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# The Effect of Rice Husk Ash Geopolymer Microstructure Reactivity on the Bonding of Alkaline Solutions and Its Impact on Geopolymer Concrete Strength

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**Abstract:** This study explored the impact of rice husk ash (RHA) granulometry on the adhesive strength of geopolymer concrete material and examined how the various sizes of RHA influence the overall strength of geopolymer concrete. The RHA is burned at a temperature of 700°C using a furnace, followed by filtration and grinding to produce a finer RHA powder. The RHA powder is mixed with sand, ordinary Portland cement (OPC), and a 12M alkaline solution until it becomes a paste, then placed into a mold to form test specimens. The compressive strength of the test specimens was evaluated after a curing period of 28 days. The Scanning Electron Microscopy (SEM) test was carried out to demonstrate that the bonding of RHA particle sizes affects the adhesive strength. The results show that (a) typical chains of manually and furnace-burned RHA both result in amorphous particles with short-chain bonds, and (b) manually burned RHA exhibits higher compressive strength, which can be explained by the fact that amorphous silica reacts with $Ca(OH)_2$ in the cement to form C-S-H gel, enhancing strength. These findings are discussed in the context of the reactivity of the geopolymer microstructure between manually burned RHA and furnace-ground RHA.

**Keywords:** reactivity of geopolymer particles; rice husk ash; activator alkaline solution; influence of geopolymer compound strength; OPC.



## 1. Introduction

Substantial amounts of rice husk ash (RHA) are produced each year as a by-product of the rice milling industry. RHA has significant potential for applications in the cement and concrete industries. It is an abundant agricultural by-product in many rice-producing countries worldwide [1]. RHA is derived from the combustion of rice husks at approximately 700°C, resulting in a reactive, amorphous material suitable for use as a pozzolan in composite binders. It typically consists of 80–90% amorphous silica [2]. For every 1,000 kg of rice milled, approximately 220 kg (22%) of husk is produced. When subjected to combustion, around 55 kg (25%) of RHA is obtained. The husk comprises 75% combustible material, with the remaining 25% converting into ash. This makes RHA a viable material to partially replace cement (cementitious materials) [3].

Rice husk ash (RHA) is considered an effective complementary cementing material in concrete manufacturing due to its minimal energy consumption and greenhouse gas emissions during both processing and its service life. Additionally, RHA exhibits significant pozzolanic reactivity. This reactivity is influenced by factors such as the amorphous silica content, particle fineness, mix ratios, available alkaline environment, and processing temperature, all of which play a critical role in the dissolution of silica from RHA. As a result, precise control over the incineration time, temperature, and grinding process of RHA is necessary to achieve its optimal pozzolanic reactivity [4,5].

RHA is primarily composed of lignocellulosic biomass but is distinguished by its high silica content. When burned at temperatures of 400–500°C (it is called manually burned RHA), manually burned RHA often contains unburnt carbon (5–20%) due to insufficient oxygen. The material form in manually burned RHA is amorphous and may require post-treatment (re-burning, grinding) to reduce carbon content. Meanwhile, furnace-burned RHA is produced through controlled combustion at a temperature of 600–800°C and results in a uniform granular shape. Furnace-burned RHA has a higher silica content due to controlled conditions, with a carbon content of around 2–5%, and it has higher reactivity due to its larger surface area and amorphous silica. When combustion continues above 1000°C, the RHA particles become crystalline silica. Amorphous silica is a key component in the formation of geopolymer concrete. The properties of RHA, including its silica and carbon content, are influenced by the duration and temperature of the incineration process. The pozzolanic reactivity of RHA, linked to its amorphous content, specific surface area, and particle fineness, can be improved through precise control of the combustion and grinding processes, rendering it appropriate for use in structural concrete applications [2,4].

Rice husk ash is produced in the form of dry powder that has been ground to a higher fineness than cement powder. This material condition results in amorphous particles. It reacts more actively in alkaline solutions compared to crystalline rice husk ash grains. This is because the fineness of amorphous grains is greater than that of cement powder, while crystalline grains do not go through a refining process. Consequently, amorphous silica grains are preferred over crystalline silica grains [5,6].

The geopolymerization process consists of chemical reactions occurring in highly alkaline conditions, resulting in a robust gel with an amorphous (non-crystalline) microstructure, primarily based on the Al-Si system. Geopolymers possess desirable properties such as hardness, durability, and chemical stability. Notably, high-alkaline binders do not induce alkali-aggregate reactions. The geopolymer structure comprises three-dimensional networks of $SiO_4$ (silicate) and $AlO_4$ (aluminate) tetrahedra linked by shared oxygen atoms. The chemical reactions in geopolymerization involve the interaction of silicate and alumino-oxide compounds with alkaline solutions. These reactions produce a semi-crystalline polymeric system consisting of Si–O–Si and Si–O–Al bonds, which contribute to the material's structural integrity [4,6].

Figure 1 shows the bonds that occur in geopolymer compounds. In the chain, there is a Si-O-Si bond (siloxane chain) formed from silicon and oxygen atoms. This chain maintains its strength and stability. Meanwhile, the Si-O-Al bond (aluminosilicate) is a combination of silicon, aluminum, and oxygen atoms that play a role in chemical resistance and temperature stability. There are three types of chain bond forms in geopolymer compounds, namely: (a) linear chains, which are bonds between silicon and oxygen atoms; (b) cross-linked chains,

which are a combination of linear chains that form a three-dimensional network; and (c) ring-structured types, which are repeating arrangements of silicon and oxygen atoms [5].

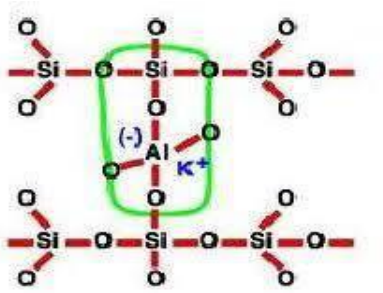


**Figure 1.** The bonding that occurs in geopolymers.

Geopolymers are considered a class of modern aluminosilicate materials with compositions and properties suitable for application in numerous emerging technologies. The chemical composition of rice husk ash (RHA) includes $SiO_2$, $Al_2O_3$, $Fe_2O_3$, CaO, $K_2O$, $TiO_2$, CrO, MnO, NiO, and CuO. Geopolymer concrete (GC) has become a significant alternative to conventional Portland cement-based concrete. The concept of "geopolymer" was coined by Joseph Davidovits in the 1970s to refer to a group of alkali-activated aluminosilicate binders derived from industrial by-products. The source materials for geopolymers are generally categorized into two groups: (i) reactive aluminosilicate solids, such as fly ash and calcined clays, and (ii) an alkaline activating solution, typically comprised of alkali metal hydroxide or silicate solutions [4].

The geopolymerization process was founded by Davidovits in 1972, and he invented geopolymer high-strength cement 11 years later. Geopolymer cement represents an alternative building material that does not rely on Portland cement to achieve strength. However, geopolymers from Davidovits' research require raw materials that contain $Al_2O_3$ and $SiO_2$, such as kaolin and blast furnace slag, in order to form Si-O-Al bonds [4].

The raw materials for geopolymers are typically abundant in silicon (Si) and aluminum (Al) and may include natural minerals like kaolinite and clays, as well as industrial by-products such as fly ash, silica fume, slag, RHA, and red mud [6]. The selection of raw materials is influenced by factors including availability, cost, application needs, and specific requirements of the end user. Alkaline liquids, derived from dissolvable alkali metals (typically sodium- or potassium-based), are critical for the geopolymerization process. The most commonly used alkaline liquids are mixtures of sodium hydroxide (NaOH) or potassium hydroxide (KOH) with sodium silicate or potassium silicate [4].

RHA may contain non-crystalline silica and is considered a highly reactive pozzolan derived from the controlled combustion of rice husks. Under different conditions, a lower-quality "residual RHA" is produced, typically containing residual carbon (which increases water demand) and some silica in crystalline form [2]. However, residual RHA can be enhanced by grinding it to the desired particle size, though this process incurs significant costs. Both methods involve energy expenditures and require careful strategies for material selection and disposal [2,6].

The incorporation of rice husk ash (RHA) into geopolymer cementitious mixtures with alkaline solutions significantly influences the adhesive strength between materials. One of the critical factors affecting this strength is the particle size of the RHA material [7]. Various sizes of amorphous RHA particles can be produced by incinerating rice husks at a controlled

temperature of 700°C in a furnace [2]. The ash is then filtered using sieves of different sizes to produce RHA particles of varying granular dimensions [4].

Recent advancements in RHA geopolymer concrete research have predominantly focused on enhancing material properties, durability, and sustainability. For instance, some studies emphasize the importance of refining RHA to improve its material properties [8], while others focus on enhancing workability by blending RHA with fly ash [9]. Research on durability, such as the work conducted by Zhang *et al*. [10], demonstrates that RHA-based geopolymer concrete exhibits superior resistance to sulfate and chloride exposure. Additionally, studies on sustainability reveal a significant reduction in carbon footprint when RHA is used as a cement substitute [11]. Emerging trends in geopolymer concrete research also involve innovative approaches, such as the use of nano-engineered materials and hybrid binders [12,13].

Previous research related to the investigation of adhesive behavior between materials in geopolymer concrete is limited to the problem of alkaline mixture concentration, assuming that the strength depends on the molarity of the alkaline mixture as a cement substitute adhesive in geopolymer concrete. Research on the investigation of tensile strength between materials in geopolymer concrete, including the size of RHA particles, has not existed. This study aims to examine the impact of RHA particle size on the bonding strength in geopolymer composites with an alkaline solution of 12 M. It is expected that the results of the study can add information about the role of RHA material size in influencing the bonding strength in geopolymer composites, which can be determined by preparing rice husk ash granules of the right size. Briefly, this research aims to evaluate the cohesive strength between ground and unground RHA particles of sizes passing through a sieve no. 200, using cube-shaped test specimens with dimensions of 50 mm × 50 mm × 50 mm.

## 2. Materials and Methods

### *2.1. Materials*

#### 2.1.1. RHA Production

To produce RHA, rice husk is burned in a boiler under a controlled temperature to achieve the desired physical properties and chemical composition of mineral admixtures. Its pozzolanic activity is influenced by factors such as the silica crystallization phase, silica content, size, and surface area of the ash. Rice husk is combusted for silica production purposes, and the ash produced is then mixed with an alkaline solution [14]. The carbon content in RHA should be kept to a minimum, as an increased carbon concentration may reduce the strength of the concrete [4, 6].

The rice husk is burned in a ferrocement furnace or, in some cases, in boilers to generate RHA under controlled temperature conditions. In furnaces, air ducts are provided to serve dual functions: supplying air for the combustion process and creating passages for fire. Air ducts help regulate the combustion temperature. Additionally, electric fans are installed within the air ducts to enhance temperature control. The presence of air ducts also contributes to reducing the carbon content in RHA, as their absence would result in higher carbon levels in the ash, leading to lower concrete strength [4]. Amorphous RHA can be obtained by burning the husk in a controlled environment rather than through uncontrolled combustion, and the optimal burning temperature should range between 500°C and 700°C for 12 hours. When RHA is

incinerated at a temperature of 700°C, the particles are predominantly in an amorphous state [15].

RHA acts as a precursor in the geopolymerization process that supplies important components to replace cement, in this case, silicate ($SiO_2$), to form a geopolymer network. When combined with aluminosilicate precursors, it will react to form an alkaline activator solution ($Na_2SiO_3$, NaOH). RHA precursors also play a role in improving mechanical properties, increasing compressive strength, durability, thermal insulation, and sustainability to reduce environmental impacts ($CO_2$ emissions) [16].

This study used rice husk ash taken from a rice milling machine located in Bayu Village, North Aceh, Indonesia. The rice husk ash from the milling was then taken to the laboratory and placed in a furnace. Furthermore, the rice husk was burned until the temperature reached 700°C for 24 hours. If the combustion is carried out for 12 hours, the silica granules in RHA are still amorphous with a percentage of around 85–90%. However, if the combustion is carried out for 24 hours, the silica granules contained in RHA undergo partial crystallization with a percentage of 60–70%. The combustion conditions after 24 hours are expected to accelerate the reactivity of silica in alkaline solutions. The temperature decreased from 700°C to approximately 52°C, and then to 25°C within the following 24 hours. After cooling, the rice husk ash from the combustion was processed by filtering using a sieve no. 200. Some of the material that passed the filtration was ground using a Los Angeles abrasion machine in accordance with ASTM C131/C131M-20 (test method) [17]. The process of grinding RHA with a Los Angeles abrasion machine involved using 6 steel balls (diameter 46 mm) for 30 minutes at an intensity of 30 rpm. Figure 2 shows RHA produced by combustion at 700°C and refined using the Los Angeles machine.

**(a)** **(b)**

**Figure 2. (a)** Amorphous RHA; **(b)** Test objects made of amorphous RHA.

2.1.2. Alkaline Solution

The alkaline solution is a new geopolymer concrete mixture that can activate amorphous RHA particles or react when the activator is involved. In this study, the alkaline solution was used as an activator, comprising a mixture of sodium silicate ($Na_2SiO_3$) and sodium hydroxide (NaOH). These components play distinct and essential roles: (a) sodium hydroxide serves as a catalyst, accelerating the reaction process during geopolymerization; (b) sodium silicate provides silicon dioxide ($SiO_2$), which is very important due to its adhesive function in the formation of geopolymer compounds. In addition, sodium silicate also forms a gel network that acts as a strengthener in the polymerization process. Meanwhile, the combination of NaOH and $Na_2SiO_3$ plays a role in the geopolymerization reaction to form aluminosilicate gels that create strong chains. Thus, due to the presence of this strong chain series, mechanical strength is formed that is resistant to degradation. This alkaline solution also plays a synergistic role in maintaining pH stability [18].

In terms of alkaline molarity, one of the factors influencing the mechanical properties of geopolymer concrete is the concentration of the alkaline solution. The compressive capacity tends to increase with higher alkaline solution concentration. Another factor influencing compressive capacity is the alkaline-to-binder ratio and the ratio of $Na_2SiO_3$ to NaOH. A higher concentration results in a greater presence of -OH ions, which accelerates the disintegration process marked by increased solubility of silica-alumina chains. Previous research has utilized molarities of 4M, 8M, 10M, 12M, 14M, 16M, and 25M. Commonly, the molarity range for RHA-based geopolymers is 8M–14M of NaOH. For the highest compressive strength, the concentration of NaOH is 12M to 14M, although it reduces workability. The optimum compressive strength came from an alkaline solution with 12M after 28 days of testing the test samples [4,5]. In this study, the alkaline solution was used at 12M.

#### 2.1.3. Fine Sand

Fine sand aggregate, used as a component of the geopolymer concrete mixture, has undergone a series of examinations. Each mixture contains 500 grams of fine sand, as specified in ASTM C778-21, which requires 500 grams of fine sand for a mixer volume of 10 liters. According to ASTM, the amount of sand used relates to the specific gravity of the formulated concrete, which typically ranges from 1600 to 2000 kg/m³ [19]. For mix designs, ASTM C144 (Standard Specification for Fine Sand) was referred to [20].

On the other hand, the role of sand in geopolymer mixtures and cement substitution is that fine sand increases mechanical strength in the form of compressive strength and durability. Fine sand also minimizes shrinkage, which reduces the effect of cracks during the water evaporation process. The presence of sand also affects the increase in viscosity (workability), which will improve the viscosity of the mixture. Another role of fine sand in geopolymer mixtures is to increase density by reducing pores. In addition, fine sand can be obtained at a low cost, so it can reduce construction costs [21].

#### 2.1.4. Ordinary Portland Cement (OPC)

Another material used in this research is cement (OPC). A total of 150 grams of cement is used in this research, mixed with 500 grams of fine sand. This is according to ISO 22199, which specifies the specification and test method for geopolymer [22]. However, until now, cement still has a significant function in geopolymer concrete. Even though the use of OPC is intended to reduce the overall role of cement, the binding agent still underlies the strength of concrete. In addition, a hydration reaction occurs when cement reacts with water, leading to the formation of a calcium silicate hydrate (C-S-H) gel bond that plays a role in the performance and longevity of normal concrete [23].

In geopolymer concrete, OPC serves as a cementitious supplement that enhances mechanical properties and functions as a binder. Additionally, OPC acts as an alkaline activator, providing the necessary alkalinity to facilitate geopolymerization reactions. Another role of OPC in geopolymer concrete is as a filler material, which reduces cavities, increases density, and decreases permeability. The combination of OPC and geopolymer components can improve the performance of geopolymer concrete, particularly in terms of workability, mechanical performance, and longevity. However, the inclusion of cement in geopolymer concrete mixtures contributes to an increased carbon footprint, reducing overall sustainability. As a result, many researchers are actively exploring alternatives to replace OPC [23].

*2.2. Methods*

2.2.1. Sample Preparation

The test object was made in the form of a cube with dimensions of 50 mm × 50 mm × 50 mm. The dimensions and the sample preparation procedure were chosen because the standardized testing method for compressive strength of hydraulic cement mortar complies with ASTM C109/C109M-13 [24]. The sample was made through three process stages as follows:

2.2.1.1. Preparing the Alkaline Solution

The preparation of the alkaline solution began by dissolving 480 grams of solid NaOH into 1 L of water to achieve a molarity of 12M. Once the NaOH was fully dissolved, it was mixed with 1 L of liquid $Na_2SiO_3$. This mixture of NaOH and $Na_2SiO_3$ is referred to as the alkaline solution. The solution was then left for 24 hours before use.

The ratio of NaOH to $Na_2SiO_3$ is 1:1, based on considerations related to chemical balance, where the optimal alkaline solution is obtained from a 1:1 ratio that facilitates geopolymerization reactions. Other considerations include preparing a sufficient amount of silica ions to form adequate cross-linking bonds and network structures [4]. In the context of mechanical properties, according to the results of compressive strength tests, a 1:1 ratio often results in optimal compressive strength. Additionally, this ratio promotes homogeneous geopolymer gel formation, reducing porosity and enhancing durability [5]. Thus, this study utilized a 1:1 ratio of sodium silicate to sodium hydroxide.

2.2.1.2. Mixing and Molding Precursor

In this research, two types of RHA were prepared: RHA furnace with refining (Mix 1) and RHA furnace without refining (Mix 2). Each mixture was treated using the same procedure. First, 350 grams of RHA, 150 grams of OPC (around 15% used to accelerate setting or improve mechanical properties), and 500 grams of fine sand were weighed and placed into a mixing container until thoroughly combined. The prepared alkaline solution, which had been left for 24 hours, was then added to the mixture in a mixing container with dimensions of 78 × 38.5 × 78.5 cm and a capacity of 10 liters. The geopolymer mixture was stirred for 10 minutes until it was evenly blended. Subsequently, the geopolymer concrete mortar was poured into 20 cube molds with dimensions of 50 × 50 × 50 mm, which had been pre-coated with oil. The test specimens were then left undisturbed for 24 hours. The composition of the materials used is shown in Table 1.

**Table 1.** Number of cube test objects 50 x 50 x 50 mm

| Mixed type RHA | Composition | | Alkaline solution | $Na_2SiO_3$ | NaOH | Number of test objects |
|---|---|---|---|---|---|---|
| | RHA (gr) | OPC (gr) | | | | |
| Mix 1 (amorphous) | 350 | 150 | 1:1 | 1 | 1 | 10 |
| Mix 2 (crystalline) | 350 | 150 | 1:1 | 1 | 1 | 10 |

2.2.1.3. Curing

The cube molds were removed, and the specimens were cured in an oven at a temperature of 60 ℃ for 96 hours [9]. After 96 hours, the test objects were taken out of the

oven and allowed to rest at room temperature for 28 days. At this stage, the water content was completely eliminated, and the test objects were ready for compressive strength testing.

2.2.2. Testing Methods

The test objects from both mixture groups (Mix 1 and Mix 2), aged 28 days, were subjected to compressive strength testing using a testing machine in accordance with ASTM C109/C109M standards. The test objects were weighed and tested for mortar compressive strength using an ELE-brand compressive strength machine with a capacity of 250,000 lbf (1.112 kN) [24].

The method of testing compressive strength involved placing the test specimen on the test table, followed by lowering the hydraulic press until it contacted the test specimen. Pressure was applied until the test specimen cracked. The maximum compressive strength was then recorded, and the average compressive strength value of the test specimens was calculated. Data processing was carried out using statistical analysis with the sample T-test method.

In this study, the RHA microstructure was examined using scanning electron microscopy (SEM) (JEOL-JSM-6380 model). The SEM testing procedure began by preparing a fraction of the test object and placing it on a glass slide. The test object was then coated with a conductive material. After coating, documentation was performed to record material properties, composition, and history. The test procedure continued by inserting the glass slide with geopolymer concrete sample fragments into the SEM machine. The SEM machine was set to the appropriate vacuum level, and the focus was aligned. Images were captured at magnifications ranging from 100x to 100,000x. Elemental analysis, including energy-dispersive spectroscopy, was performed to determine the elemental composition. The final step involved analyzing the images using specialized software [25]. Figure 3 shows the compressive strength machine for testing RHA geopolymer cube test objects.


**Figure 3.** Testing of RHA geopolymer cube test objects using a compressive strength machine.

2.2.3. Data Analysis

The data obtained from the results of this study include compressive strength data and scanning electron microscopy (SEM) images for the two mixture groups (Mix 1 and Mix 2). The compressive strength data were processed statistically using a T-test analysis.

Additionally, the results of the compressive strength tests were presented in the form of a histogram. Observations were made on the data obtained from both Mix 1 and Mix 2 groups.

2.2.4. Safety Considerations

During RHA combustion, the temperature needs to be maintained consistently at 700°C for approximately 24 hours. This control is crucial as it affects the amount of silica produced during combustion. Throughout the procedure, safety protocols and measures were followed, including the use of masks to protect against respiratory issues, gloves, safety glasses, and lab coats to prevent skin and eye irritation. Special attention was given during the burning process, with heat-resistant clothing worn and knowledge of fire extinguisher operation. Furthermore, a designated disposal container for RHA waste and chemicals was used. There are no potential environmental hazards associated with the disposal of RHA or the chemicals used in this study.

## 3. Results and Discussion

*3.1. Microstructural Analysis Outcomes*

SEM analysis outcomes for the furnace and ground RHA categories show that the particle size ranges from nanoscale to microscale, with the majority of particles measuring approximately 10 µm and a total porosity of 20%, which is still classified as a mesoporous structure. The red markers (length x width) in Figure 4 indicate some of the gap sizes: 3.6 x 2.7 µm, 2.9 x 2.4 µm, and 2.8 x 1.8 µm. The quantitative data indicate that the ground RHA particles exhibit characteristics of an amorphous form.

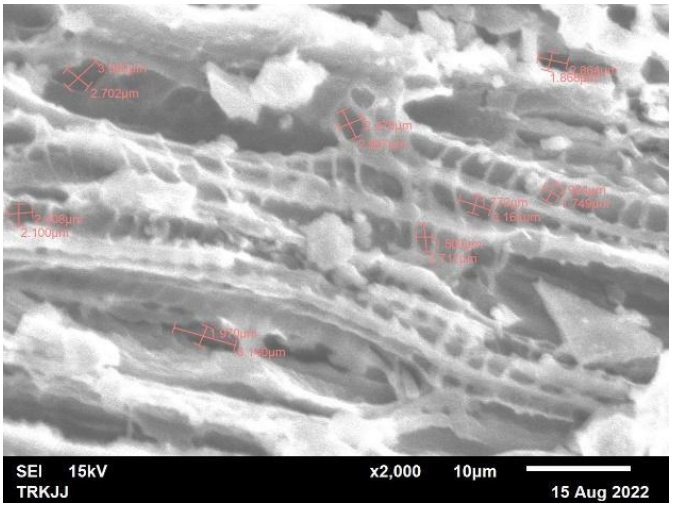


**Figure 4.** SEM photo of the furnace and grounded RHA.

In Figure 4, the morphology of the RHA geopolymer particles appears dense with short chains, and there are few visible pores. The particle size of the furnace RHA is <200 nm, thus increasing the density in the cement matrix. This also reduces the pores, so with this density, the particles from the furnace-burned RHA function as a filler. On the one hand, if the pores are interconnected, they will form a weak zone, which reduces compressive strength.

The particles generally have an irregular shape, a microporous surface, and are not well distributed. After 30 minutes of grinding, the RHA particles exhibited an excellent filler effect and enhanced pozzolanic reactivity [26]. This indicates that the geopolymer microstructure particles are more reactive, resulting in short-chain or long-carbon-chain bonds [8,10]. The

presence of long carbon chain bonds suggests that the geopolymerization reaction is more complete, leading to stronger microstructural bonds [8].

The physical properties of the furnace-burned RHA in this study show a higher density of 1.39 g/cm³ due to the irregular particle shape, so it is less effective in arranging particle density, which results in gaps between particles. The gaps observed between particles appear in SEM images as cavities of varying sizes. The presence of gaps can reduce density. In the group of RHA test objects that were ground, the particle size distribution varied (wide range of particle sizes), thus affecting the consolidation process. The irregular shape causes a rough surface area, which results in friction between particles. To improve the specific surface area of RHA and enhance its activity, it is necessary to grind RHA to increase its fineness [27].

In contrast, the SEM image of furnace RHA without grinding (manual RHA), shown in Figure 5, reveals several gap sizes marked with orange markers (length x width), such as 20.6 x 19.7 µm, 18.5 x 14.8 µm, and 19.0 x 14.08 µm. The particle size distribution of manual RHA is uniform, the particle shape is regular, and its density is lower at 1.17 g/cm³ compared to furnace-burned RHA. This lower density indicates more pores. The pores are well-distributed, which makes the material more resistant to compressive strength [6]. The surface condition of the test object shows more pores, indicated by high porosity, as evidenced by a longer initial setting time [7,8]. The lower reactivity is attributed to the larger particle size compared to the furnace-burned RHA group.

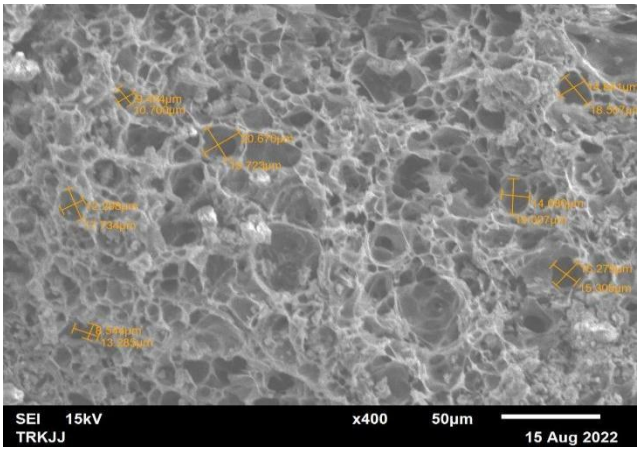


**Figure 5.** SEM photo of furnace RHA without grinding (manual RHA).

The differences in geopolymer material from the SEM examination results between the two groups of test objects are presented in Table 2.

**Table 2.** Quantitative data of manual and furnace RHA test objects.

| Quantitative data | Manual RHA (unground furnace RHA) | Furnace RHA (ground) |
|---|---|---|
| Order structures | Ordered periodic structures ($SiO_2$) | Disordered structure ($SiO_4$) |
| Reactivity | Lower (reacts slower than furnace RHA) | High reactivity |
| Surface area | High surface area | Low surface area |
| Porosity | High porosity | Lower porosity |
| Density | Low density | Higher density |
| Compressive strength at an early age | 16.85 MPa | 13.70 MPa |

*3.2. Chemical Composition of Rice Husk Ash*

In this study, the chemical composition of rice husk ash is provided in Table 3. Most of the components of RHA are SiO2, which is as high as 94.9%. This silicon dioxide compound forms a stronger Si-O-Si chain in geopolymer concrete due to several factors: (a) the covalent

bond factor, where the Si-O-Si chain is a strong covalent chain that distributes electrons between silicon atoms and oxygen atoms; (b) high bond energy, which makes the Si-O-Si chain resistant to breakage; (c) a stable tetrahedral configuration, where silicon atoms combined with oxygen are more stable [28]. In addition, the Si-O-Si chain forms a rigid three-dimensional network that provides excellent mechanical strength. Silica tetrahedra (SiO4) have cross-linking that makes the structure stable and robust [29]. A metric with low porosity can reduce water penetration and minimize interference with the bond.

**Table 3.** Chemical composition of rice husk ash.

| Oxide | Content (%) |
|---|---|
| $SiO_2$ | 94.9 |
| $Al_2O_3$ | 0.67 |
| $Fe_2O_3$ | 0.84 |
| CaO | 2.84 |
| $K_2O$ | 0.69 |
| $TiO_2$ | 0.03 |
| CrO | 0.03 |
| MnO | 0.37 |
| NiO | 0.03 |
| CuO | 0.05 |

### *3.3. Compressive Strength of RHA Geopolymer Mortar*

The compressive strength data for test objects made from furnace RHA that has been ground ($RHA_f$) are shown in Table 4, and the compressive strength data for the manual RHA test objects without grinding ($RHA_m$) are presented in Table 5. Both groups of data were subjected to statistical analysis using the T-test method and the SPSS application. The calculation results yielded an average compressive strength of 13.70 MPa for the RHAf group and 16.85 MPa for the RHAm group. The standard deviation for the $RHA_f$ test group is 1.57, and for the $RHA_m$ test group, 0.92. The T value is 2.89 with a degree of freedom of 18 and a P value of 0.001 ($\leq$ 0.05). It can be inferred that the compressive strength of the $RHA_m$ is significantly higher than that of $RHA_f$.

**Table 4.** Compressive strength of furnace RHA geopolymer mortar cured at 60°C.

| No. | Test the object code | Age (day) | Weight (g) | Compressive strength (MPa) |
|---|---|---|---|---|
| 1. | $RHA_f$ 60.1 | 28 | 138.6 | 14.4 |
| 2. | $RHA_f$ 60.2 | 28 | 149.7 | 11.85 |
| 3. | $RHA_f$ 60.3 | 28 | 154.0 | 15.43 |
| 4. | $RHA_f$ 60.4 | 28 | 136.0 | 13.27 |
| 5. | $RHA_f$ 60.5 | 28 | 142.5 | 13.58 |
| 6. | $RHA_f$ 60.6 | 28 | 165.7 | 17.1 |
| 7. | $RHA_f$ 60.7 | 28 | 145.0 | 12.63 |
| 8. | $RHA_f$ 60.8 | 28 | 134.0 | 14.4 |
| 9. | $RHA_f$ 60.9 | 28 | 160.2 | 14.3 |
| 10. | $RHA_f$ 60.10 | 28 | 149.0 | 13.43 |

**Table 5.** Compressive strength of manual RHA geopolymer mortar cured at 60°C.

| No. | Test the object code | Age (day) | Weight (g) | Compressive strength (MPa) |
|---|---|---|---|---|
| 1. | $RHA_m$ 60.1 | 28 | 183.2 | 16.13 |
| 2. | $RHA_m$ 60.2 | 28 | 187.0 | 17.31 |
| 3. | $RHA_m$ 60.3 | 28 | 178.4 | 16.7 |
| 4. | $RHA_m$ 60.4 | 28 | 185.2 | 16.9 |
| 5. | $RHA_m$ 60.5 | 28 | 189.0 | 17.26 |
| 6. | $RHA_m$ 60.6 | 28 | 172.0 | 17.6 |
| 7. | $RHA_m$ 60.7 | 28 | 174.0 | 17.57 |
| 8. | $RHA_m$ 60.8 | 28 | 185.0 | 18.36 |
| 9. | $RHA_m$ 60.9 | 28 | 170.2 | 15.13 |

| No. | Test the object code | Age (day) | Weight (g) | Compressive strength (MPa) |
|---|---|---|---|---|
| 10. | $RHA_m$ 60.10 | 28 | 175.3 | 16.58 |

Regarding the test objects, curing is based on references stating that geopolymer mortars have higher compressive strength when cured at a temperature of 60°C (140°F) compared to those cured at room temperature [30]. The results of this study prove that test objects treated at a temperature of 60°C for 96 hours have accelerated hydration, making the reaction between cement and water faster, which improves early strength. On the other hand, increased density with reduced porosity enhances durability. Certainly, higher durability increases compressive strength. Based on the research, compressive strength can be enhanced by about 20%–30% in 28 days. Additionally, curing at a temperature of 60°C also makes the test object surface smoother, with a more uniform texture.

The ground material affects the surface of the test object. Test objects with ground RHA produce a smoother surface than those without grinding. $RHA_f$ has a smoother surface texture than $RHA_m$. This significantly affects the compressive strength. There is a bond between RHA and the cement matrix in $RHA_m$, which is better than the bond between RHA and the cement matrix in $RHA_f$ test objects. This better bond is also evidenced by the higher compressive strength value. The roughness of RHA (unground RHA) also affects friction between particles, which contributes to higher compressive strength. Besides the positive effects, there are also negative effects. RHA roughness increases the need for more water, which causes an increase in porosity and reduces compressive strength [31]. For more clarity regarding the performance of test objects with ground RHA ($RHA_f$) and unground RHA ($RHA_m$), see Figure 6 below.

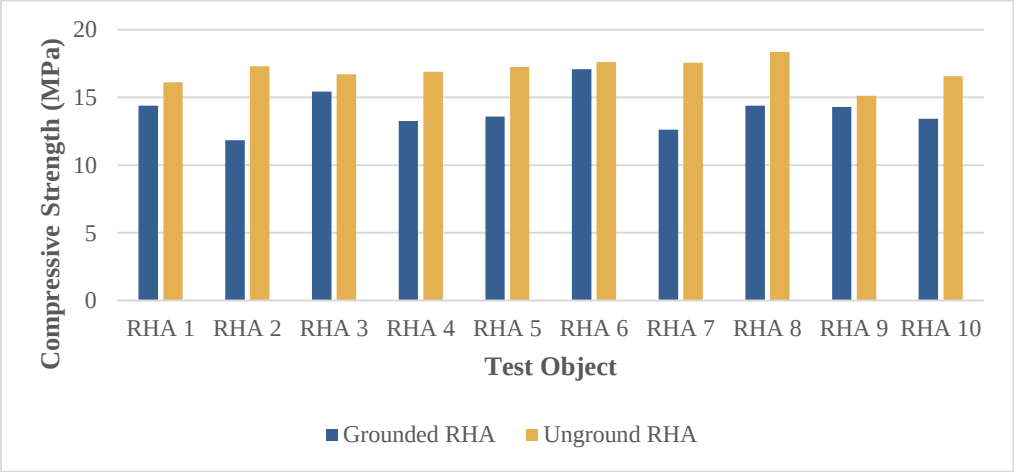


**Figure 6.** Compressive strength comparison of grounded ($RHA_f$) and unground RHA ($RHA_m$).

Siddika *et al.* [4] stated that "as the fineness and content of RHA increase, there is a corresponding rise in concrete compressive strength, which occurs due to the physical filler effect, which outweighs the pozzolanic reactivity during the early stages of curing (<14 days)." In contrast, this study contradicts previous literature, as finer RHA results in lower compressive strength compared to unground RHA. The expected filler effect, as noted in prior references, was not observed in this study.

Pore size refinement in concrete is attributed to the pozzolanicity and filler effect of RHA. As the pore sizes decrease, compressive strength improves [4]. The results of this study align with previous research, indicating that as the density of the geopolymer material increases, so does its compressive strength.

The fineness of the material is directly correlated to the density of the geopolymer material. It was indicated that a finer particle size results in a larger specific surface area and increased reactivity [6]. The material fineness causes high reactivity, which is in line with the results of this study. The ground RHA material has higher reactivity than the unground one. The fineness of the aggregates plays a crucial role in assessing the performance of geopolymer materials.

Most researchers have reported the remarkable durability of geopolymer systems, attributing this to various factors such as reduced steel corrosion, creep, drying shrinkage, resistance to acid and chloride attacks, low water absorption, porosity, high-temperature resistance up to 600℃, heat insulation, robust interfacial bonding, and greater sustainability [6]. However, this geopolymer mortar study did not test resistance to sulfates, acid attacks, corrosion, creep, drying shrinkage, chloride attacks, or water absorption.

An increase in NaOH molarity and a reduction in fine aggregate content lead to higher water absorption, while curing at ambient temperature results in lower water absorption compared to curing at elevated temperatures [6]. This study does not provide data on resistance to degradation but relies only on previous literature. Additionally, the use of higher $Na_2SiO_3$ content results in reduced water absorption and enhanced corrosion resistance [32]. Nonetheless, increasing the alkaline solution-to-binder ratio negatively affects water absorption. Jaf, D *et al*. [6] noted that "increasing the $H_2O$ to $Na_2O$ ratio reduces the compressive strength due to the increased porosity."

## 4. Conclusions

While RHA has been researched and used extensively, the role of particle size in geopolymer concrete in contributing to adhesive concrete strength is often overlooked. Evidence suggests that rice husk ash (RHA) is rich in amorphous reactive silica, with the silica content varying depending on the control over the furnace process. The chemical composition of RHA exhibits variation. An optimized controlled furnace at around 700℃ is ideal for the production of RHA.

On the other hand, smaller RHA particles release more silica and show an enhanced filler effect, thus exhibiting increased pozzolanic reactivity. The microstructure, density, and strength of concrete are closely linked to the hydration process and curing duration of the geopolymer concrete. The typical density of geopolymer concrete at early stages is due to the gradual pozzolanic activity of RHA, leading to slower strength development. However, after 28 days, the significant increase in pozzolanic reactivity and the filler effect substantially improve the concrete’s strength by contributing to a denser microstructure through the formation of additional C-S-H gel.

The use of RHA in the concrete industry provides a sustainable, eco-friendly, and energy-efficient cement alternative and increases the utilization of recycled waste materials in construction. With the increasing number of research studies related to RHA, it will be more effective and efficient to find geopolymer concrete with the best performance. Further research is needed to examine the appropriate RHA size that can accelerate the geopolymer reaction and maintain the function of RHA as a filler, thereby maintaining the density of geopolymer mortar and ensuring high-quality geopolymer concrete. Many factors affect geopolymer concrete; one factor causes another, and they have a cause and effect. Therefore, more information is needed through further research in the coming years.

## Author Contributions

Conceptualization, C.Y., and H.; methodology, C.Y.; software, C.Y.; validation, C.Y., and H.; formal analysis, C.Y.; investigation, H.; resources, C.Y.; data curation, C.Y.; writing—original draft preparation, C.Y.; writing—review and editing, H.; visualization, C.Y.; supervision, H. All authors have read and agreed to the published version of the manuscript.

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Not applicable.

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Not applicable.

## Data Availability Statement

Data supporting the findings of this study are available upon reasonable request from the corresponding author.

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## Conflicts of Interest

The author confirms that there are no known financial conflicts of interest or personal relationships that could have been perceived as influencing the work presented in this paper.

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