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Development of Geopolymer Concrete Using Blended Rice Husk Ash and Palm Frond Ash

Mohammad Z. Yousif[1*], Ruqaya F. Hamada[2], Hussein Falah Hasan[3]

[1] Department of Civil Engineering, Engineering College, Mustansiriyah University, Baghdad 10045, Iraq
[2] College of Applied Sciences, University of Technology, Baghdad 10069, Iraq
[3] Department of Building Engineering and Construction Projects Management, Civil Engineering College, University of Technology, Baghdad 10069, Iraq

Corresponding Author Email: dr.mohammadalrawas@uomustansiriyah.edu.iq

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ABSTRACT

The increasing need for eco-friendly and sustainable construction materials has forced researchers to seek alternative binders that may reduce the dependence on ordinary concrete. In this study, geopolymer concrete was prepared using rice husk ash (RHA) and palm frond ash (PFA) as alternative eco-friendly construction materials from agricultural wastes. Five mixtures with varying RHA and PFA ratios ranging from 0 to 100% were prepared using sodium hydroxide and sodium aluminate solutions as alkaline activators. The properties of fresh and hardened concrete were investigated using slump, compressive strength, split tensile strength, flexural strength, dry density, and water absorption tests. The results revealed that a mixture containing equal amounts of RHA and PFA produced better properties than the others, including higher mechanical strengths and lower water absorption values. Moreover, it produced a denser microstructure than the other mixtures. In this study, the combined use of RHA and PFA in geopolymer concrete was demonstrated to be a promising and sustainable construction material.

1. INTRODUCTION

The construction industry is generally identified as a significant consumer of environmental resources and a significant contributor to environmental degradation. A substantial portion of this environmental impact is generally associated with ordinary Portland cement (OPC) production, which requires significant amounts of energy and produces considerable amounts of CO_2 owing to clinker production methods [1, 2]. The ever-increasing trend in urban development and infrastructure expansion is expected to create a high demand for concrete materials in the near future. This has prompted several researchers to investigate other materials that can effectively substitute for conventional concrete materials while simultaneously mitigating environmental degradation [3]. Among the materials identified as potential substitutes for conventional concrete is geopolymer concrete. Geopolymer is an inorganic binder produced through an alkaline activation reaction between an aluminosilicate source and an alkaline solution such as sodium hydroxide and sodium aluminate. This results in a three-dimensional aluminosilicate structure that is rich in Si-O-Al bonds, which improves the mechanical properties and rapid strength gain, as well as high resistance to chemical and thermal attacks [4-6]. Moreover, geopolymer technology has shown unprecedented potential for mitigating greenhouse gas emissions, which can be as high as 80% compared to other conventional materials [7]. The properties of geopolymer concrete are largely dependent on the chemical composition of the precursor materials used in the geopolymerization process. Various industrial waste materials, such as fly ash (FA) and ground granulated blast furnace slag (GGBFS), have been widely researched as potential precursor materials for geopolymer concrete owing to the availability of rich silica and alumina content in these materials [8]. However, the availability of industrial waste products is generally limited in developing nations, especially agricultural nations, where large amounts of biomass waste are produced annually [9]. Hence, the use of agricultural waste materials as potential precursors for geopolymers has recently gained importance. Rice husk ash (RHA), one of the most studied forms of agricultural waste in the context of cementitious systems as well as geopolymer systems, is derived from the controlled burning of rice husks, which are a major by-product of the rice mill industry. Globally, rice production exceeds 500 million tons every year, which translates into 120 million tons of rice husks and almost 20-25 million tons of RHA following the controlled burning of the former [10]. RHA, following the controlled burning of rice husks at a temperature range of 600 ℃, has a very high percentage of amorphous silica, which is well over 85-90%, thus rendering it a highly reactive material in alkaline environments [11, 12]. Owing to its high specific surface area, RHA has shown considerable potential as a supplementary cementitious material and geopolymer precursor. This property increases the reactivity of RHA, and thus increases the compressive strength and decreases the permeability of the concrete produced, increasing its durability [13, 14]. However, the low alumina content of RHA has been cited as a disadvantage in terms of its geopolymerization potential when used solely as a precursor material [15].

Palm frond ash (PFA), another form of agricultural waste, results from the incineration of palm fronds that are produced in large quantities as a result of oil palm and date palm farming activities. In many countries in the tropics and Middle East, large amounts of palm biomass waste materials are produced annually and disposed of through open burning and landfilling, causing environmental problems [9, 16]. Previous studies have shown that palm ash is rich in silica, alumina, and calcium oxide compounds, making it a useful supplementary cementitious material for concrete and other applications [17, 18]. Although PFA have the potential for wide usage, their utilization in geopolymer concretes has been poorly explored.

Blending different types of precursor materials has been generally recognized as an effective method to optimize the chemical composition of geopolymer binders, dissolution kinetics, and overall performance of geopolymer concrete [19, 20]. In this context, blending RHA with PFA is believed to offer a promising opportunity. RHA is known to offer a high level of silica, whereas PFA may offer additional levels of alumina and calcium oxide, which may further support the geopolymerization reaction [15, 16]. However, the co-use of RHA and PFA as blended precursor materials for geopolymer concrete has not been adequately explored in the existing literature.

Based on the hypothesis that a mixture of RHA, which is rich in reactive amorphous silica, and PFA, which is rich in alumina and alkaline oxides, can produce a balanced aluminosilicate composition that can improve the geopolymerization reaction, it is anticipated that geopolymer concrete made from a mixture of RHA and PFA precursors can exhibit superior microstructural development, compressive strength, and durability compared to geopolymer concrete made from a precursor material alone.

Based on the proposed hypothesis, this study aimed to produce geopolymer concrete using a combination of RHA and PFA as sustainable sources in a blended system. An alkaline activator solution containing sodium hydroxide and sodium aluminate was used to accelerate geopolymerization.

This study is based on investigating the fresh properties and durability of the produced geopolymer concrete to assess its potential use as a sustainable and eco-friendly construction material.

2. METHODOLOGY

The materials used in this study were RHA, PFA, alkaline solutions, fine aggregates, coarse aggregates, and water. RHA was obtained by controlled burning of rice husks obtained from rice milling waste. The RHA was subjected to burning at 600 ℃ for two hours in order to obtain the maximum amount of amorphous silica. The obtained ash contained a high percentage of amorphous silica. PFA was obtained by the controlled burning of dried palm fronds obtained from the waste material of the agricultural field. The obtained ash was ground into a fine powder suitable for the production of geopolymer binders.

The chemical compositions of RHA and PFA were analyzed using X-ray fluorescence (XRF) and are summarized in Table 1. Based on these analyses, it can be confirmed that the major constituent of RHA is silica, whereas the major constituents of PFA include alumina and calcium oxide, which are both important materials for achieving a better geopolymerization process. that improves the performance of the geopolymer concrete.

The alkaline activator used in this study was a solution of sodium aluminate and sodium hydroxide. To prepare the NaOH solution, a certain amount of NaOH was dissolved in distilled water. The addition of sodium aluminate improved the availability of silica, thereby facilitating the geopolymerization reaction.

The coarse aggregate consisted of crushed gravel, and the fine aggregate was river sand. Every aggregate was completely dry on the top. The entire experimental work was conducted using potable water.

Rice husks and palm fronds were cleaned and dried at normal temperature before burning in the furnace at 600 ℃ for two hours in order for the resulting ashes to contain amorphous silica. After the burning process, the resulting ash was left to cool to normal temperature. The resulting ashes were crushed using a ball mill and sieved through a 45 μm sieve in order for the resulting geopolymer materials to have a uniform particle size distribution and thus enhance the reactivity of the materials in the geopolymerization process.

Geopolymer concretes were formulated using RHA and PFA as the main sources of aluminosilicates for the geopolymerization process. To determine the effect of the composition of geopolymer sources on the properties of geopolymer concretes, five geopolymer concretes were formulated using different compositions of rice husk and PFA.

In both cases, the RHA/PFA contents varied between 0% and 100%, while the content of both binders remained constant to have an equal comparison of their influence. This method will enable us to evaluate the impact of the precursor composition on the properties of geopolymer concrete, as shown in Table 2.

Table 1. Chemical composition of rice husk ash (RHA) and palm frond ash (PFA) (X-ray fluorescence (XRF) analysis)

Oxide (%)	RHA (%)	PFA (%)
SiO_2	88.5	52.3
Al_2O_3	1.8	14.6
CaO	1.2	12.8
Fe_2O_3	0.9	5.4
K_2O	3.5	6.1
MgO	0.6	3.2
Na_2O	0.3	1.1
SO_3	0.2	0.8
LOI	3.0	3.7
Total	100	100

Table 2. Mixture proportions of geopolymer concrete using blended rice husk ash (RHA) and palm frond ash (PFA)

Mix ID	RHA (%)	PFA (%)
M1	100	0
M2	75	25
M3	50	50
M4	25	75
M5	0	100

The proportions of the geopolymer concrete mixtures were based on previously established optimal designs for rice-husk ash-based systems, as reported by Abbass and Singh [21]. The total binder content was maintained at 500 kg/m³ with a constant alkaline activator/binder mass ratio of 0.4. The chemical composition of the activator solution was composed of sodium hydroxide ($NaOH$) and sodium aluminate ($NaAlO_2$), with a $NaAlO_2/NaOH$ molar ratio of 2.0. The concentration of the NaOH solution was fixed at 14 M. To study the influence of variations in the composition of the precursors, two control mixtures with 100% RHA and 100% PFA and mixtures with gradual substitution of one material with another were also prepared. This approach was adopted to study the influence of variation in the precursor composition, as well as the possible synergistic effects of RHA and PFA. A solution with the desired molarity of NaOH was prepared by dissolving NaOH pellets in distilled water. This exothermic reaction required at least 24 h to prepare the solution before it could be used. Furthermore, a certain proportion of sodium hydroxide solution was mixed with sodium aluminate to prepare the alkaline activator, which then had to equilibrate before use. In addition, geopolymer concrete mixtures were produced using a concrete mixer. Initially, the dry materials used in the geopolymer concrete mixture, that is, RHA, PFA, fine aggregate, and coarse aggregate, were mixed for 3–5 min to ensure a uniform distribution. In addition, an alkaline activator solution was gradually added to the mixture during mixing to produce a geopolymer concrete mixture.

Freshly prepared geopolymer concrete mixtures were then poured into steel molds to obtain the specimens. The mixtures were compacted using a vibrating table to ensure that the air bubbles were expelled from the mix. Finally, the surfaces of the specimens were finished to ensure minimal moisture loss during the early curing stages.

The samples were cured within the molds for approximately 24 h before extraction from the molds. The samples were then allowed to undergo primary curing at 60 °C for 24 h. After that process, the samples were allowed to cure in the atmosphere with a temperature range of (25 ± 2 °C) and relative humidity of 60-70% for 28 days.

The fresh mixtures were subjected to slump tests according to ASTM standard C143 to evaluate the workability of the concrete. The standards for calculating the strength of concrete include the compressive stress as per ASTM standard C39, split tensile stress as per ASTM standard C496, and flexural stress as per ASTM standard C78. Finally, the dry density of the hardened concrete was determined by dividing its mass by its volume. To determine the permeability of the geopolymer concrete, it was subjected to water absorption, as per the ASTM standard for concrete specimens (ASTM C642). The internal structure of the geopolymer concrete and the bonding qualities of the aggregates with the geopolymer paste were determined by conducting microstructural tests using scanning electron microscopy (SEM).

3. RESULTS AND DISCUSSION

3.1 Workability of geopolymer concrete

The workability of the fresh geopolymer concrete mix was evaluated using a slump test, according to ASTM C143. The results obtained, as presented in Figure 1 and Table 3, indicate that the slump of the geopolymer mixture depends on the percentages of RHA and PFA used to produce the binder system.

The slump value was 53 mm at its lowest in the M1 combination, which contained 100% RHA. The alkaline solution was absorbed owing to the relatively large specific surface area of the rice RHA. This combination exhibited the lowest slump value owing to the high specific surface area present in the RHA. The use of RHA increases the amount of water required for the generation of the mixture, as noted by other researchers. This is due to the extremely porous nature of RHA, which reduces the workability of the mixture [13].

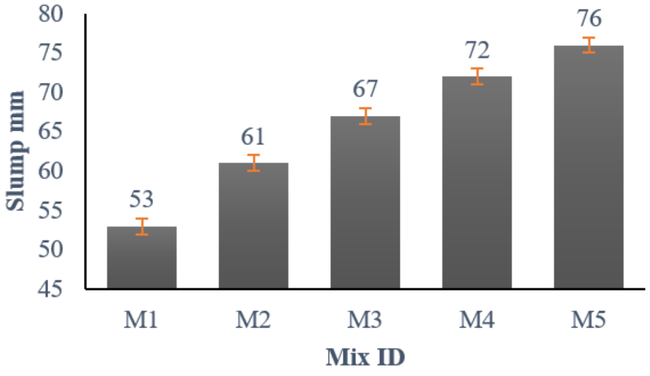

Figure 1. Slump results

Table 3. Results of all test of geopolymer concrete mixtures in this study

Mix ID	Slump mm	Compressive Strength MPa	Split Tensile Strength MPa	Flexural Strength MPa	Dry Density kg/m³	Water Absorption %
M1	53	34.8	3.1	4.9	2180	6.83
M2	61	38.6	3.5	5.4	2210	6.12
M3	67	42.3	3.9	6.1	2240	5.41
M4	72	40.1	3.6	5.7	2225	5.79
M5	76	31.7	2.8	4.5	2195	6.47

With an increase in the PFA percentage, the slump values increased gradually. The slump reached 76 mm when the mixture contained 100% of PFA. The increase in the workability of the mixture may be attributed to the relatively smaller surface area of palm ash than that of RHA. Similar trends have been observed by other researchers who have studied the properties of palm ash used to produce cementitious materials. The addition of palm ash was found to improve the workability of the mixtures [17, 18].

The slump values were between 61-72 mm for blended mixtures M2, M3, and M4. The findings indicated that the workability of the geopolymer concrete mixture improved with the addition of PFA. The findings of this study were in agreement with those of previous studies, indicating that the combination improved the workability of the geopolymer mixture. A significant influence on the workability of the mixture was observed after blending [20].

3.2 Compressive strength

Using the ASTM C39 test method, the compressive strength of the geopolymer concrete mixes was evaluated after 28 d of curing. According to Table 3 and Figure 2, the impact of the RHA to PFA ratio on the development of the compressive strength is substantial.

A compressive strength of 34.8 MPa was measured for the mixture that only contained RHA. This is because RHA contains a large amount of amorphous silica. Amorphous silica is primarily responsible for the geopolymerization reaction and stability of the final geopolymer gel product. Moreover, in previous studies, it was noted that RHA increased the compressive strength owing to its high reactivity [13].

An increase in the compressive strength was also observed when a mixture containing equal percentages of RHA and PFA was used to produce the geopolymer concrete. The compressive strength of the mixture containing equal percentages of RHA and PFA (M3) was the highest at 42.3 MPa. This is because the mixture is rich in silica, alumina, and calcium oxide, which are reactive components that can be used to produce dense geopolymer concrete mixtures. Other researchers have also confirmed that a mixture containing equal percentages of RHA and palm oil fuel ash is effective in producing a dense geopolymer concrete mixture [19, 22].

The compressive strength did, however, drop somewhat as the fraction of PFA was further increased. With a compressive strength of 31.7 MPa, the mixture composed entirely of PFA (M5) was the weakest. This may be because palm-based ash is less reactive and has a lower silica content than RHA. Researchers have observed that when the geopolymer concrete's primary binder material is a less reactive precursor material, the material's mechanical qualities decrease [17, 20].

The results revealed that the combination of RHA and PFA had a significant positive effect on the mechanical properties of the geopolymer concrete. The mixture composed of equal proportions of both types of agricultural waste ash exhibited the best compressive strength. This indicates that a balanced aluminosilicate content is essential for enhancing the geopolymer reaction to obtain denser and stronger geopolymers.

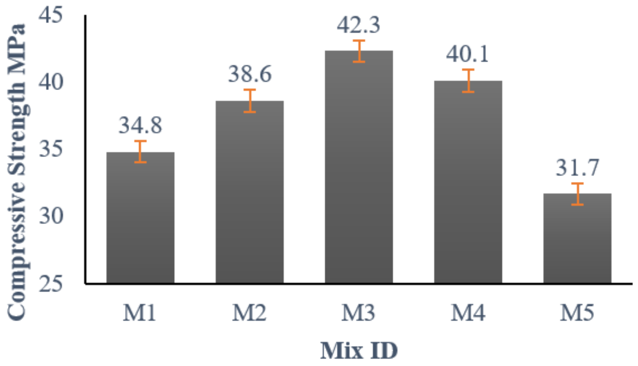

Figure 2. Compressive strength results

3.3 Split tensile strength

A test was performed to confirm the tensile properties of the mixtures. The cylindrical specimens were tested using the ASTM C496 method after curing for 28 d. The results are shown in Table 3 and Figure 3. The split tensile strength of the mixtures in this investigation ranged from 2.8 MPa to 3.9 MPa, depending on the amount of RHA/PFA utilized in the mix design. It was noted that mixture M3 had the highest split tensile strength, measuring 3.9 MPa, while mixture M5 had the lowest, measuring 2.8 MPa.

The balanced chemical composition of the blended materials used in the test improved the tensile strength of the geopolymer concrete mixtures containing blended raw materials. This is because amorphous silica is an essential ingredient in the geopolymerization process and is also a substance that enhances bonding. Amorphous silica is also known to be present in RHA in large amounts [13]. Palm-based ash is known to contain alumina and calcium compounds, which improve the dissolution of aluminosilicate and the geopolymerization reactions [17, 18].

The mixture with an optimal combination of RHA and PFA contents (M3), that is, with an equal percentage of RHA and PFA, was expected to have an optimal combination of silica and alumina contents, resulting in the formation of a denser geopolymer matrix. This enhances the bonding between the binder and aggregate particles, thereby increasing the tensile strength of the concrete. Similar results were obtained by other researchers who studied geopolymer concrete prepared by blending different types of precursors. The mechanical properties of geopolymer concrete made by combining several precursors were found to be improved. This was thought to be because the geopolymerization process was improved [19, 22].

The tensile strengths of concrete made with just one precursor were lower than those of the combined results. Owing to the comparatively low alumina concentration of RHA, which may restrict the creation of a fully formed aluminosilicate network, M1 exhibited a high tensile strength. One possible explanation for M5's high tensile strength is that PFA has less silica than RHA. Blending the two kinds of ash enhanced the geopolymerization process, which in turn increased the tensile strength of geopolymer concrete, according to the results.

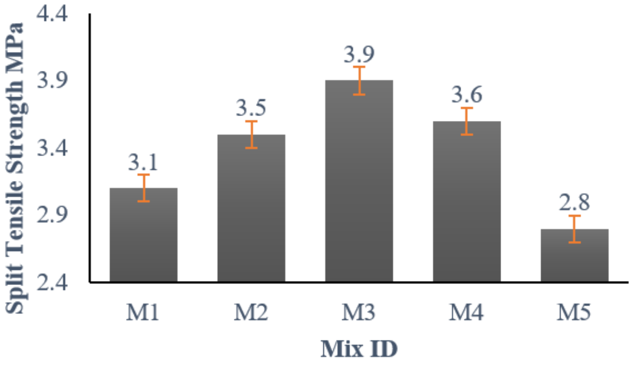

Figure 3. Split tensile strength results

3.4 Flexural strength

The flexural strength of the geopolymer concrete mixtures was tested according to the ASTM C78 standards, which are used to measure the bending strength of concrete mixtures. Figure 4 shows a graphical representation of the results, and Table 3 contains the tabular data from this method. The flexural strength of M3 mix is between 4.5 and 6.1 MPa, the strongest of all the mixes, while that of M5 mix is the lowest. There was a link between the flexural strength test results and compressive and tensile strength test results.

The blended mixtures of RHA and PFA exhibited better flexural strength because of the interaction of RHA and PFA. First, a geopolymer gel is formed when the reactive silica content is high; then, when combined with alumina, polymerization is more effective, resulting in a better three-dimensional structure [4, 5].

According to various studies, it has been reported that the mechanical properties of geopolymer materials are largely dependent on the chemical composition of the precursor materials and the structure of the resulting geopolymer matrix [4, 5, 20]. A good mixture of alumina and silica improves the strength and durability of the geopolymer binder. The presence of a balanced composition of alumina and silica can significantly improve the mechanical properties of geopolymer binders owing to the formation of dense and homogeneous structures.

The enhanced flexural strength of M3 was due to the balanced composition of RHA and PFA. This indicates that the presence of a balanced composition of alumina and silica enhances the geopolymerization reaction, resulting in improved bonding and enhanced bending strength. Similar trends of enhanced flexural strength have been reported in various studies involving blended geopolymer concrete mixtures [22].

In contrast, mixtures M1 and M5 exhibited lower flexural strengths. This was due to the unbalanced composition of alumina and silica. An unbalanced composition is not beneficial for enhancing geopolymerization. This was attributed to the presence of unreacted particles, which reduced the bending strength.

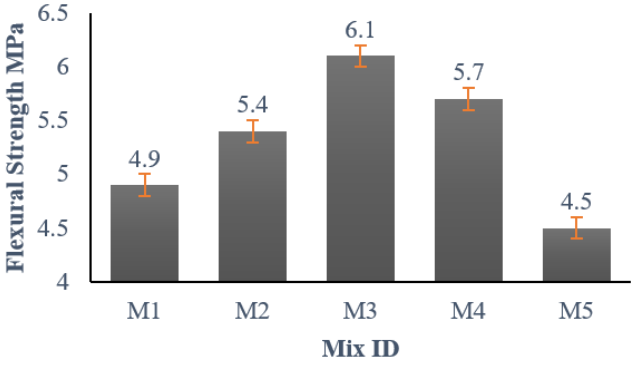

Figure 4. Flexural strength results

3.5 Dry density

The dry densities of the geopolymer concrete mixtures were determined to assess the compactness of the hardened geopolymer matrices. As indicated in the results provided in Table 3 and Figure 5, the density values varied between 2180 kg/m³ and 2240 kg/m³, depending on the proportions of RHA and PFA.

Mixture M3 recorded the highest density of 2240 kg/m³, whereas the lowest density of 2180 kg/m ³ was recorded for mixture M1.

The low density of the mixtures was attributed to the porous nature of the RHA particles, which had a high specific surface area. RHA is known to have a porous microstructure, which may lead to an increase in the internal voids created in cementitious or geopolymer matrices [13].

In contrast, mixtures containing high proportions of PFA recorded a higher density than mixtures containing high proportions of RHA. This was attributed to the denser nature of the particles, which may have reduced the number of internal voids created in the geopolymer matrix. The blended mixtures exhibited intermediate densities, which could improve the packing density of the geopolymer matrix.

The high-density value recorded for M3 was consistent with the improved mechanical properties recorded in the compressive, tensile, and flexural strength tests. Previous studies have established that the denser nature of the geopolymer matrix is strongly related to the improved mechanical properties of geopolymer concrete [5, 20].

The compact nature of the geopolymer matrix may reduce the internal porosity created in the geopolymer concrete, thereby enhancing the load-transfer capacity of the material. Therefore, it is evident that the blending of RHA and PFA leads to the formation of a more compact geopolymer matrix, which enhances the mechanical and physical properties of the geopolymer concrete.

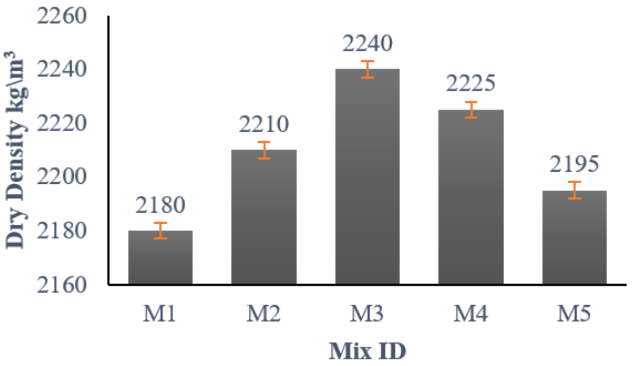

Figure 5. Dry density results

3.6 Water absorption

The water absorption of the geopolymer and concrete combinations was calculated using the ASTM C642 test method, which evaluates the permeability of geopolymer concrete. The water absorption values of the geopolymer concrete mixtures changed with the proportions of RHA and PFA used to prepare the binder, according to the results provided in Table 3 and Figure 6. The mixture composed of 100% RHA (M1) exhibited a relatively high water absorption of 6.83%. This was attributed to the porous structure of the RHA particles, which had a large specific surface area. The large specific surface area of the RHA particles was expected to increase the volume of the pores of the produced geopolymer. Similar trends in water absorption have been observed by other researchers when RHA was used to improve the porosity of cementitious binders [13].

A significant decrease in water absorption was achieved when part of the mixture was composed of PFA. The mixture comprising equal parts of RHA and PFA, that is, M3, had a minimum water absorption of 5.41%. This is because of the enhancement of the geopolymerization reaction owing to the chemical composition of the blended precursors. The addition of higher amounts of alumina and calcium oxide to the geopolymer precursor may have contributed to the denser geopolymer gel, which reduced its permeability. Improvements in permeability have been reported when more than one precursor material is used to prepare geopolymer materials [19, 22].

It was also observed that when more PFA was added to the mixture, the water absorption values increased slightly, as observed for M5. This is because of the lower reactive silica content available in PFA than in RHA. This leads to the development of a porous microstructure inside the matrix. This has also been observed by previous researchers when investigating the effect of precursor composition on porosity [17, 20].

The denser microstructure observed by SEM, particularly in the M3 mixture, indicates reduced pore connectivity and a refined pore structure. This directly limits water ingress, resulting in lower water absorption values and improved durability.

These results indicate that blending RHA with PFA is beneficial for enhancing the microstructural densification of geopolymer matrices. The durability characteristics of geopolymer concrete also improve when a part of the mixture is composed of PFA. The mixture made up of equal parts of RHA and PFA exhibited better performance than the others.

Based on the results obtained, a denser geopolymer matrix with lower pore connectivity was obtained for the tested blends, especially the M3 sample. This change in the pore structure leads to increased durability of the material because low permeability is one of the main factors affecting durability. A dense microstructure reduces the entry of aggressive agents, including chloride ions and sulfate solutions, into the matrix, thereby increasing its resistance to various types of damage and deterioration.

Previous studies have shown that a high degree of densification of geopolymer matrices positively affects the resistance of materials to chloride migration and sulfate attack [5, 20]. Moreover, the presence of a well-formed aluminosilicate gel improves the properties of the material owing to decreased porosity and ion transfer paths. Although water absorption was measured in this study, there is evidence that the developed material is highly durable.

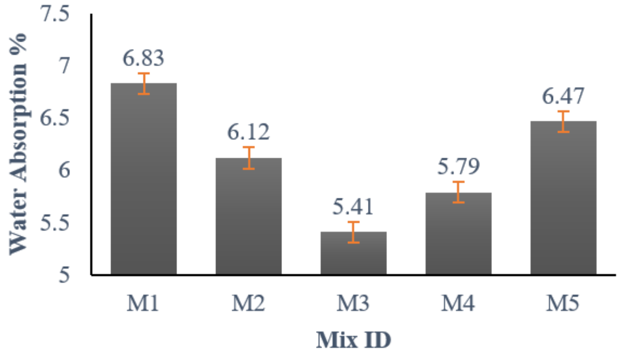

Figure 6. Water absorption results

3.7 Microstructural analysis

The microstructural properties of the geopolymer concrete mixtures were examined using SEM to assess the internal structure of the geopolymer matrix. A gold coating was applied to the test samples before analysis to guarantee that proper electric conductance was maintained by the sample. Magnification levels in the SEM ranged between ×1000 and ×5000, and this is denoted in every image. The microstructures of the geopolymer concrete mixtures (Figures 7–9) exhibited significant variations depending on the proportions of RHA and PFA.

The microstructure of the mixture with 100% RHA (M1) revealed partially reacted particles within a relatively dense geopolymer matrix that showed the presence of microvoids. This behavior is attributed to the low alumina content in RHA, which limits the formation of a fully developed aluminosilicate network. Similar observations have been reported in previous studies on silica-rich systems, where incomplete geopolymerization occurred owing to the insufficient alumina content [5, 15].

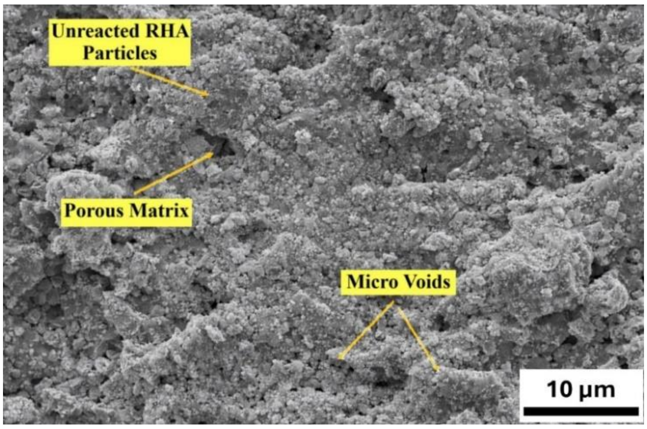

Figure 7. Scanning electron microscope (SEM) of M1 mixture

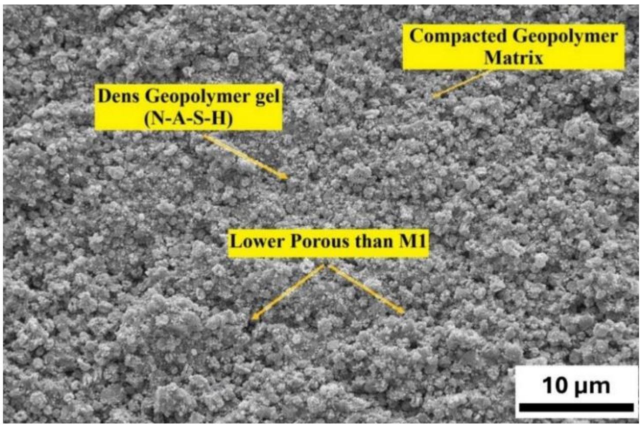

Figure 8. Scanning electron microscope (SEM) of M3 mixture

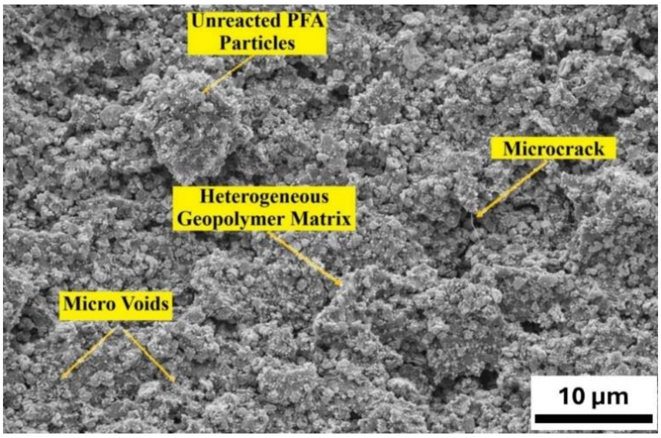

Figure 9. Scanning electron microscope (SEM) of M5 mixture

In contrast, the microstructures of the blended mixtures were significantly denser. The incorporation of PFA enhanced the geopolymerization reaction by increasing the availability of alumina and alkaline oxides, which promoted dissolution and gel formation. This resulted in a matrix that was more homogeneous and denser with low porosity and fewer internal voids. This microstructural densification improved the bonding between the geopolymer binder and aggregates. Similar findings have been reported for blended geopolymer systems [19, 22].

The M3 mixture, which contained equal proportions of RHA and PFA, exhibited the most refined microstructures. It can be seen that there is a highly developed geopolymer gel with low microvoids and better interactions of particles owing to the proper ratio of silica and alumina. This observation is consistent with the mechanical performance results discussed in the previous sections.

Furthermore, the superior compressive strength and lower water absorption observed in M3 can be directly attributed to this refined microstructure. With lower porosity and better compactness of the matrix, fluid entry into the pores becomes restricted, resulting in better durability properties.

However, no Energy Dispersive X-ray Spectroscopy (EDS) analysis was carried out for this experiment; therefore, morphological studies of the microstructure were performed. The results of the microstructural investigation confirmed that the blended use of RHA and PFA significantly enhanced the geopolymerization process, leading to the formation of a dense and homogeneous geopolymer matrix with improved mechanical properties and durability.

4. CONCLUSION

The findings of this study indicate that geopolymer concrete mixes benefit from the addition of agricultural ash, which enhances their freshness, mechanical quality, and durability. The workability of the mix improved in proportion to the PFA content. However, it was also noted that because of the porous nature of the mix, the slump values decreased with increasing RHA content in the mix. The compressive, tensile, and flexural strengths were the highest in the geopolymer concrete mix in which RHA and PFA were present in equal quantities. In addition, it possessed the highest dry density and lowest water absorption. This was due to the balanced aluminosilicate content in the mixture, which enhanced the geopolymerization reaction and created a denser and more homogeneous geopolymer concrete structure. It is also noted that the microstructural analysis verified that a dense structure with minimal internal voids was created in all mixtures. These observations indicate that RHA and PFA have great potential to be used as sustainable precursors to produce geopolymer concrete that not only performs better mechanically and in terms of durability, but is also environmentally friendly.

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REFERENCES

[1] Abdulrehman, M.A., Atiyah, I.A., Abbas, A.S., Salman, A.A., Moften, A.Q., Mohammed, A.H.M. (2025). Modifying the properties of granulated blast furnace slag mortar to adhere to international standards. Revue des Composites et des Matériaux Avancés–Journal of Composite and Advanced Materials, 35(4): 635-642. https://doi.org/10.18280/rcma.350405

[2] Ghadban, R., Kamil, L., Abdulhussein, S., Abdulrehman, M., Flayyih, A. (2026). Sustainable translucent geopolymer concrete based on metakaolin and recycled glass. AIMS Materials Science, 13(1): 80-98. https://doi.org/10.3934/matersci.2026005

[3] Chen, L., Yang, M., Chen, Z., Xie, Z., et al. (2024). Conversion of waste into sustainable construction materials: A review of recent developments and prospects. Materials Today Sustainability, 27, 100930. https://doi.org/10.1016/j.mtsust.2024.100930

[4] Hardjito, D., Wallah, S.E., Sumajouw, D.M.J., Rangan, B.V. (2004). On the development of fly ash-based geopolymer concrete. ACI Materials Journal, 101(6): 467-472. https://doi.org/10.14359/13485

[5] Duxson, P., Fernández-Jiménez, A., Provis, J.L., Lukey, G.C., Palomo, A., van Deventer, J.S. (2007). Geopolymer technology: The current state of the art. Journal of Materials Science, 42: 2917-2933. https://doi.org/10.1007/s10853-006-0637-z

[6] Rangan, V. (2010). Fly ash-based geopolymer concrete. In Proceedings of the International Workshop on Geopolymer Cement and Concrete, Mumbai, India, pp. 68-106.

[7] Abdulrehman, M., Moften, A., Noori, A., Mutair, M., Al-Kamal, A.K. (2024). Investigating the mechanical and physical properties of lightweight geopolymer concrete. Al-Qadisiyah Journal for Engineering Sciences, 17(2): 88-96. https://doi.org/10.30772/qjes.2024.183784

[8] Noori, A.S., Oweed, K.M., Raouf, R.M., Abdulrehman, M.A. (2021). The relation between destructive and non-destructive tests of geopolymer concrete. Materials Today: Proceedings, 42(5): 2125-2133. https://doi.org/10.1016/j.matpr.2020.12.296

[9] Khankhaje, E., Salim, M.R., Mirza, J., Salmiati, Hussin, M.W., Khan, R., Rafieizonooz, M. (2017). Properties of quiet pervious concrete containing oil palm kernel shell and cockleshell. Applied Acoustics, 122: 113-120. https://doi.org/10.1016/j.apacoust.2017.02.014

[10] Fapohunda, C., Akinbile, B., Shittu, A. (2017). Structure and properties of mortar and concrete with rice husk ash as partial replacement of ordinary Portland cement–A review. International Journal of Sustainable Built Environment, 6(2), 675-692. https://doi.org/10.1016/j.ijsbe.2017.07.004

[11] Cordeiro, G.C., Toledo Filho, R.D., Tavares, L.M., Fairbairn, E.M.R. (2009). Ultrafine grinding of sugar cane bagasse ash for application as pozzolanic admixture in concrete. Cement and Concrete Research, 39(2): 110-115. https://doi.org/10.1016/j.cemconres.2008.11.005

[12] Jaya, R.P., Bakar, B.H.A., Johari, M.A.M., et al. (2011). Strength and permeability properties of concrete containing rice husk ash with different grinding time. Central European Journal of Engineering, 1(1): 103-112. https://doi.org/10.2478/s13531-010-0003-4

[13] Bui, D.D., Hu, J., Stroeven, P. (2005). Particle size effect on the strength of rice husk ash blended gap-graded Portland cement concrete. Cement and Concrete Composites, 27(3): 357-366.

https://doi.org/10.1016/j.cemconcomp.2004.05.002

[14] Andrade, C., Sanjuán, M.Á. (2021). Carbon dioxide uptake by pure Portland and blended cement pastes. Developments in the Built Environment, 8: 100063. https://doi.org/10.1016/j.dibe.2021.100063

[15] Pouhet, R., Cyr, M. (2016). Formulation and performance of flash metakaolin geopolymer concretes. Construction and Building Materials, 120: 150-160. https://doi.org/10.1016/j.conbuildmat.2016.05.061

[16] Mo, K.H., Alengaram, U.J., Jumaat, M.Z., Lee, S.C., Goh, W.I., Yuen, C.W. (2018). Recycling of seashell waste in concrete: A review. Construction and Building Materials, 162: 751-764. https://doi.org/10.1016/j.conbuildmat.2017.12.009

[17] Salih, M.A., Abang Ali, A.A., Farzadnia, N. (2014). Characterization of mechanical and microstructural properties of palm oil fuel ash geopolymer cement paste. Construction and Building Materials, 65: 592-603. https://doi.org/10.1016/j.conbuildmat.2014.05.031

[18] Abdul Awal, A.S.M., Hussin, M.W. (2011). Effect of palm oil fuel ash in controlling heat of hydration of concrete. Procedia Engineering, 14: 2650-2657. https://doi.org/10.1016/j.proeng.2011.07.333

[19] Kovalchuk, G., Fernández-Jiménez, A., Palomo, A. (2007). Alkali-activated fly ash: Effect of thermal curing conditions on mechanical and microstructural development – Part II. Fuel, 86(3): 315-322. https://doi.org/10.1016/j.fuel.2006.07.010

[20] Mehta, A., Siddique, R. (2016). An overview of geopolymers derived from industrial by-products. Construction and Building Materials, 127: 183-198. https://doi.org/10.1016/j.conbuildmat.2016.09.136

[21] Abbass, M., Singh, G. (2022). Optimum mix design of rice husk ash-based geopolymer concrete based on workability, setting time, and compressive strength cured in ambient temperature condition. In Recent Developments in Sustainable Infrastructure (ICRDSI-2020), pp. 59-74. https://doi.org/10.1007/978-981-16-8433-3_7

[22] Ranjbar, N., Mehrali, M., Behnia, A., Alengaram, U.J., Jumaat, M.Z. (2014). Compressive strength and microstructural analysis of fly ash/palm oil fuel ash based geopolymer mortar. Materials & Design, 59, 532-539. https://doi.org/10.1016/j.matdes.2014.03.037