonate (Na<sub>2</sub>CO<sub>3</sub>) and natural quartz sand (SiO<sub>2</sub>) undergoes high-temperature treatment in a specialised furnace, reaching temperatures ranging from 1400 to 1500 °C. This process yields a substance referred to as “solid glass”. Subsequently, this “solid glass” undergoes dissolution in water within a reactive vessel under high-pressure and high-temperature conditions. The resulting solution goes through filtration to attain the desired purity level. Lastly, water evaporation is employed to achieve the desired solution density. Nevertheless, this conventional manufacturing process is characterised by high costs, energy-intensive demands, and environmental concerns, including the emission of greenhouse gases such as carbon dioxide (CO<sub>2</sub>) (Foletto et al., 2006). The energy-intensive and inherently expensive production process of sodium silicate is a significant factor that may impede the sustainability of geopolymer binder manufacturing. This factor can potentially limit the broader adoption and promotion of geopolymer binders compared to conventional Portland cement. To overcome this obstacle, it is crucial to delve into alternative production methods that are not only more cost-effective but also align with sustainable practices. Previous studies have investigated methods for mitigating or abandoning the need for energy-intensive sodium silicate in the geopolymer manufacturing procedure, demonstrating prospective feasibility. These methods centre on the interaction between noncrystalline silica from various origins, such as rice husk ash, silica fume, corncob, and sugarcane bagasse ash, with aqueous sodium hydroxide. These alternative methods of producing alternative forms of sodium silicate aim to reduce both environmental impact and production costs while yielding valuable sodium silicate compounds [7].

More recently, rice husk ash (RHA) has been investigated as a viable source of silica for sodium silicate production. Kamseu et al. [8] investigated the substitution of sodium silicate with an RHA-based solution in metakaolin geopolymer cement. Their findings indicated that sodium silicate derived from RHA, when cured at room temperature (open-air environment), exhibited characteristics similar to those of standard commercial sodium silicate, with an equivalent bulk composition and SiO<sub>2</sub>/Na<sub>2</sub>O molar ratio of 3.1.

In a similar alternative approach but using a different SiO<sub>2</sub>/Na<sub>2</sub>O molar ratio of 1.5, Tchakounte et al. [9] achieved satisfactory results in metakaolin-based geopolymer production by employing alternative alkaline activators. These activators were prepared

using waste glass and rice husk ash. However, limited publications have explored the use of RHA-based sodium silicate solutions for the alkaline activation of other precursors, such as GGBS and fly ash. Additionally, there have not been many studies concerning the alteration of key parameters associated with geopolymer concrete, such as the alkali/precursor (A/P) ratio, water-to-binder (W/B) ratio, the concentration of alkali activator, and the ratio of sodium hydroxide (NaOH) to sodium silicate alternative (SSA).

This study was proposed to investigate and comprehensively analyse the consistency, compressive strength, and tensile strength behaviour of GGBS-based geopolymer concrete activated by an alternative alkaline activator synthesised from a sodium silicate alternative (SSA) solution such as rice husk ash (RHA) and a 10 M sodium hydroxide solution. The study involves varying the W/B ratio and A/P ratio. Furthermore, the incorporation of supplementary materials, such as rice husk ash (RHA), is explored to enhance the sustainability and economic viability of geopolymer concrete, aiming for a reduced environmental impact and tailored engineering properties.

## 2. Materials

A comprehensive understanding of the materials under investigation is crucial. The materials used in this study include ordinary Portland cement (OPC), ground granulated blast furnace slag (GGBS), rice husk ash (RHA), sodium hydroxide (NaOH), and coarse and fine aggregate components. Lafarge Cement UK manufactured and supplied ordinary Portland cement (OPC) in strict compliance with the standards outlined in BS EN 197-1:2011 [10]. Ground granulated blast-furnace slag (GGBS) was used as the precursor material in this study, and adhered to BS EN 15167-1:2006 standards [11]. Civil and Marine Slag Cement Ltd., Llanwern, Newport, UK, manufactured and supplied the GGBS used throughout this research. Detailed information regarding the oxide composition of OPC, GGBS, and RHA is available in Table 1 [12]. In addition, the physical characteristics of OPC and GGBS are detailed in Table 2 [13].

**Table 1.** Major oxides in OPC, GGBS, and RHA [12].

Oxide	Composition (wt%)		
	OPC	GGBS	RHA
CaO	61.49	37.99	0.56
MgO	3.54	8.78	0.30
SiO <sub>2</sub>	18.84	35.54	93.20
Al <sub>2</sub> O <sub>3</sub>	4.77	11.46	0.58
Na <sub>2</sub> O	0.02	0.37	0.08
P <sub>2</sub> O <sub>5</sub>	0.1	0.02	-
Fe <sub>2</sub> O <sub>3</sub>	2.87	0.42	0.20
Mn <sub>2</sub> O <sub>3</sub>	0.05	0.43	-
K <sub>2</sub> O	0.57	0.43	3.04
TiO <sub>2</sub>	0.26	0.70	-
V <sub>2</sub> O <sub>5</sub>	0.06	0.04	-
BaO	0.05	0.09	-
SO <sub>3</sub>	3.12	1.54	-
Loss on ignition	4.3	2.00	1.20

The alkaline activator used in the current study (sodium hydroxide) was used to activate the abundant silica (SiO<sub>2</sub>) present in RHA to produce the sodium silicate activator (SSA) necessary for initiating the polymerisation process and contributing to the unique properties of the geopolymer cement. Rice husk ash produced a sodium silicate activator (SSA), an essential ingredient for initiating the polymerization reaction. The raw materials for this research comprised RHA obtained from the combustion of rice husk sourced from a paddy rice mill in Bamenda, located in the North-West Region of Cameroon. The rice husk underwent a controlled firing process at 700 °C for 2 h to obtain the RHA. Key oxide composition data for the RHA can be found in Table 1 [12]. The alkaline activator

used in this study was a 10 M sodium hydroxide (NaOH) solution with a density of  $1.33 \text{ g/cm}^3$ , formulated using laboratory-grade NaOH pellets with a purity of 98% from Fisher Scientific UK, and prepared by dissolving the pellets in de-ionised water as described by Adeleke et al. [12].

**Table 2.** Physical properties of OPC, GGBS, and RHA [13].

Properties	OPC	GGBS	RHA
Insoluble residue	0.5	0.3	0.42
Bulk density ( $\text{kg/m}^3$ )	1400	1200	781
Specific gravity ( $\text{g/cm}^3$ )	3.15	2.9	2.14
Glass content	-	90	-
Blaine fineness ( $\text{m}^2/\text{kg}$ )	365	450	332
Alkalinity value (pH)	13.41	10.4	7.2
Colour	Grey	Off-white	Brownish-white
Physical form	Fine powder	Fine powder	Fine powder

In this study, fine aggregate material was sourced from natural river sand dredged from the Bristol Channel. The sand, supplied by a local supplier, met the specifications outlined in 14 BS EN 12620:2002+A1:2008 [14]. Two different grades of coarse aggregates were used, specifically 20 mm and 10 mm in size. Both coarse aggregates were supplied from a local quarry and delivered by a local supplier, ensuring compliance with the specifications outlined in 14 BS EN 12620:2002+A1:2008 [14]. Table 3 provides an overview of the fundamental physical characteristics of coarse and fine aggregates [12].

**Table 3.** Physical characteristics of coarse and fine aggregates [12].

Property	Fine Aggregates (Sand)	Coarse Aggregates	
		10 mm	20 mm
Uniformity coefficient (CU)	0.11	3.3	1.3
Curvature coefficient (CC)	1.75	1.5	7.5
Flakiness index (%)	-	30–35	23
Elongation index (%)	-	17–22	12
Shape index (%)	-	12	7
Impact value	-	23	15
Fineness modulus (mm)	1.54	4	-
Uncompacted bulk density ( $\text{g/cm}^3$ )	1.5	1.35	2.57
Predried particle density ( $\text{g/cm}^3$ )	2.6	2.69	-
Water absorption (%)	21	2	1.1

### 3. Methodology

#### 3.1. Mix Design

This study investigated the formulation of geopolymer mixtures using an alternative sodium silicate solution made from RHA and sodium hydroxide as the alkaline activator, which is combined with GGBS as a precursor for geopolymer concrete production. The first approach focused on determining the optimal water-to-binder ratio by employing RHA-derived sodium silicate solution and sodium hydroxide as alkaline activators for geopolymer concrete production. The second approach involved examining the impact of varying the alkaline activator/precursor (A/P) ratio on the properties of geopolymer concrete. In the second approach, the same alkaline activator, precursor, and the preliminary test determined the optimal water-to-binder ratio were used with varying the alkaline activator/precursor (A/P) ratio.

##### 3.1.1. Mix Design for Geopolymer Mortar

Six samples of geopolymer mortar mixtures were prepared to achieve the first objective. A consistent binder-to-fine aggregate ratio of 1:3 was maintained for all the mixtures used

in this study. GGBS was the sole and exclusive precursor material used in the context of the study. Furthermore, an alkaline activator comprising SSA and SH in a 1:1 proportion was utilised. To optimise the alkali content, an alkali/precursor ratio of 0.2 was upheld in the GGBS-based geopolymer cement mortar mixtures utilised in this preliminary investigation. This was achieved by varying the water-to-binder (W/B) ratio to 0.40, 0.42, 0.44, 0.46, and 0.50. These mixtures were labeled as GPM1, GPM2, GPM3, GPM4, GPM5, and GPM6, as detailed in Table 4.

**Table 4.** Mix proportions for geopolymer mortar cube production for compressive strength test.

Mix Code	W/B Ratio	A/P Ratio	Precursor (kg)	Alkaline Activator (SS:SH = 1:1)		Fine Agg. (kg)	Water (kg)
			GGBS	SSA (kg)	SH (kg)		
GPM1	0.40	0.2	550	0.064	0.046	1.980	0.195
GPM2	0.42	0.2	550	0.064	0.046	1.980	0.208
GPM3	0.44	0.2	550	0.064	0.046	1.980	0.221
GPM4	0.46	0.2	550	0.064	0.046	1.980	0.234
GPM5	0.48	0.2	550	0.064	0.046	1.980	0.247
GPM6	0.50	0.2	550	0.064	0.046	1.980	0.260

### 3.1.2. Mix Design for Geopolymer Concrete

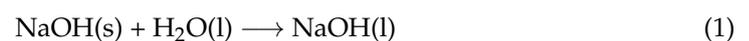
The second approach was centred on examining the impact of varying the alkaline activator/precursor (A/P) ratio on the properties of GGBS-based geopolymer concrete activated by a sodium silicate solution synthesised from rice husk ash and sodium hydroxide. A binder-to-sand-to-aggregate ratio of 1:2:3 and a 0.55 water/binder ratio were adhered to for the control mix in this phase. In this control mix, the binder consisted of 100 percent Portland cement with a content of 372 kg/m<sup>3</sup>, corresponding to what is commonly classified as C30 concrete. This particular mixture was labelled as 100 PC.

In contrast, GGBS-based geopolymer cement was employed instead of Portland cement in all other mixtures. A water-to-binder (W/B) ratio of 0.50, determined through preliminary testing, was adopted for all GGBS-based geopolymer concrete mixes. Within the alkaline activator, sodium silicate alternative (SSA) and sodium hydroxide (SH) were utilised in a 1:1 ratio using 1.84 g/cm<sup>3</sup> and 1.33 g/cm<sup>3</sup>, respectively. The alkali/precursor ratio was then systematically adjusted to 0.2, 0.4, 0.6, and 0.8, resulting in the labelling of these mixtures as GPC1, GPC2, GPC3, and GPC4, respectively, as elaborated in Table 6.

### 3.2. Preparation of Alkaline Activators (AA)

An alkaline activator was produced by mixing sodium hydroxide solution (SH) with a sodium silicate alternative solution (SSA) synthesised from rice husk ash in a 1:1 volume ratio. This selection of a 1:1 (SH:SSA) volume ratio aligns with previous research, which has shown to be a commonly used proportion suitable for specific geopolymer formulations [15].

For this research, a sodium hydroxide (NaOH) mixture with a molarity of 10 (10 M) was considered. To prepare a 10 M solution, 400 g of NaOH must be dissolved in 1 L of water, as shown in Equation (1).



An alternative sodium silicate solution (SSA) was created by mixing NaOH solution with rice husk ash (RHA). Equation (2) illustrates the reaction, where two moles of sodium hydroxide (NaOH) in liquid form react with two moles of silicon dioxide (SiO<sub>2</sub>) in solid form to produce one mole of sodium disilicate (Na<sub>2</sub>O(SiO<sub>2</sub>)<sub>2</sub>) and one mole of water (H<sub>2</sub>O) in liquid form.



To prepare the sodium silicate alternative solution (SSA) sample, an additional batch of 10 M Sodium Hydroxide (NaOH) solution was meticulously prepared. This step involved carefully mixing the rice husk ash (RHA) with the freshly prepared 10 M NaOH solution. To calculate the required amount of rice husk ash (RHA) for the SSA sample, Equation (2) was considered, taking into account the desired molarity of the NaOH solution (10 M) and the purity of the RHA (which has a SiO<sub>2</sub> content of 93.2%). Consequently, 643.78 g of RHA is mixed with 1 L of the 10 M NaOH solution to prepare the 5 mole SSA sample.

The solution containing SH and SSA was carefully prepared and sealed in a container, maintained at an ambient temperature of  $20 \pm 2$  °C for a 24-h period before its subsequent use as an activator for the aluminosilicate precursor. This step is crucial to achieve chemical equilibrium in the exothermic reaction involving SH and to ensure the complete dissolution of rice husk ash particles. This step holds significant importance because the exothermic nature of the activator has the potential to expedite the geopolymerisation process, which could have adverse effects on the properties of geopolymer concrete in its fresh state, as highlighted in previous studies [12].

### 3.3. Preparation of Geopolymer Mortar Specimens and Testing Methods

The mixed ingredients were placed in a mortar mixer for 3 min to prepare fresh geopolymer mortar for each mix design, as detailed in Table 4. After achieving homogeneity, initial setting time tests were performed on the fresh geopolymer mortar using an automatic penetrometer (Vicatron) equipped with a penetration needle at an ambient temperature of  $23 \pm 2$  °C according to BS EN 196-3:2016 [16]. In addition, nine geopolymer mortar test cube specimens (50 × 50 mm) were prepared for each mix composition as specified in Table 5 for compressive strength testing. The mixed ingredients were placed in a mortar mixer for 3 min to create fresh geopolymer mortar for each mix design. Subsequently, the fresh geopolymer mortar was filled into steel moulds in three layers, with each layer being hand-compacted. The mortar was then allowed to cure in the moulds for 24 h at ambient temperature. After demolding, the hardened mortar samples were placed in a container and subjected to moist curing at  $23 \pm 2$  °C and a humidity level of at least 70%. The compressive strength of each mix was tested in the hardened geopolymer mortar following BS EN 1015-2:1999 guidelines after 3, 7, and 28 days of moist curing [17]. The cube specimens were subjected to a crushing load at a rate of 3 kN/s. The average compressive strength for each mix composition at each age was determined by calculating the mean of three results.

**Table 5.** Mix proportions for geopolymer mortar cylinder production for initial setting time test.

Mix Code	W/B Ratio	A/P Ratio	Precursor (kg)	Alkaline Activator (SS:SH = 1:1)		Fine Agg. (kg)	Water (kg)
			GGBS	SSA (kg)	SH (kg)		
GPM1	0.40	0.2	96	0.011	0.008	0.345	0.034
GPM2	0.42	0.2	96	0.011	0.008	0.345	0.036
GPM3	0.44	0.2	96	0.011	0.008	0.345	0.039
GPM4	0.46	0.2	96	0.011	0.008	0.345	0.041
GPM5	0.48	0.2	96	0.011	0.008	0.345	0.043
GPM6	0.50	0.2	96	0.011	0.008	0.345	0.046

### 3.4. Preparation of Geopolymer Concrete Specimens and Testing Methods

A mixing procedure was initially employed to prepare the geopolymer concrete. Firstly, the dry ingredients (cement, precursor, and fine and coarse aggregates) were accurately weighed, as detailed in Table 6. Thereafter, they were mixed in a mechanical mixer for 2 min to achieve a uniform dry mixture. Subsequently, a premeasured quantity of SS and SH solution was slowly introduced to the dry mixture and mixed for two minutes. Additional water was added, followed by a final two-minute mixing phase, to create the fresh concrete.

Table 6. Mix proportions for concrete.

Mix Code	Elaborated Abbreviation	W/B Ratio	OPC (kg)	Precursor (kg)	A/P Ratio	Alkaline Activator (SS:SH = 1:1)		Fine Agg. (kg)	Coarse Agg. (kg)		Water (kg)
				GGBS		SSA (kg)	SH (kg)		10 mm	20 mm	
100 PC	OPC (Control)	0.55	4.8					9.6	4.8	9.6	2.64
GPC1	GPC1-AP0.2	0.5		4.0	0.2	0.464	0.335	9.6	4.8	9.6	1.90
GPC2	GPC2-AP0.4	0.5		3.4	0.4	0.813	0.588	9.6	4.8	9.6	1.52
GPC3	GPC3-AP0.6	0.5		3	0.6	1.045	0.755	9.6	4.8	9.6	1.26
GPC4	GPC4-AP0.8	0.5		2.7	0.8	1.277	0.923	9.6	4.8	9.6	1.01

OPC—ordinary Portland cement; GGBS—ground granulated blast-furnace slag; A/P—activator/precursor ratio; SS:SH—sodium silicate to sodium hydroxide ratio; Fine Agg.—fine aggregate.

The consistency of the fresh concrete was assessed using the slump test in accordance with BS EN 12350-2:2019 [18]. Afterwards, eight cubes (100 mm × 100 mm × 100 mm) and two cylindrical specimens (100 mm diameter × 200 mm height) were prepared for each mix composition in accordance with BS EN 206:2013+A2:2021 [18,19]. The test specimens were demoulded after 24 h and subsequently underwent moisture curing in a container for 7 days, 28 days, and 56 days, according to BS EN 12390-2:2019 [20]. The hardened properties of all concrete specimens were assessed for unconfined compressive strength (UCS) at curing durations of 7, 14, 28, and 56 days and for tensile splitting strength (TSS) at 28 days. These tests were carried out in compliance with BS EN 12390-3:2019 [21] and BS EN 12390-6:2009 [22], respectively. The produced concrete cubes were crushed (UCS test) at a rate of 6 kN/s, while the cylindrical specimens for the TS test were crushed at a rate of 2 kN/s. The reported results for the UCS and TS tests are the average values obtained from two cube and two cylinder specimens for each batch mix composition tested at specified curing ages (7, 14, 28, and 56 days) [23].

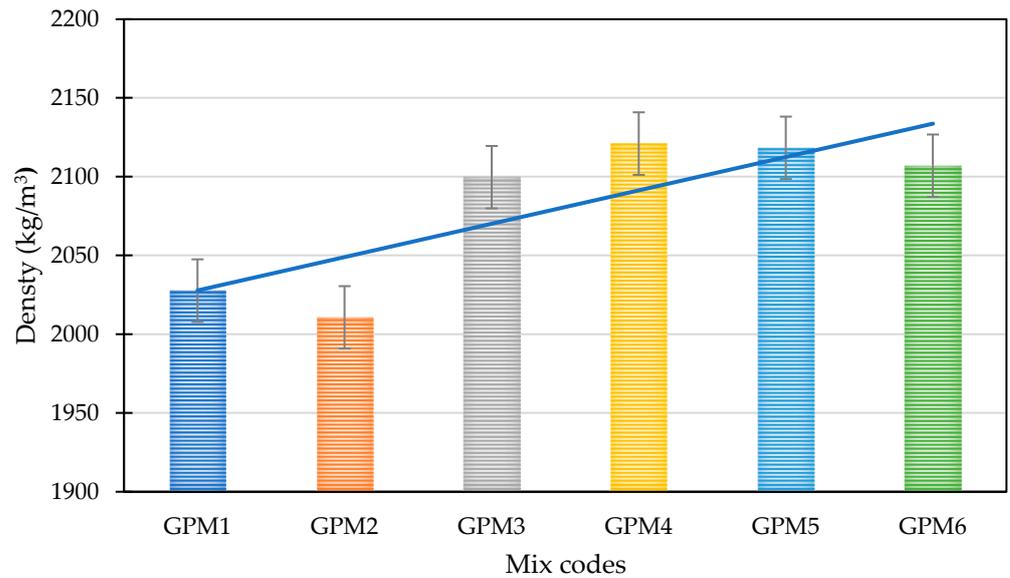
#### 4. Results

##### 4.1. Initial Setting Time of Fresh Geopolymer Mortar

The analysis of initial setting time test results for various geopolymer mortar mixtures were labelled GPM1, GPM2, GPM3, GPM4, GPM5, and GPM6. These mixtures were prepared with varying water-to-binder (W/B) ratios of 0.40, 0.42, 0.44, 0.46, 0.48, and 0.50 and they exhibited initial setting times of 17, 12, 10, 9, 18, and 39 min, respectively. It is noteworthy that as the W/B ratio increased from 0.40 to 0.46, the initial setting time decreased, but after reaching a W/B ratio of 0.46, it began to increase again more rapidly. The above results indicate a significant variation in initial setting times with changes in the W/B ratio. The highest W/B ratio used in this research (0.50) generally resulted in the longest initial setting time (39 min). For all other samples, the initial setting times did not show a substantial difference, ranging from 9 min to 18 min, and were not within the reliable workability range.

##### 4.2. Density of Geopolymer Mortar

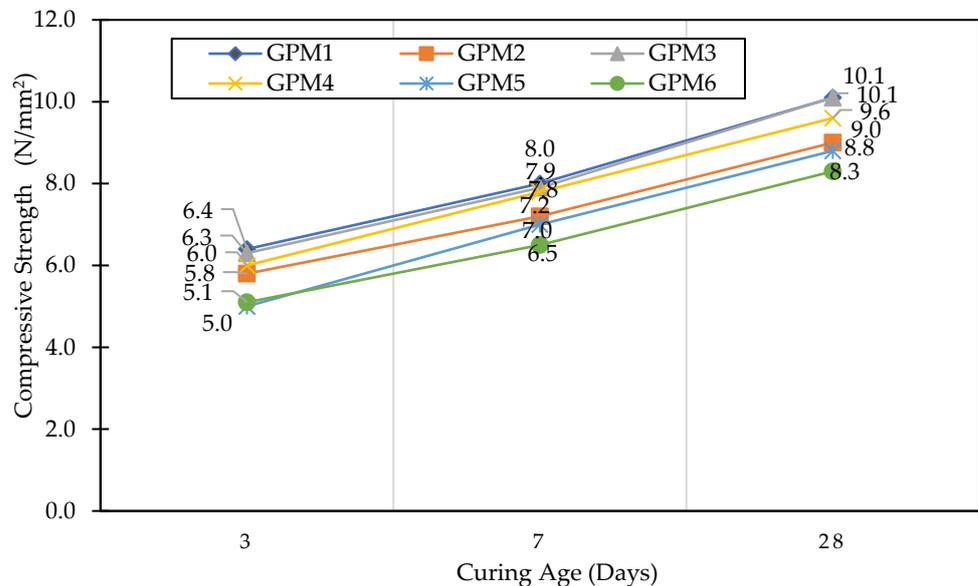
The results of the average density of hardened geopolymer mortar are presented in Figure 1. Individual density values of the test cubes were considered to calculate the average density. Among the various mixes, GPM4, with a water-to-binder (W/B) ratio of 0.46, achieved the highest density at 2121 kg/m<sup>3</sup>. Conversely, the lowest densities were observed in GPM2, which had a W/B ratio of 0.42, with a value of 2010.7 kg/m<sup>3</sup>. The trend in the data suggests that density generally increases as the W/B ratio increases up to a certain point (from W/B ratio 0.40 to 0.46). Beyond that point, with increasing W/B ratios, the density starts to decrease. For instance, GPM5 and GPM6 with W/B ratios of 0.48 and 0.50, respectively, exhibited densities of 2118.3 kg/m<sup>3</sup> and 2107.0 kg/m<sup>3</sup>.



**Figure 1.** The average density of hardened geopolymer mortar cubes.

4.3. Results of Compressive Strength of Geopolymer Mortar

Figure 2 shows the results of the compressive strength tests of the geopolymer mortar mixtures at 3 days, 7 days, and 28 days are presented in Figure 2. All the mixtures exhibited an increase in strength over time. Specifically, the compressive strength of the GPM1 mixture, which had the lowest water-to-binder ratio (0.4), showed the highest values at 7, 14, and 28 days, measuring 6.4, 8.0, and 10.1 N/mm<sup>2</sup>, respectively. On the other hand, Mix GPM5 exhibited the lowest strength values at 3 days with a value of 5.0 N/mm<sup>2</sup>. Meanwhile, GPM6, with the highest water-to-binder ratio of 0.50, demonstrated the lowest strength values at 7 days and 28 days, measuring 7.0 and 8.3 N/mm<sup>2</sup>, respectively.

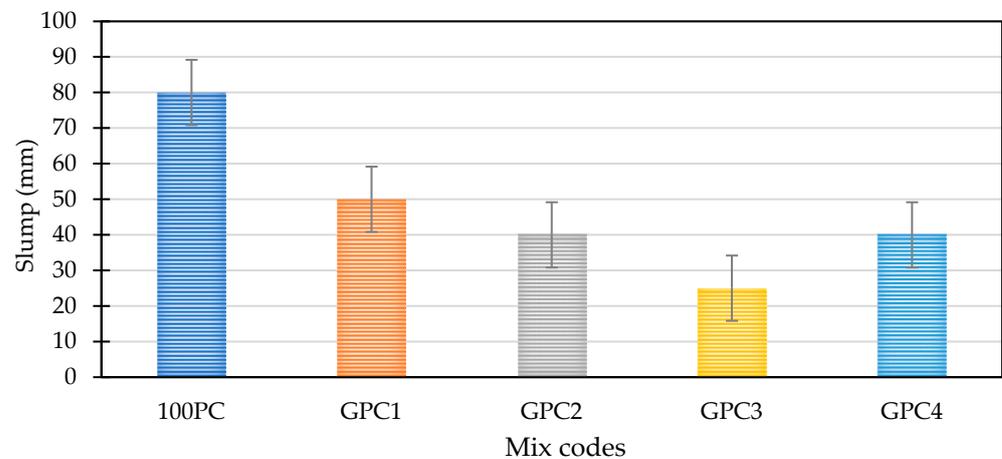


**Figure 2.** Compressive strength of geopolymer mortar cubes at 3, 7, and 28 days.

4.4. Slump Test Results of Geopolymer Concrete

Figure 3 illustrates the results obtained from the slump test, which was conducted to evaluate the consistency of the fresh concrete. The control mix, labeled as 100 PC, displayed the highest slump value of 80 mm. The lowest slump value of 25 mm was observed in GPC3, while the highest slump value among the geopolymer concrete mixes was recorded

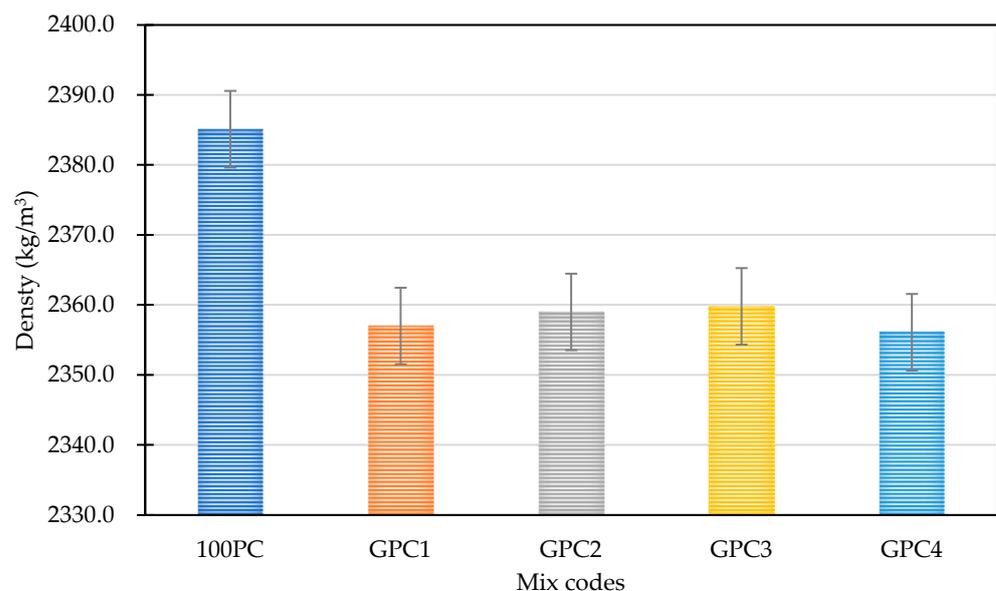
for GPC1 with a value of 50 mm. Analysing the data trends, it becomes apparent that the consistency generally decreases as the A/P ratio increases. However, it is noteworthy that GPC4, which had the highest A/P ratio, deviated from the observed slump pattern.



**Figure 3.** Result of the slump test of fresh geopolymer concrete.

#### 4.5. Density of Geopolymer Concrete

The average density results for hardened concrete are presented in Figure 4. The average density of the individual density values of the test cubes was taken into account. The control mix (100 PC) achieved the highest density at  $2385.1 \text{ kg/m}^3$ . In contrast, the lowest density was observed in the geopolymer mixture GPC4, characterised by the highest alkali/precursor (A/P) ratio of 0.8 used in the study, with a recorded density of  $2356.1 \text{ kg/m}^3$ . Among the geopolymer concrete mixes, the highest density was recorded for GPC3, with a value of  $2359.8 \text{ kg/m}^3$ . It is worth noting that the differences in density among the geopolymer concrete mixes were very small. However, the control mix with 100% OPC, consistently displayed considerably higher density when compared to all the geopolymer concrete mixes.

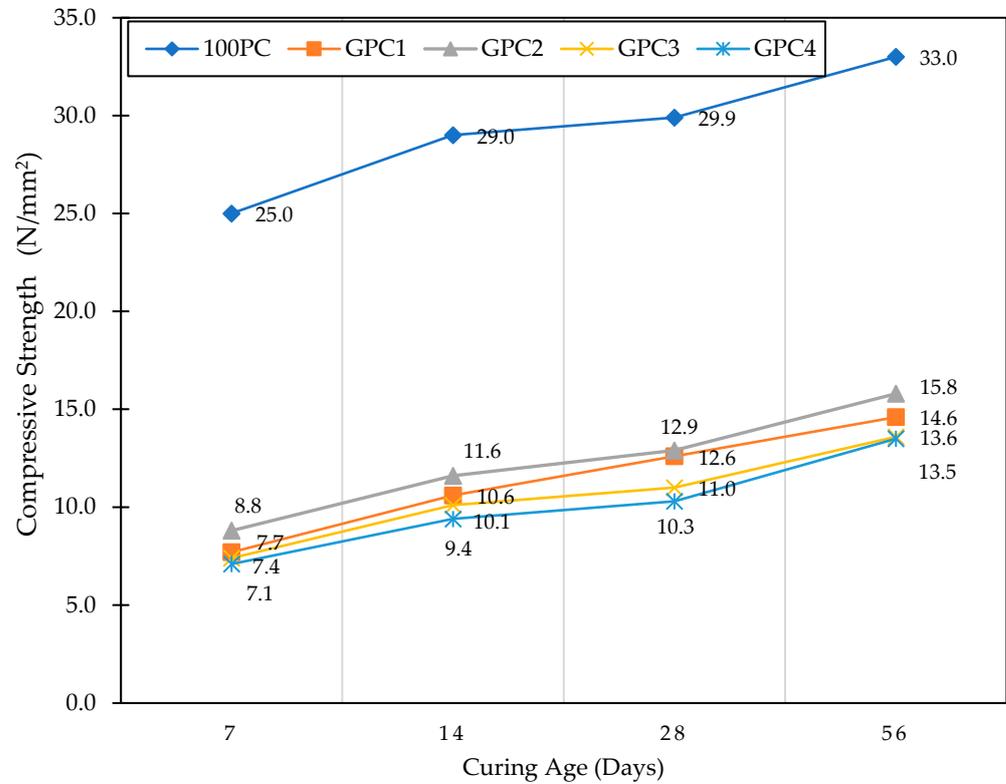


**Figure 4.** Average density of hardened concrete.

#### 4.6. Compressive Strength Results at Various Curing Times

The results of the compressive strength tests at 7 days, 14 days, 28 days, and 58 days are illustrated in Figure 5. All of the mixes gained strength with time. The control mix

consistently displayed the highest compressive strength at all four testing intervals with values of 25.0 N/mm<sup>2</sup> at 7 days, 29.0 N/mm<sup>2</sup> at 14 days, 29.9 N/mm<sup>2</sup> at 28 days, and 33.0 N/mm<sup>2</sup> at 58 days.



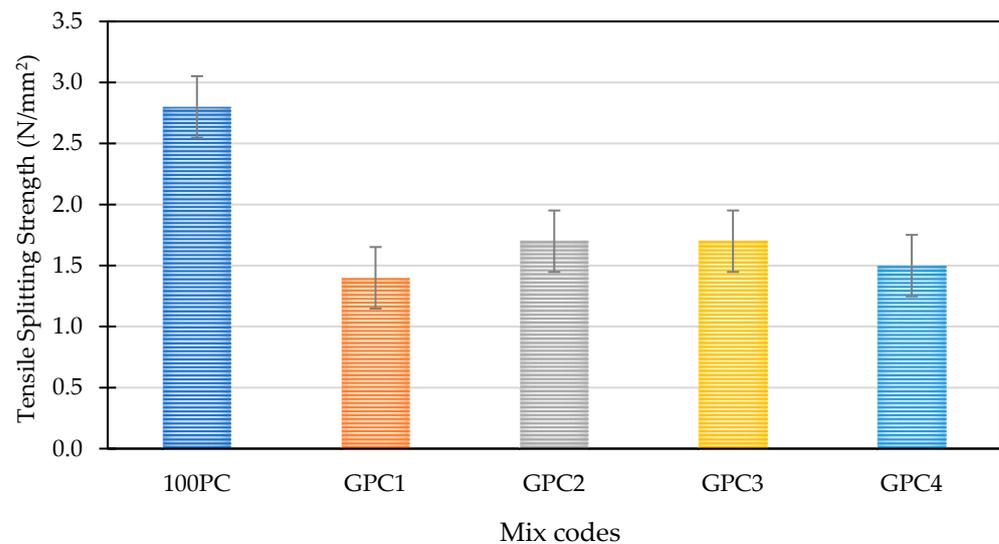
**Figure 5.** Compressive strength results at various curing times of concrete mixtures.

In contrast, the geopolymer concrete mixture GPC4 consistently displayed the lowest strength values at all four intervals, recording values of 7.1 N/mm<sup>2</sup> at 7 days, 9.4 N/mm<sup>2</sup> at 14 days, 10.3 N/mm<sup>2</sup> at 28 days, and 13.5 N/mm<sup>2</sup> at 58 days. Among the geopolymer concrete mixtures, the GPC2 mixture, characterised by an alkali/precursor (A/P) ratio of 0.4, consistently achieved the highest compressive strength at all time intervals, measuring 8.8 N/mm<sup>2</sup> at 7 days, 11.6 N/mm<sup>2</sup> at 14 days, 12.9 N/mm<sup>2</sup> at 28 days, and 15.8 N/mm<sup>2</sup> at 58 days.

The observed trend in the data suggests that, for all geopolymer concrete mixtures, compressive strength generally increases as the A/P ratio rises up to a certain point, which is observed from an A/P ratio of 0.2 to 0.4. However, beyond that point, with increasing A/P ratios, the compressive strength starts to decrease. It is important to note that when assessing the compressive strength of all geopolymer concrete mixtures at all time intervals, they consistently displayed significantly lower strength compared to the control mix (100 PC), with the difference ranging between 50% and 60%.

#### 4.7. Tensile Splitting Strength Results at 28 Days Curing

Figure 6 presents the results for tensile splitting strength for all concrete mixtures after 28 days of curing. A significant difference in tensile splitting strength was observed between the OPC control sample and GGBS-based geopolymer samples.



**Figure 6.** Tensile splitting strength results at 28-day curing times of concrete mixtures.

The control mix (PC100) achieved the highest tensile splitting strength value of 2.8 N/mm<sup>2</sup>. In contrast, the geopolymer mixture GPC1, featuring the lowest A/P ratio of 0.2 as utilised in the study, exhibited the lowest tensile splitting strength, recording a value of 1.4 N/mm<sup>2</sup>. Among the geopolymer concrete mixtures, both GPC2 and GPC3, characterised by alkali/precursor (A/P) ratios of 0.4 and 0.6, respectively, consistently attained the highest tensile splitting strength at 28 days of curing, with a value of 1.7 N/mm<sup>2</sup>.

The observed trend in the data indicates that, for all geopolymer concrete mixtures, tensile splitting strength generally increases as the A/P ratio rises up to a certain point, which is observed within an A/P ratio range of 0.2 to 0.6. However, beyond that point, with increasing A/P ratios, the tensile splitting strength begins to decrease.

It is important to note that when assessing the highest tensile splitting strength of geopolymer concrete mixtures at 28 days, they consistently have lower strengths (39%) than the control mix (100 PC).

## 5. Discussion

This study investigates the development and optimisation of GGBS-based geopolymer concrete using an alternative alkaline activator synthesised from rice husk ash (RHA)-derived SSA and sodium hydroxide. While prior research by Kamseu et al. [8] and Tchakounte et al. [9] established RHA's potential in geopolymer systems, this study delves into the impact of W/B ratio and A/P ratio on geopolymer properties, particularly in GGBS-based geopolymer concrete.

The study finds that a W/B ratio of 0.50 strikes a balance between workability and structural performance, offering suitable initial setting times, competitive compressive strength, and reasonable density. This aligns with the importance of balancing these factors, as highlighted by previous research [24].

Regarding the A/P ratio, an increase tends to decrease workability, as indicated by reduced slump values. GPC4, with an A/P ratio of 0.8, deviates from this pattern, suggesting a potential optimal threshold. This finding contrasts with traditional geopolymer behaviour, necessitating further exploration into higher A/P ratios for enhanced workability. This finding is consistent with the previous research, which found that increasing the A/P ratio can reduce workability due to the rapid formation of solid gel phases [25].

Interestingly, these findings regarding the impact of A/P ratios on geopolymer consistency differ from some traditional geopolymer concrete behaviours. Previous research has shown that the slump value tends to decrease as the A/P ratio decreases [26]. This decreasing trend in slump values is typically associated with a reduction in activator (liquid) content [26,27]. This reduction in activator content can lead to higher friction between

dry material particles, resulting in a stickier system and, consequently, reduced overall consistency [27,28].

In terms of compressive strength, geopolymer concrete lags behind the control mix (100 PC) but exhibits promising strength development over time. GPC2 consistently achieves the highest compressive strength with an A/P ratio of 0.4. The strength gain observed in the control mix (100 PC) was attributed to the initial hydration of the cement components with water, forming cementing gels (C-S-H) crucial for strength development. In contrast, the increase in strength in geopolymer concrete resulted from a polymerisation process involving the chemical reaction of aluminosilicate minerals (GGBS) under alkaline conditions (SS/SH solution). This process yields a three-dimensional amorphous aluminosilicate matrix with strength properties comparable to or exceeding those of OPC concrete [13]. However, it is essential to note that, when assessing the compressive strength of all geopolymer concrete mixtures at all time intervals, they consistently exhibited significantly lower strength compared to the control mix (100 PC), with the difference ranging between 50% and 60%. Nath and Sarker (2014) support the earlier hypothesis, suggesting that the alkali activation process is primarily influenced by the chemical composition of the geopolymer mixes, including alkali activators and source materials. They also note that the activation mechanism remains unclear, leading to the conclusion that the final products of geopolymerization are predominantly influenced by the chemical composition of the geopolymer mixes, encompassing both alkali activators and source materials. Therefore, further investigations are essential, particularly through the variation of the concentration of the alternative alkali activator derived from RHA and the SH:SSA ratio, to gain a deeper understanding of these complex processes.

The tensile strength trend indicates an increase up to an A/P ratio of 0.6, beyond which it decreases. Although lower than the control mix, the tensile strength of geopolymer concrete remains promising, emphasising its viability as a low-carbon alternative. Tensile strength offers details on the type of cross-linkages formed in a material matrix in addition to compressive strength. The degree of matrix densification and its impact on the microstructure characteristics inside the matrix may also be indicated by tensile strength [8].

While GPC2, with a 0.4 A/P ratio and 0.5 W/B ratio, displays lower strength than the control mix, its environmental benefits make it a valuable alternative. Future research should focus on enhancing the mechanical properties of geopolymer concrete by varying the concentration of the alternative alkaline activator, exploring different SH:SSA ratios, and partially replacing GGBS with other precursor materials to develop a sustainable, high-performance mixture.

## 6. Conclusions

This research embarked on a comprehensive investigation into the development and optimisation of GGBS-based geopolymer concrete activated by an alternative alkaline activator synthesised from sodium hydroxide (SH) and a sodium silicate alternative solution (SSA) derived from rice husk ash (RHA). Based on the research findings, the following conclusions can be drawn:

1. The study determined that a W/B ratio of 0.50 with an initial setting time of 39 min provides a balanced mix of workability and structural performance for geopolymer concrete.
2. The research demonstrated that as the alkali/precursor (A/P) ratio increases, the consistency of geopolymer concrete generally decreases, as evidenced by slump tests. It is important to note that all geopolymer mixtures, except for GPC3 with an A/P ratio of 0.6, exhibited suitable workability results, with slump values between 50 and 40 mm.
3. Compressive strength increased with increasing A/P ratio up to a certain point (between 0.2 and 0.4) and then started to decrease. GPC2, with an A/P ratio of 0.4, consistently achieved the highest compressive strength at all tested time intervals

- among geopolymer mixes. However, all geopolymer concrete mixes exhibited significantly lower strength than the control mix (100 PC).
4. Tensile splitting strength generally increased with increasing the A/P ratio up to a certain point (within an A/P ratio range of 0.2 to 0.6) and then began to decrease. GPC2 and GPC3, with A/P ratios of 0.4 and 0.6, respectively, consistently exhibited the highest tensile splitting strength at 28 days of curing among geopolymer mixes, although significantly lower than the control mix (100 PC).
  5. Geopolymer concrete mixtures with an A/P ratio of 0.4 and a W/B ratio of 0.50 demonstrated favourable properties, including good workability, competitive compressive strength, and reasonable density. This mix design can be recommended for practical applications.
  6. Future research should focus on enhancing the mechanical properties of geopolymer concrete by varying the concentration of the alternative alkaline activator, exploring different SH:SSA ratios, and partially replacing GGBS with other precursor materials to develop a sustainable, high-performance mixture.

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