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Influence of Rice Husk Ash and Wood Bark Ash on Geopolymer Mortar Mechanical Properties at Varying Molarity Ratios

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Abstract

Air pollution, a major global challenge, is increased by cement manufacturing, which emits significant amounts of carbon dioxide and contributes to global warming. To support sustainable development, there is a pressing need to adopt eco-friendly alternatives. Agricultural waste burning, which generates methane, further exacerbates air pollution and poses risks to public health. As agricultural waste continues to rise due to growing food demand, researchers have explored utilizing agricultural waste ashes as substitutes for cement in both traditional and geopolymer concrete. These ashes, rich in silica and alumina, enhance pozzolanic reactions and improve concrete durability. Industrial byproducts like fly ash, along with agricultural byproducts such as rice husk ash (RHA) and wood ash (WA) are increasingly used in replacing Portland cement, leading to the development of environmentally sustainable geopolymer concrete. This study aims to optimize geopolymer mortar production by utilizing (RHA), wood bark ash (WBA), and fly ash (FA) in combination with sodium hydroxide (NaOH) as an alkaline activator at two molarities (12M and 14M). The study investigated the mechanical properties of geopolymer mortar with varying agricultural ash replacement percentages (5%, 10%, 15%, 20%, and 30%) for fly ash. The best results were observed at a 20% replacement level, with enhanced mechanical properties at 14 molar than 12 molar.

Keywords

Geopolymer Mortar (GPM), Natural Agriculture Waste Ashes, Rice Husk Ash (RHA), Wood Bark Ash (WBA), Fly ash (FA)

1. Introduction

Portland cement is the most widely used material in construction, but its production emits harmful gases such as CO_2, NO_2, and SO_2 due to the calcination of limestone and fossil fuel combustion. Estimates indicate cement output will increase from the present 2.8 billion tons to 4.68 billion tons per year by 2050 (Schneider, 2019a). The cement industry's manufacturing processes significantly harm the environment, generating 8% of worldwide CO_2 emissions and driving climate change, as CO_2 is responsible for roughly 65% of global warming effects (Andrew, 2018; Jindal, 2019; Schneider, 2019b).

During production, each ton of cement releases between 600 kg and 900 kg of CO_2 greenhouse gas through the chemical conversion of $CaCO_3$ to CaO (den Elzen et al., 2022; Nagaraju et al., 2023). This process not only contributes to environmental degradation but also requires significant energy, approximately 2.8 tonnes of raw materials to manufacture one tonne of cement, which results in nearly one tonne of carbon dioxide emissions (Lee et al., 2017).

To mitigate these issues, geopolymer technology has emerged as a promising alternative material that can reduce carbon emissions and conserve energy. Introduced by Davidovits in 1978, geopolymer is an inorganic polymer created by activating aluminosilicates with alkaline solutions, such as sodium hydroxide (NaOH) and potassium hydroxide (KOH), along with various industrial byproducts rich in aluminum and silicon, including metallurgical slags and coal combustion ashes (Davidovits, 1988). Unlike traditional cement hydration and pozzolanic reactions, the geopolymerization process involves the dissolution of silicon and aluminium in an alkaline medium, leading to the formation of three-dimensional cross-linked structures through orientation and polycondensation. The basic aluminosilicate structures can be categorized into three types: Poly(sialate) (–Si–O–Al–O–), Poly (sialate–siloxo) (Si–O–Al–O–Si–O) and Poly(sialate–disiloxo) (Si– O–Al–O–Si–O–Si–O). The general composition of geopolymer can be expressed as nM2OAl2O3xSiO2yH2O, where M represents an alkali metal (Davidovits, 1991; Kaur et al., 2018).

Geopolymers exhibit properties comparable to ordinary cement in terms of strength, hardness, and chemical stability while offering excellent resistance to fire and acid attacks(Guades, 2016). They also demonstrate low creep, minimal shrinkage, and quick setting times without compromising compressive strength(Soutsos et al., 2016). Furthermore, geopolymers present a sustainable option by utilizing environmentally harmful by-products, making them suitable for applications such as stabilized pavement materials(Hoy et al., 2016).

Rice husk, a major agricultural byproduct, is abundant in rice-producing countries. As the second most significant cereal crop globally, rice production is projected to reach 537 million metric tons in the 2024/2025 season, generating approximately 0.28 kg of rice husk per kg of rice (*Global Rice Production in the 2024/2025 Season* , 2024). This results in an annual production of around 120 million tons of rice husk (Das et al., 2022; Siddika et al., 2021). Burning one ton of paddy yields about 0.2 tons of rice husks and 0.05 tons of rice husk ash (RHA) (Endale et al., 2022; Ramezanianpour, 2014) . Rice cultivation occupies about 11% of the world's arable land, equivalent to 145 million hectares (Ahmad et al., 2017; Pode, 2016). In Egypt, approximately 1,700,000 tons of rice husk are produced annually (General Authority for Investment in Egypt, 2023).

RHA is recognized as a high-purity pozzolanic material which contains 90–95% silica and serves as an alternative cementitious binder (Basri et al., 2017). Its use in concrete enhances workability and compressive strength and reduces permeability by reacting with calcium hydroxide to form additional C-S-H gel (Jagadeep et al., 2023). Jagadeep K,Studies, et al., showed that replacing 20% of fly ash with RHA increases compressive strength from 35.7 MPa to 43.2 MPa (Jagadeep et al., 2023). Chaitanya MSK, et al., found that increasing RHA content from 0% to 20% raises compressive strength from 43.4 MPa to 47.5 MPa (Chaitanya et al., 2023).

Raju et al. demonstrated that replacing 20% of RHA with ground granulated blast furnace slag (GGBS) achieved a maximum compressive strength of about 49.5 MPa at 28 days due to effective pozzolanic reactions forming dense C-S-H structures (Krishnam Raju et al., 2023a).

Wheat, an annual plant, thrives in various environments. Global wheat production is projected to reach approximately 790.38 million metric tons in 2023/2024 (*Wheat | USDA Foreign Agricultural Service*, n.d.). Each kilogram of wheat grain yields around 1.3 to 1.4 kg of wheat straw, which is often burned, resulting in approximately 8.6% wheat straw ash (WSA) from the ash and raising environmental concerns due to pollution (Pan & Sano, 2005).

Memon et al. found that mechanically activated wheat straw ash (WSA) replacing 20% of cement showed comparable or superior mechanical performance to control mortar (Memon et al., 2018). Qudoos et al. reported that extensively ground WSA improved compressive strength at all ages (7, 28, and 91 days) and enhanced resistance to sulfate attacks, alkali-silica reactions, and freeze-thaw cycles due to better pore structure (Qudoos et al., 2018a).

Bheel et al. investigated self-compacting geopolymer concrete's fresh and mechanical properties using metakaolin (MHA) and WSA as substitutes. All mixes met workability standards (Bheel et al., 2021).

Amin et al. studied the mortar with 15% WSA matched control strength at 7 days and exceeded it by 3% and 4% at 28 days; a 20% mix outperformed the control at 91 days, but higher percentages led to reduced strength (Amin et al., 2019).

Qudoos et al. examined how mechanical processing impacted the pozzolanic efficiency of WSA, finding that it reduced particle size, increased specific surface area, and enhanced amorphousness. Finer ash particles improved compressive strength in mortar mixes up to a 20% cement replacement level; beyond this level, strength decreased due to dilution effects (Qudoos et al., 2018).

Many studies have shown that increasing sodium hydroxide concentration significantly impacts the compressive strength of geopolymer concrete (GPC). While higher concentrations generally lead to increased strength, the optimal concentration varies depending on factors like curing temperature and curing time. For instance, Singhal D, et al. studied a 40% improvement in compressive strength was noted when the concentration rose from 8 M to 12 M, followed by an 8% increase from 12 M to 16 M (Singhal et al., 2018). Ghafoor et al. found that compressive strength improved by 55.8%, 10.5%, and 33% when molarity changed from 8 to 10 M, 10 to 12 M, and 12 to 14 M, respectively. However, a decrease of approximately 9% in compressive strength was observed when sodium hydroxide concentration increased from 14 M to 16 M (Ghafoor et al., 2021).

Wood cement composites (WCCs) are excellent materials for green buildings due to their environmental friendliness and cost-effectiveness (Amziane & Sonebi, 2016; Vo & Navard, 2016). Their unique multiscale porosity and hygroscopic properties enhance sound, moisture, and heat regulation, creating a comfortable indoor environment while reducing energy consumption year-round (Ahmed et al., 2018; Amziane & Sonebi, 2016; Vo & Navard, 2016; Wolfe & Gjinolli, 1996). WCCs have thermal conductivity similar to that of glass wool and expanded polystyrene (Li et al., 2017), they can sequester carbon (Amziane & Sonebi, 2016), and they resist decay, fungi, and insects (Coatanlem et al., 2006; Wolfe & Gjinolli, 1996), contributing to sustainability.

These bio-based materials are also well-suited for modular construction, exhibiting energy-dissipating properties and high deformability under stress without fracturing (Li et al., 2019; Wolfe & Gjinolli, 1996). This flexibility is attributed to the wood aggregate's nature, allowing it to absorb strains even after reaching maximum strength (Amziane & Sonebi, 2016). WCCs are particularly advantageous in warm, humid climates prone to termite damage and decay. Studies indicate that CCA-treated woods can enhance flexural toughness and improve wood-cement composites' physical and mechanical properties, making them a viable option for sustainable building practices (Huang & Cooper, 2000; Zhou & Kamdem, 2002).

Hassan et al., developed a one-part white geopolymer cement using high-calcium wood ash as a substitute for white Portland cement in decorative projects. The findings showed that compressive strength initially increased and then decreased with higher wood ash percentages, reaching up to 48 MPa and 85% whiteness at a 21.5 wt.% replacement rate (Hassan et al., 2019).

Research by Abdulkareem et al., indicated that a geopolymer with 20% wood ash demonstrated greater strength and porosity at an early age compared to the control group. Meanwhile, a 10% wood ash geopolymer achieved the highest compressive strength at 28 days, attributed to its lower surface porosity and denser microstructure. The high specific surface area and moisture absorption of wood ash particles accelerate condensation, while the presence of CaO and K2O enhances the formation of geopolymeric products, improving strength development (Abdulkareem et al., 2019).

Cheah et al. investigated new geopolymers with reduced alkaline activator levels and ambient temperature curing. Their results showed that geopolymers made from high-calcium wood ash and pulverized fuel ash exhibited strong mechanical and durability performance. The formation of calcium aluminum silicate hydrate (C-A-S-H) gels contributed to early strength development and a denser microstructure, enhancing both compressive and flexural strength (Cheah et al., 2015, 2017).

Additionally, Arunkumar et al., utilized low-calcium wood ash's inherent alkaline compounds to create geopolymers, incorporating waste rubber fiber to further improve strength. This low-calcium geopolymer with up to 1% fiber showcased maximum strength and superior setting properties (Arunkumar et al., 2021; Arunkumar & Muthiah, 2022) .

This research aims to investigate how varying proportions of rice husk ash (RHA) and wood bark ash (WBA) substituted for fly ash impact geopolymer mortar production by using two various concentrations of morality (12M and 14M).

2. Methodology

2.1. Materials

Fly Ash: In this study, fly ash is the main element utilized to make a geopolymer paste binder, which is then used to make geopolymer mortar.

In this experiment, Class F low-calcium fly ash, compliant with ASTM C618-19 (ASTM C618, 2010), was utilized. The specific gravity of fly ash was 2.3 g/cm^3. The chemical composition of the fly ash is presented in **Table 1.**

Fine Aggregate: The fine aggregate utilized in this study is siliceous sand, which adheres to the specifications outlined in the Egyptian Code of Practice (ECP 203/2018) (E. 203, 2018).

Table 1. Chemical compositions of the Fly ash used in this research.

Elements	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	MgO	SO_3	Cl
FA	52.14	24.72	5.64	4.91	0.92	0.42	0.38	0.24	0.678

The characteristics of the fine aggregate include a particle size ranging from 4.75 mm to 0.15 mm that can be effectively utilized for producing the geopolymer mortar mixture. It is pure and nearly impurity-free and has a specific gravity of 2.72 t/m^3, and a fineness modulus of 2.55. The physical properties of this sand are detailed in **Table** 2 and its grain size distribution is represented Error! Reference source not found..

Table 2. Physical properties of the used sand.

Property	Value
Specific gravity (t/m^3)	2.72
Volumetric weight (t/m^3)	1.63
Voids ratio (%)	40.3%
Percent of clay, silt, and dust (by weight)	0.6%

Table 3. Grading of fine aggregate and grading of natural sand used.

Sieve size(mm)	9.5 mm	4.75 mm	2.36 mm	1.18 mm	0.6 mm	0.3 mm	0.15 mm
% Passing	100	100	97.54	76.76	33.37	5.67	0.17

Natural Ashes: The natural agricultural waste utilized in this study, sourced from local agriculture in Egypt, was categorized into two types: rice husk ash (RHA) and wood bark ash (WBA), as illustrated in Error! Reference source not found. and the chemical compositions of the rice husk ash (RHA) and wood bark ash (WBA) used in this research is shown in **Table 4**.

Table 4. Presents detailed information on the chemical compositions of the rice husk ash (RHA) and wood bark ash (WBA) used in this research.

Elements	Sio_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	MgO	SO_3	Cl
RHA	74.17	2.96	0.48	3.71	0.29	3.49	1.87	1.93	0.782
WBA	27.14	4.36	1.67	51.43	0.48	2.13	1.48	1.07	0.61

The processing and treatment of these materials involved seven key steps:

Collection: Agricultural waste was collected from local sources.

Washing: The collected waste was thoroughly washed with clean water.

Drying: The smaller pieces were sun-dried for varying durations until they reached a semi-dry state.

Burning: The semi-dry material underwent continuous burning at 500 °C for six hours.

Milling: After burning, the product was milled to achieve a fine consistency.

Sieving: Finally, the milled product was passed through a 170 µm mesh sieve to filter out any larger particles.

Alkaline Liquid: In this experimental study, a combination of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) solutions with a molarity of 14M was employed as the alkaline liquid. The sodium hydroxide solution was prepared in the laboratory by dissolving sodium hydroxide pellets, which had a purity of 98%. To reduce the exothermic reaction that occurs when NaOH is dissolved in water, the solution was allowed to cool for approximately 24 hours before being mixed with sodium silicate.

The sodium silicate solution, Na_2SiO_3, contained 29.4% SiO_2, 14.7% Na_2O, and 55.9% water, and it was obtained from Al-Radwan Chemicals Company in Tanta to serve as the alkaline activator.

Mixing and preparation: The mix proportions for used mortar mixtures are shown in **Table** 5 in kg/m^3. In this study, two different moralities 12M (CT-12) and 14M (CT-14) were used as a control specimen with 100% fly ash. Curing at room temperature, the geopolymer mortar mix, which contains percentages of natural agricultural waste ashes replacing fly ash, is 5%, 10%, 15%, 20%, and 30% (RH05-12, RH10-12, RH20-12, RH30-12, WB05-14, WB10-14, WB15-14, WB20-14, and WB30-14). An activator-to-binder mass ratio of 0.4 was used to create the geopolymer mortar.

Figure 1. The used natural ash (a) Wood Bark Ash (WBA), (b) Rice Husk Ash (RHA).

Table 5. The proportions of the blended geopolymer mortar in kg/m^3.

Item	Fly Ash	RHA/WBA	Fine Aggregate	NaOH	$NaSio_2$
Control	240	0	720	57	115
5% replacement	228	12	720	57	115
10% replacement	216	24	720	57	115
15% replacement	204	36	720	57	115
20% replacement	192	48	720	57	115
30% replacement	168	72	720	57	115

At room temperature, the mixing process was conducted in the laboratory. An alkaline activator was prepared using 12 and 14-molar sodium hydroxide (NaOH) combined with liquid sodium silicate. The NaOH solutions needed to be prepared 24 hours before mixing.

Molarity (M) is defined as the number of moles of solute per liter of solution:

$$Molarity\ M = \frac{moles\ of\ solute}{liters\ of\ solution} \quad (1)$$

Molar mass of NaOH = 22.99 (Na) + 15.999 (O) + 1.008 (H) = 40.00 g/mol.

Mass of NaOH required for 12 and 14 moles:

Mass=12moles×40.00g/mol=480g
Mass=14moles×40.00g/mol=560g
Since the NaOH is 97% pure, the actual mass of NaOH pellets needed is:
Mass of NaOH pellets for 12 moles =480g x 0.97= 495.87g ≈ 496 g
Mass of NaOH pellets for 14 moles =560g x 0.97= 543.2g ≈ 543 g
For the dissolution process, the weighed NaOH pellets were placed into a large beaker or flask. Then after, distilled water was gradually added while continuously stirring to ensure complete dissolution of the pellets. Finally, the solution was transformed into a volumetric flask and distilled water was added until the total volume reaches exactly 1 liter.

Fly ash (FA), fine aggregate, and agricultural waste were blended in a concrete pan mixer at a predetermined replacement ratio for three minutes until a uniform colour was achieved in the pan mixture used.

The prepared alkali activator solution was then gradually incorporated with the solid materials. The mixture was thoroughly homogenized by the mixing process for five minutes. Finally, the samples were allowed to be cured at room temperature for 24 hours before being removed from the moulds and stored in the laboratory until the testing day.

To assess the mechanical properties tests (compressive, tensile and flexural strength), tests were executed according to Egyptian code(ECP 203/2018) (E. 203, 2018). To determine the compressive strength freshly mixed mortar was poured into 70.7 x 70.7 x 70.7 mm cubes in three layers, as seen in **Error! Reference source not found.** Each mix is evaluated using three cubes at a designated age, and the average strength of these three specimens is recorded for that specific age, and the machine used for measuring compressive strength. Digital testing machine has a maximum capacity of 2000 kN was used measuring the compressive strength.

Figure 2. Compressive strength and tensile strength test moulds .

The equation was used to determine the compressive strength of the geopolymer mortar moulds.

$$\delta = \frac{P}{A} \quad (2)$$

Where, δ = compressive strength (MPa), P is the maximum applied force (N), and A is the area of the specimens in mm^2.

Additionally, the mixture was placed into cylinders with a diameter of 50 mm and a length of 100 mm to evaluate the splitting strength, as displayed in Figure 2. To eliminate any remaining air bubbles, the mortar sample vibrated on a table for an additional minute. The samples are tested using a 100-mm-long cylinder and a testing machine with a maximum capacity of 2000 kN to measure its split tensile strength values.

The equation was used to determine the splitting tensile strength of the specimens.

$$T = \frac{2P}{\pi LD} \quad (3)$$

Where, T = Tensile strength (MPa), P is the maximum applied force (N), L is the length of the cylinder in (mm), D is the diameter of the cylinder in (mm), and π= 3.14 .

For the flexural strength, the mixture cast into samples measuring 40 × 40 × 160 mm with a span length of 150mm, as displayed in **Error! Reference source not f ound.** . Prisms are positioned on two supports that are 150 mm apart, with the load applied at the midpoint between them.

The modulus of rupture was determined using the following equation:

$$F_{cf} = \frac{MY}{I},\quad where\ M = \frac{PL}{4}\ \&\ I = \frac{bh^3}{12} \tag{4}$$

Where F_{cf} is the modulus of rupture (MPa), L is the span length (mm), P is the maximum applied force as indicated by the testing machine (N), Y is the average thickness of the specimen at the point of failure (mm), h is depth of the specimen at the point of failure (mm), and b is the width of the specimen at the point of failure (mm).

Figure 3. Flexural strength test prism.

3. Results and Discussion

3.1. Compressive Strength Test Results

The most popular test used to accept or reject concrete and mortar is compressive strength. The compressive strength was calculated by averaging the results of casting three cube samples at each age and replacement %. The effects of replacing fly ash with natural agricultural waste ashes like rice husk ash (RHA), and wood bark ash (WBA), for fly ash on the development of compressive strength over 3, 7, and 28 days for 12M are depicted from **Figure 4** to **Figure 6** and for 14 M are shown from **Figure 7** to **Figure 9**. Studied for replacement of FA with RHA and WBA with replacement ratio ranging from 0% to 30%.

Figure 4 illustrates that the compressive strength increased in 3 days. RHA increased from 20.73 MPa to 23.81 MPa, reflecting a notable rise of 12.94%. Similarly, for WBA, the strength reaches 22.15 MPa, marking an increase of 6.41%. Notably, a 20% substitution for Fly Ash with Rice Husk Ash (RHA) yielded the highest compressive strength, reaching 25.03 MPa, while a similar substitution with Wood Bark Ash (WBA) resulted in a compressive strength of 23.04 MPa. For 7 days, the compressive strength of the geopolymer mortar enhanced significantly, with RHA increasing from 24.89 MPa to 28.11 MPa, representing a substantial rise of 11.45%. In comparison, the strength for WBA improved to 26.93 MPa, reflecting an increase of 7.58%. Notably, a 20% replacement of Fly Ash with Rice Husk Ash (RHA) produced the highest compressive strength at 29.04 MPa, while substituting Fly Ash with Wood Bark Ash (WBA) achieved a compressive strength of 27.41 MPa, as shown in **Figure 5**. The geopolymer mortar samples exhibited remarkable improvements in their compressive strength at 28 days. The specimens containing Rice Husk Ash (RHA) demonstrated good performance, with strength values increasing from 29.04 MPa to 32.78 MPa, marking an enhancement of 11.41%. Meanwhile, the Wood Bark Ash (WBA) samples also showed positive results, with strength values rising to 31.56 MPa, representing a 7.98% improvement. Most notably, when 20% of fly ash was replaced with rice husk ash (RHA), the mixture achieved the highest compressive strength of 33.99 MPa. In comparison, the substitution of fly ash with wood bark ash (WBA) resulted in a good compressive strength of 32.06 MPa, as illustrated in the corresponding **Figure 6**.

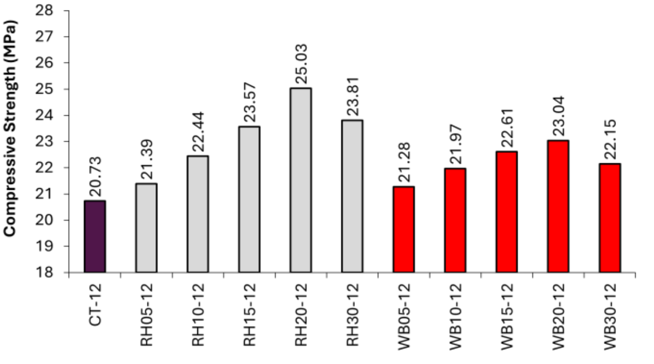

Figure 4. Compressive strength at 3 days for 12M geopolymer mortar.

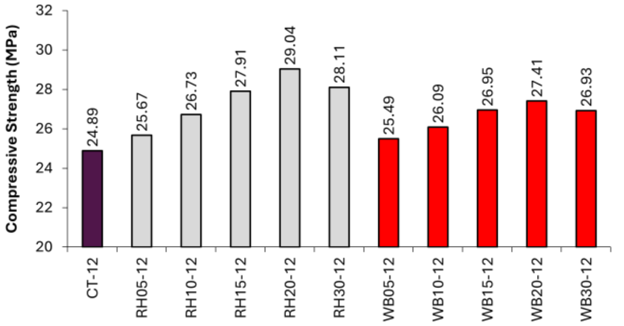

Figure 5. Compressive strength at 7 days for 12M geopolymer mortar.

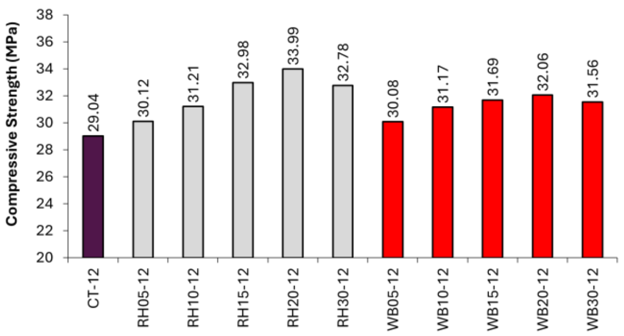

Figure 6. Compressive strength at 28 days for 12M geopolymer mortar.

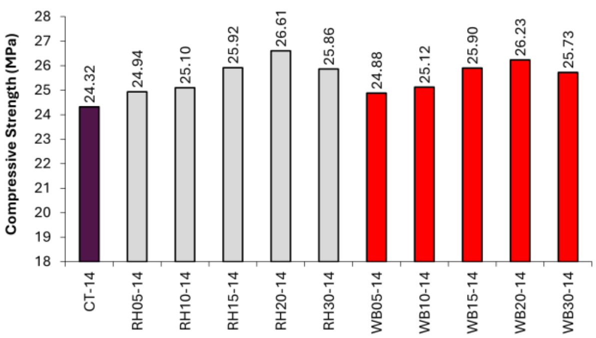

Figure 7. Compressive strength at 3 days for 14M geopolymer mortar.

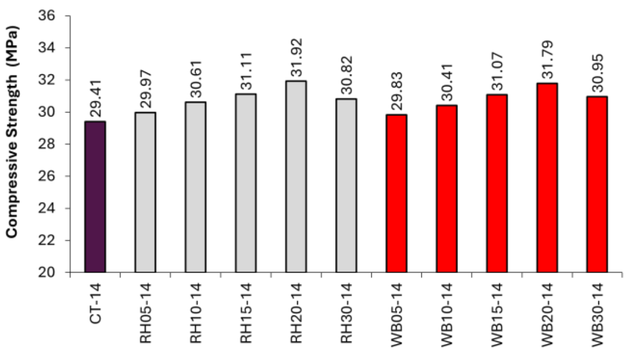

Figure 8. Compressive strength at 7 days for 14M geopolymer mortar.

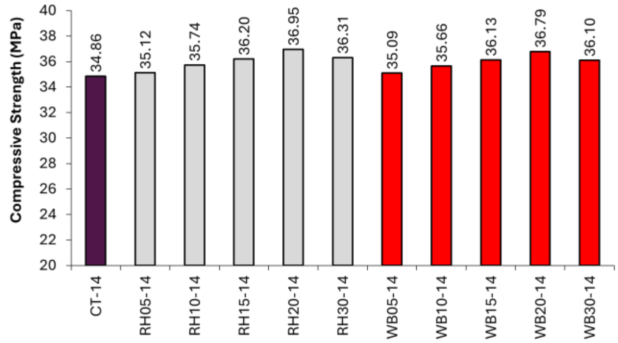

Figure 9. Compressive strength at 28 days for 14M geopolymer mortar.

For a concentration of 14 M, the figures from 7 to 9 show the impact of replacing natural agricultural waste ashes, such as wood bark ash (WBA) and rice husk ash (RHA), for fly ash on the development of compressive strength over 3, 7, and 28 days, respectively. The compressive strength at 3 days, as seen in Figure 7, shows that the strength of RHA increased from 24.32 MPa to 25.86 MPa, reflecting a rise of 5.96%. Similarly, the compressive strength for WBA increased to 25.73 MPa, marking an increase of 5.48%. The highest compressive strength recorded was 26.61 MPa, achieved by substituting 20% of the fly ash with rice husk ash (RHA). Also, a similar substitution with wood bark ash (WBA) resulted in a compressive strength of 26.23 MPa.

The compressive strength of geopolymer mortar with rice husk ash (RHA) and wood bark ash (WBA) at 7 days. RHA specimens showed a strength increase from 29.41 MPa to 30.82 MPa, representing a 4.57% improvement. WBA specimens increased to 30.95 MPa, marking a 4.97% strength gain. The optimal performance was observed when 20% fly ash replacement with RHA resulted in the highest compressive strength of 31.92 MPa and 31.79 MPa for WBA, as displayed in **Figure 8**. The compressive strength after 28 days of geopolymer mortar containing wood bark ash (WBA) and rice husk ash (RHA). As shown in the **Figure 9**, RHA specimens showed a 3.99% gain in strength, rising from 34.86 MPa to 36.31 MPa. WBA specimens showed a 3.43% strength rise, reaching 36.10 MPa.

The best performance was noted when 20% fly ash was replaced with RHA, yielding the maximum compressive strengths of 36.95 MPa and 36.79 MPa for WBA.

The results indicate that incorporating amorphous silica-rich agricultural waste significantly enhances the compressive strength of the mortar. Specifically, 15% and 20% replacement ratios yielded the highest compressive strength values. The geopolymerization process facilitated the formation of robust Na-Al-Si bonds, further improving the material's compressive strength at 28 days.

Rice husk ash (RHA) exhibits superior reactivity and a higher surface area compared to fly ash (FA), attributed to its greater amorphous silica content and more favorable SiO_2/Al_2O_3 ratio (Krishnam Raju et al., 2023b; Shilar et al., 2023). This strong Na-Al-Si bonding, generated through the GPC polymerization mechanism, is a key factor contributing to the high compressive strength observed at 28 days. The test results show a significant upward trend in compressive strength as the concentration of sodium hydroxide molarity increases. For instance, when the molarity increased from 12M to 14M, the compressive strength improved from 33.99 MPa to 36.95 MPa with a 20% replacement of rice husk ash (RHA) at 28 days of curing at room temperature. This highlights the effectiveness of using these sustainable agricultural waste materials to enhance the mechanical properties of geopolymer mortar.

3.2. Indirect Tensile Strength Test Results

The objective of this test was to determine the tensile strength of the sample cylinders, with an average of three cylinders tested per mixture. These samples were left at room temperature for periods of 7 and 28 days. The indirect tensile strength was measured for various mixtures of rice husk ash (RHA) and wood bark ash (WBA) at each replacement percentage. The flexural strength exhibited a progressive increase over time. As shown in the **Figure 10**, the results of the split tensile test at 28 days for 12 M reveal that, with the increase in rice husk ash (RHA) and wood bark ash (WBA) contents from 0% to 30%, the tensile strength of the geopolymer mortar incorporating natural agricultural waste ash demonstrates a significant enhancement. The tensile strength for RHA increased from 2.88 MPa to 3.21 MPa, reflecting a rise of 10.28%, while for WBA, it increased from 2.88 MPa to 3.16 MPa, marking an 8.86% increase.

The optimal tensile strength values of 3.36 MPa and 3.20 MPa were achieved with a 20% replacement of both rice husk ash (RHA) and wood bark ash (WBA), respectively.

As illustrated in the **Figure 11,** the split tensile test results at 28 days for 14 M indicate a remarkable enhancement in the tensile strength of geopolymer mortar when incorporating natural agricultural waste ash. Specifically, as the content of rice husk ash (RHA) and wood bark ash (WBA) gradually increased from 0% to 30%, good improvements were observed. For RHA-based samples, the tensile strength showed a good increase from 3.28 MPa to 3.59 MPa, representing a substantial improvement of 8.63%. Similarly, WBA-containing specimens exhibited a notable increase from 3.28 MPa to 3.55 MPa, corresponding to an enhancement of 7.61%.

The results revealed that the optimal performance was achieved at a 20% replacement level for both agricultural waste materials. At this optimal replacement percentage, rice husk ash (RHA) specimens achieved a peak tensile strength of 3.67 MPa, while wood bark ash (WBA) samples reached a maximum value of 3.62 MPa.

The test results indicate a noticeable increasing trend in split tensile strength corresponding to higher concentrations of sodium hydroxide molarity, such as, from 12M to 14M, the split tensile strength raised from 3.36 MPa to 3.67 MPa for a 20% replacement ratio of rice husk ash (RHA).

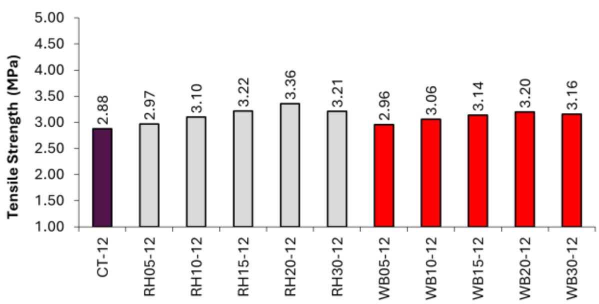

Figure 10. Spilt tensile strength at 28 days for 12M geopolymer mortar.

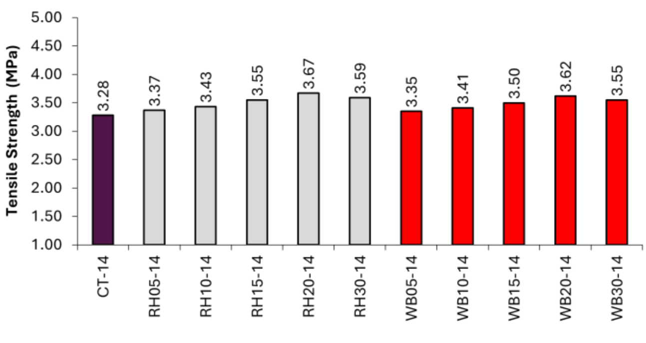

Figure 11. Spilt tensile strength at 28 days for 14M geopolymer mortar.

3.3. Flexural Strength Test

The determination of the load-bearing capacity of concrete and mortar structures is commonly achieved through flexural strength testing of hardened concrete and mortar. The flexural strength results of GPC prism specimens tested 28 days after casting and cured at room temperature. The flexural test results at 28 days for 12M demonstrated improvements in geopolymer mortar strength when incorporating agricultural waste ashes. As the content of rice husk ash (RHA) and wood bark ash (WBA) increased from 0% to 30%, notable strength enhancements were observed. **Figure 12** showed flexural strength for RHA-based samples, rising from 4.21 MPa to 4.68 MPa, representing a 10.04% improvement. WBA-containing specimens increased from 4.21 MPa to 4.48 MPa, marking 6.03% enhancement.

The most optimal performance was achieved at a 20% replacement level for both agricultural waste materials. RHA specimens reached a peak flexural strength of 4.77 MPa. WBA samples attained a maximum flexural strength of 4.53 MPa. The flexural test results at 28 days for 14M revealed remarkable improvements in geopolymer mortar strength through the incorporation of agricultural waste ashes. As the percentage of rice husk ash (RHA) and wood bark ash (WBA) was systematically increased from 0% to 30%, good strength enhancements became clear in the test specimens. The rice husk ash (RHA) based samples demonstrated good flexural strength values, rising from an initial 4.93 MPa to reach 5.27 MPa, representing a substantial 6.45% improvement in overall performance. Similarly, the WBA-containing specimens showed good results, increasing from 4.93 MPa to achieve 5.21 MPa, marking a notable 5.37% enhancement in flexural capacity.

Through detailed analysis, the research identified that the most favorable performance was consistently achieved at a 20% replacement level for both agricultural waste materials. At this optimal percentage, the RHA specimens achieved their peak flexural strength of 5.31 MPa, while the WBA samples reached their maximum flexural strength of 5.27 MPa, as displayed in **Figure 13.**

The test results revealed that the flexural strength values increased with higher molarity levels. For instance, at a 20% replacement ratio of rice husk ash (RHA), the flexural strength improved from 4.77 MPa to 5.31 MPa when comparing the 12M and 14M mixtures.

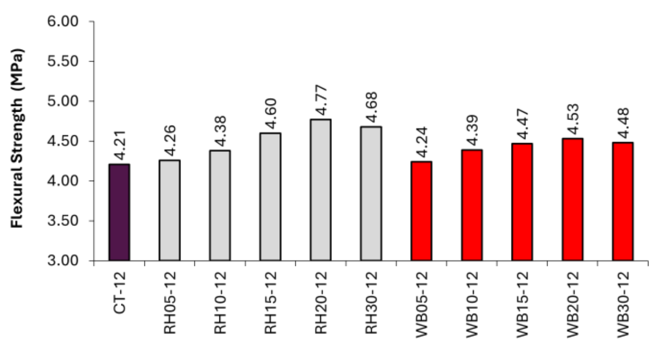

Figure 12. Flexural strength at 28 days for 12M geopolymer mortar.

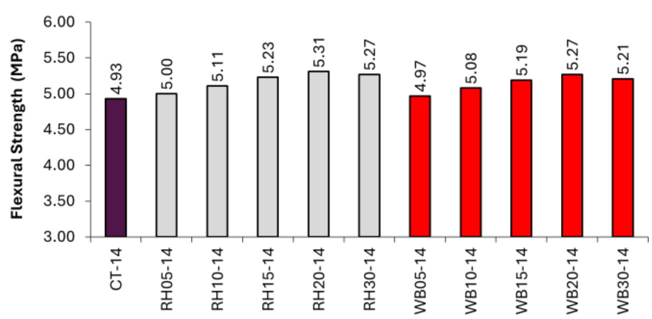

Figure 13. Flexural strength at 28 days for 14M geopolymer mortar.

4. Conclusions

This experimental study explores the potential of geopolymer mortar as a sustainable building material, highlighting key benefits such as waste reduction, lower carbon emissions, and decreased reliance on natural resources. Our research, which involved replacing fly ash with the used natural agricultural waste ashes (rice husk ash (RHA) and wood bark ash), yielded the following findings:

- The optimal replacement ratio of fly ash with the used natural agricultural waste ashes with ranging to 15-20% of fly ash content in the geopolymer mortar mix resulting in enhanced results mechanical properties.
- Mechanical properties also increased while using 14M of Alkaline activator than 12M.
- The optimal results for rice husk ash were observed when it was used as replacement for 20% fly ash content. for 28 days age the 12M mixture showed an increase in compressive strength by 14.56%, split tensile strength by 14.28%, and flexural strength by 11.74%. Additionally, at for a 14M concentration an enhanced for the mechanical properties, resulting in improvements of 5.66%, 10.63%, and 7.06% in compressive strength, split tensile strength and flexural strength, respectively, at 28 days compared with the control mix.
- For wood bark ash, the optimal results were achieved when 20% of fly ash were replaced with wood bark ash. For 12M mixture, resulting showed increases of 9.42% in compressive strength, 10% in split tensile strength, and 7.06% in flexural strength at 28days age. Furthermore, for 14M concentration also improved the mechanical properties yielding enhancements of 5.25%, 9.39%, and 6.45% in compressive strength, split tensile strength, and flexural strength, respectively, at the same age compared with the control mix.

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