The Impact of Silica Fume Addition on the Early Age Compressive and Flexural Strength of Geopolymer Mortar with Various Binders

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Abstract. The study aims to explore the early age strength of geopolymer mortars using three precursors: palm shell ash, rice husk ash, and clamshell ash, with varying silica fume additions (0%, 5%, 10%, 15%, 20%). The mortars were made with a 3:2 ratio of precursor to activator solution, using sodium hydroxide and sodium silicate in a 1:2 ratio. Beam specimens (4 cm x 4 cm x 16 cm) underwent a flexural test at three days old, followed by a compression test. Results show the highest compressive strength for geopolymer mortar with palm shell ash (GM-PSA) was 36.03 MPa, geopolymer mortar with clamshell ash (GM-CSA) was 32.47 MPa and geopolymer mortar with rice husk ash (GM-RHA) was 36.56 MPa. All of them were reached at 20% silica fume addition. The highest flexural strengths were also reached at 20% silica fume addition, which are 0.31 MPa, 0.24 MPa, and 0.34 MPa for GM-PSA, GM-CSA, and GM-RHA, respectively. Adding silica fume significantly enhanced the compressive and flexural strength of GM-RHA, GM-PSA, and GM-CSA.

1 Introduction

The construction sector is pivotal in tackling environmental sustainability challenges, such as reducing carbon emissions and efficiently using scarce natural materials [1]. The scientific and production of eco-friendly materials for construction have become increasingly crucial. The development of geopolymer mortars represents a significant advancement in this industry [1,2].

Geopolymer mortars represent a sustainable construction material, utilizing inorganic elements and a chemical procedure known as alkaline activation [3,4]. This material possesses the capacity to diminish carbon emissions in comparison to conventional concrete by reducing the dependence on limited natural resources like Portland cement [5-7]. Although geopolymer mortar offers many benefits, there is still room to enhance its mechanical strength.

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In recent years, geopolymer pastes have undergone numerous investigations, as indicated by various references. Fly ash (FA) has traditionally been the primary binder in many research studies. However, recent investigations have considered the potential of partially replacing it with aluminosilicate-rich alternatives. An assessment has been conducted to determine the compatibility of materials such as meta-kaolin, sawdust, iron ore tailings, and rice husk ash (RHA) with FA. Sodium hydroxide and sodium silicate are frequently utilized as alkali activators, one particular study has examined the impact of both acidic and alkaline environments [8]. The molarities of the activator solutions ranged from 8 to 14, with an instance of using a solution with 3 molarity [9]. According to the research examined, curing temperatures varied 20°C - 100°C. Specimens exhibiting a low sodium oxide to silica mass ratio were noted to expand during heat curing [10]. Thus, keeping curing temperatures lower than 70°C benefits increasing strength and minimizing expansion. As an illustration, when a ceramic was combined with a metakaolin-based geopolymer mortars, it resulted in a strength of 97 MPa. Additionally, a geopolymers paste made from water treatment and RHA was found to have a density of 1300 kg/m³ [11].

The exhaustion of natural resources and the impact on the environment impact of conventional construction materials have led to the search for sustainable alternatives. The RHA serves as pozzolanic materials, contributing to the polymerization process by reacting chemically with alkaline solutions to form aluminosilicate frameworks, which are essential to the structure of polymers [12]. Similar to RHA, palm shell ash (PSA), and clamshell ash (CSA) are also pozzolanic materials that can be used as binders for geopolymer mortars. One method to enhance the effectiveness of geopolymer mortars involves incorporating silica fume [13-15]. Silica fume, produced during the manufacturing of silicon or ferro-silicon, is known for its effectiveness in enhancing the mechanical properties and corrosion resistance of geopolymer mortars. Despite extensive research, the comprehension of silica fume's function in geopolymer mortars remains incomplete, particularly regarding its impact in the early age of geopolymer mortar strength [16]. Therefore, this research was conducted to examine the influence of including silica fume on the 3-day-age compressive and flexural strength of geopolymer mortars. The study involved the utilization of three different precursors, i.e. RHA, PSA, and CSA.

2 Materials and Methods

2.1 Materials

The dry materials used in this study included RHA, PSA, CSA, silica fume, and aggregate. RHA is a product of burning rice husks, the protective coatings of rice seeds. The RHA was collected from a local rice production factory that had been burned at 700°C for over 1 week. PSA was obtained from the combustion of palm fruit shells, which are used as a source of energy in palm oil mills in local industry. CSA was produced from burning clam shells at a temperature of 700°C and ground into a fine powder. The RHA, PSA, and CSA powders were sieved at a sieve #200 mesh. Silica fume as a micro-filler is the production of PT. Sika Indonesia. The particle size distribution of RHA, PSA, CSA, and silica fume is shown in Fig. 1. For aggregate, river sand was used. The activator used was a solution containing sodium hydroxide and sodium silicate in a 1:2 ratio. The concentration of sodium hydroxide and sodium silicate was 10 and 2.65 molars, respectively.

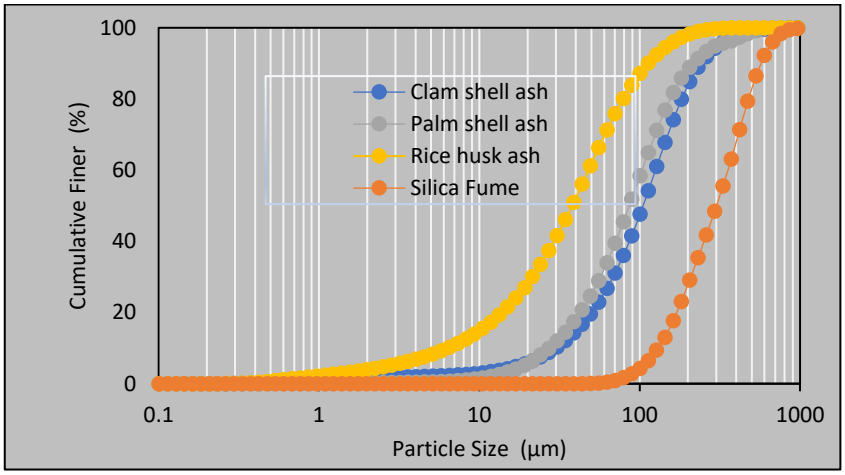

Fig. 1. Binders and silica fume gradation.

2.2 Method

The ratio of precursor to activator is 60% to 40%. Silica fume is incorporated into each mix at levels of 0%, 5%, 10%, 15%, and 20% relative to the precursor's weight. The sand quantity is derived from the amount used in conventional mortar, while the water quantity is set by a water-to-binder ratio (w/b) of 0.3. The ratio of sodium hydroxide to sodium silicate solutions was 1:2. The superplasticizer (SP) was added at 2% of the precursor's weight. Table 1 outlines the mix proportions of the geopolymer mortars.

Table 1. Mix proportions for 1 m3 of geopolymer mortars.

Materials	Percentage of additional silica fume (%)				
	0	5	10	15	20
Water (kg)	120.00	120.00	120.00	120.00	120.00
SP (kg)	8.0	8.0	8.0	8.0	8.0
Sodium silicate (kg)	106.67	106.67	106.67	106.67	106.67
Sodium hydroxide (kg)	53.33	53.33	53.33	53.33	53.33
Fine aggregate (kg)	1,570.00	1,570.00	1,570.00	1,570.00	1,570.00
Silica fume (kg)	0.00	20.00	40.00	60.00	80.00
Binders (kg)	400.00	400.00	400.00	400.00	400.00

The ash, silica fume, and fine aggregate are measured and mixed. The dry mix is stirred at 600 rpm using a mixer, gradually adding the activator to ensure even distribution. The mixture is then poured into moulds measuring 4cm x 4cm x 16cm, compressed to remove air pockets, and left to harden. After heating in an oven at 90°C for two days, the samples underwent compressive and flexural strength tests at three days old.

The flexural and compressive strength tests were conducted in accordance with EN 196-1 and ASTM C109/C109M-02 standards. A flexural test is performed by applying a force at

the centre of the specimen until it breaks, as shown in Fig. 2. The compressive strength test used half of the flexural specimen. Two steel plates, each measuring 40mm x 40mm, were placed both above and below the specimen and then a compressive load was applied between these plates. The photos of the compression and flexural tests are shown in Figs 3 and 4.

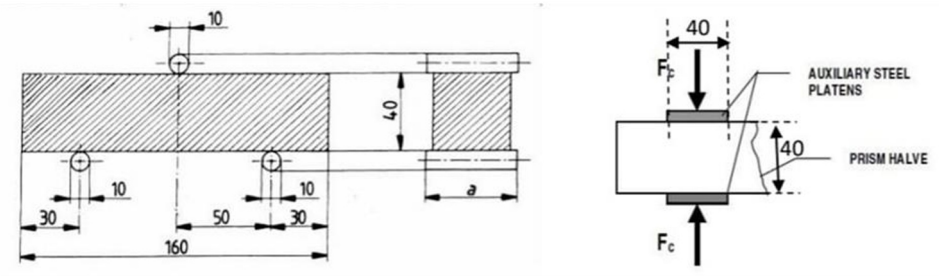

Fig. 2. Methods for testing flexural strength and compressive strength.

Fig. 3. Compression test of geopolymer mortar, a) specimens before test, b) specimens after test.

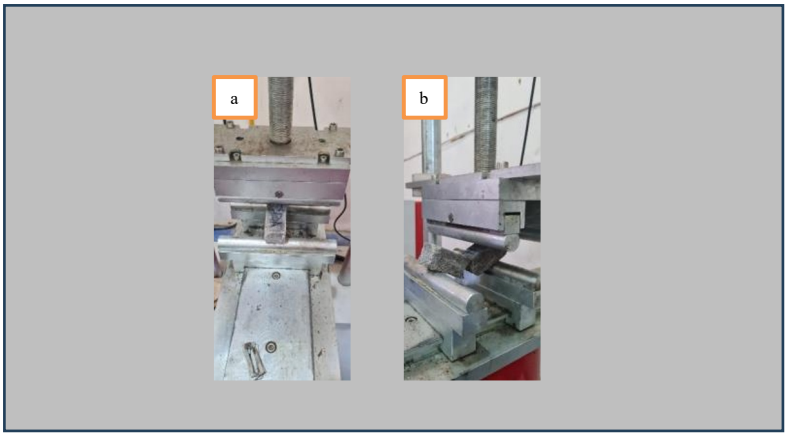

Fig. 4. Flexural test of geopolymer mortar, a) specimens before test, b) specimens after test.

3 Results and Discussion

3.1 Flexural Strength of Geopolymer Mortars

Fig. 5 shows the flexural strength of GM-PSA. The lack of silica fume led to a markedly reduced bending strength of 0.01 MPa, indicating the influence of palm shell ash alone does not enhance bending strength. The incorporation of 5% silica fumes did not increase the strength, which stayed at 0.01 MPa, suggesting that such a low percentage is ineffective. However, adding 10% silica fume resulted in a significant increase in flexural strength to 0.15 MPa, indicative of an improved microstructure. The use of 15% silica fume further enhanced the flexural strength to 0.21 MPa, reflecting better adhesion. The results indicated that incorporating silica fume into geopolymer mortars made from palm shell ash greatly increases its flexural strength. The most effective results were obtained with a 20% silica fumes addition, resulting in a flexural strength of 0.31 MPa. These findings are consistent with prior research underscoring the role of silica fumes in improving the mechanical properties of geopolymers. Previous studies [17] reported that the addition of silica fumes increases the strength due to the improved polymerization reactions and densification of microstructures. Adding silica fumes has proven to significantly enhance the mechanical strength of slag-based geopolymer mortars by improving the microstructure and fortifying the bonds between particles [18].

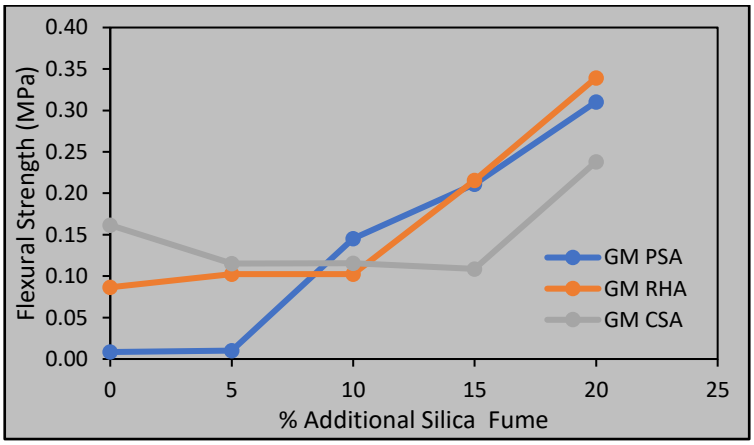

Fig. 5. Early age flexural strength of geopolymer mortar.

Fig. 5 also depicts the flexural strength of geopolymer mortar produced from rice husk ash (RHA). Without silica fume, the flexural strength was recorded at 0.09 MPa. Introducing 5% silica fume slightly raised the strength to 0.10 MPa, indicating a minimal enhancement. Maintaining the flexural strength at 0.10 MPa, even with a 10% silica fume content, suggests only a slight improvement. However, at 15% silica fume content, the flexural strength jumps to 0.22 MPa, reflecting better microstructure and bonding. The highest flexural strength of 0.34 MPa was achieved by using 20% silica fume, demonstrating significant effectiveness.

The assessment of flexural strength in geopolymer mortars made from clamshell ash and silica fume shows notable inconsistencies. Without silica fume, the flexural strength stood at 0.16 MPa. Adding 5% silica fume reduced it to 0.12 MPa, likely due to poor particle distribution or chemical reactions. Maintaining 0.12 MPa with 10% silica fume yields no improvement. However, increasing silica fume to 15% further lowered the flexural strength to 0.11 MPa, suggesting reduced efficacy with higher silica fume levels. This reduction may

stem from silica fume particle agglomeration, leading to structural flaws or adverse reactions within the geopolymers matrix. Yet, incorporating 20% silica fume significantly boosted the flexural strength to 0.24 MPa, indicating an optimal interaction with clamshell ash and an improved microstructure at elevated silica fume contents. This indicates that clamshell ash-based geopolymer mortars might benefit from greater silica fume quantities than those used in previous research on fly ash or metakaolin-geopolymers, where 5-15% silica fume is typically optimal [19-21].

3.2 Compressive Strength of Geopolymer Mortars

Fig. 6 illustrates the compressive strength of geopolymer mortars derived from rice husk ash. Initially, the compressive strength measured 20.87 MPa in the absence of silica fume. Introducing 5% silica-fumes slightly increased the compressive strength to 21.83 MPa. A 10% addition of silica fume significantly boosted compressive strength to 28.09 MPa. Incorporating 15% silica fume further raised the strength to 34.13 MPa, reflecting improvements in microstructure and strength. The strength reached its zenith at 36.56 MPa with a 20% silica fumes inclusion, demonstrating its remarkable effectiveness. Similarly, Fig. 6 also presents the compressive of palm shell ash-based geopolymers mortars. Without silica fume, compressive strength stood at 20.87 MPa. Adding 5% silica fume slightly decreased the compressive strength to 21.83 MPa, likely due to poor distribution. However, a 10% silica fume addition markedly increased the compressive strength to 29.72 MPa. With a 15% inclusion, the strength ascended to 32.16 MPa, indicating an improved microstructure. The strength culminated at 36.03 MPa with a 20% addition of silica fume, underscoring its substantial effectiveness. The same phenomenon was observed for clamshell ash-based geopolymer. The compressive strength decayed at the addition of 5% silica fume, and further increased for the addition of more silica fume.

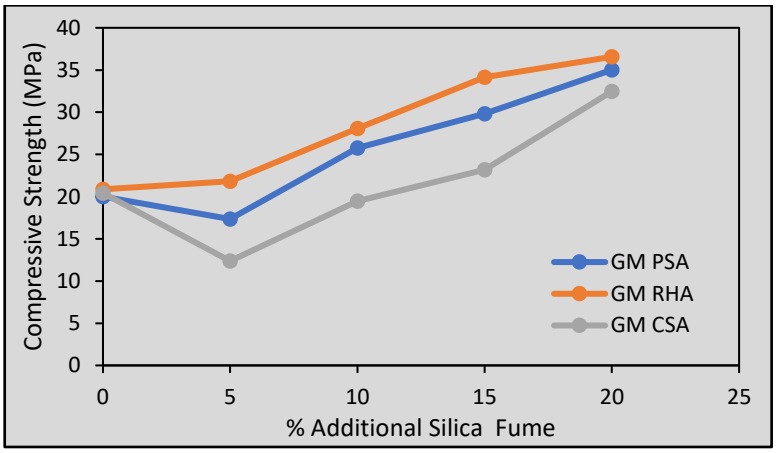

Fig. 6. Early age compressive strength of geopolymer mortar.

The results of this study show significant enhancements in the early strength of geopolymer following the addition of 10%, 15%, and 20% silica fumes. According to previous studies, adding silica fumes to fly ash-based geopolymers can significantly increase their mechanical properties, particularly when approximately 15% silica fume is used. Scientists, [22] claims suggest that silica fume boosts mechanical strength by improving polymerization processes and densifying microstructures.

4 Conclusion

Analysis and discussion lead to the following conclusions:

1. The inclusion of silica fume typically enhanced the 3-day compressive strength of geopolymer mortar. The maximum compressive strengths were observed with a 20% silica fume content, yielding 36.03 MPa, 36.56 MPa, and 32.47 MPa for GM-PSA, GM-RHA, and GM-CSA, respectively.
2. Silica fumes addition also boosted the 3-day flexural strength of geopolymer mortars derived from rice husk ash, clamshell ash, and palm shell ash. Rice husk ash base geopolymer flexural strength progressively increased from 0.09 MPa at 0% silica fume to 0.34 MPa at 20% silica fume. Clamshell ash-based geopolymer flexural strength climbed from 0.12 MPa to 0.24 MPa at 20% silica fume. Meanwhile, palm shell ash-based geopolymer flexural strength fluctuated, starting at 0.01 MPa with 0% silica fume, peaking at 0.15 MPa with 10% SF, dipping to 0.11 MPa with 15% SF, and finally ascending to 0.31 MPa with 20% silica fume.

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