

Compressive Strength and Thermal Resistance of Geopolymer Mortar Containing Fly Ash and Red Mud Blend

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Abstract

Cement is a widely used material in the construction industry. However, its production significantly contributes to carbon dioxide (CO₂) emissions and other harmful gases due to high-temperature calcination process involved in ordinary Portland cement (OPC) production. To address this environmental issue, researchers have shifted their focus toward alternative binder materials such as geopolymer. Geopolymer is synthesized through a polycondensation of aluminosilicate materials activated by an alkaline activator, utilizing industrial by-products rich in silica and alumina. This study investigates the effects of incorporating red mud in varying proportions (0%, 2%, 4%, 6%, 8% and 10%) as partial source material replacement in fly ash-based geopolymer mortar. While fly ash, with its high silica and alumina content, is a well-established geopolymer precursor, the potential of red mud remains underexplored despite its comparable chemical composition. The mortar was tested for density, compressive strength and thermal conductivity at curing intervals of 7 and 28 days. To evaluate long-term strength development, additional compressive strength tests were conducted at 56 days. Based on this study, the results showed that 6% red mud achieved the highest compressive strength of 47.04 Mpa at 7 days surpassing the control mix. Thermal conductivity decreased with increasing red mud content indicating improved thermal resistance. However, proportions above 6% reduced compressive strength due to increased porosity. This study demonstrates that the best proportion, 6% RM for balancing compressive strength and thermal resistance. These findings highlight red mud's feasibility as an alternative source material in fly ash-based geopolymer mortar contributing to sustainable construction practices and the effective utilization of industrial waste.

1. Introduction

Cement, particularly Portland cement has played a crucial role in construction since its introduction in the 19th century due to its ability to bind aggregates into solid, rock-like material [1]. Comprised primarily of silicon, calcium, aluminium and other minerals sourced from natural materials such as limestone and clay, Portland cement hardens upon mixing with water to form concrete and mortar [2]. Despite its widespread use, the production process is energy-intensive and contributes significantly to global CO₂ emissions releasing approximately one ton of CO₂ per ton of cement produced [3]. The environmental burden includes air pollution,

habitat destruction and excessive resource consumption [4]. Cement production contributes significantly to global CO₂ emissions, accounting for roughly 7% of worldwide greenhouse gas emissions [5].

Geopolymer binders have emerged as a sustainable alternative to traditional Portland cement. These binders are synthesized through the geopolymerization of aluminosilicate materials such as fly ash, slag and red mud activated by alkaline solutions [6]. In response to these challenges, geopolymer concrete has emerged as a sustainable alternative, utilizing industrial by-products such as fly ash and red mud to reduce carbon footprints while maintaining desirable structural properties [7]. Unlike traditional cement, geopolymer binders form through the geopolymerization of aluminosilicate materials in the presence of alkaline activators [6]. Geopolymer concrete offers higher early-age strength, chemical resistance and enhanced durability compared to Portland cement concrete [8].

Fly ash is well-established as a geopolymer precursor due to its high silica and alumina content. However, red mud, a by-product of the alumina refining process, presents both an environmental challenge and an opportunity for sustainable construction practices [9]. Despite its rich content of alumina, silica and iron oxide, red mud is largely underutilized with a global utilization rate of only 4% [10]. Incorporating red mud into geopolymer mortar could mitigate waste management issues while enhancing the mechanical and thermal properties of the material [11].

This study investigates the blending effects of red mud in fly ash-based geopolymer mortar to assess its viability as a sustainable construction material. By exploring the mechanical and thermal performance of mortar containing varying proportions of red mud, this research aims to contribute to sustainable development goals and support the use of industrial by-products in construction. The findings will provide insights into optimal blend ratios for enhanced compressive strength and thermal performance, promoting the adoption of eco-friendly materials in construction.

2. Materials and Methods

2.1 Materials

This study focuses on assessing the compressive strength performance of geopolymer mortar by incorporating key materials such as fly ash, red mud, alkali activators, fine aggregate and water. Fig.1 displays the constituent of geopolymer mortar which is fly ash and red mud. Fly ash, classified as Class F, was sourced from Manjung coal-based thermal power plant in Perak, Malaysia. As the primary binder, it features high concentrations of silica (SiO₂) and alumina (Al₂O₃) which are critical for the geopolymerization process. X-ray fluorescence (XRF) analysis confirmed these compositions while the particle size distribution indicated fine, spherical particles advantageous for reactivity. The presence of crystalline and amorphous phases as shown through X-ray diffraction (XRD) analysis enhances the material's structural properties.

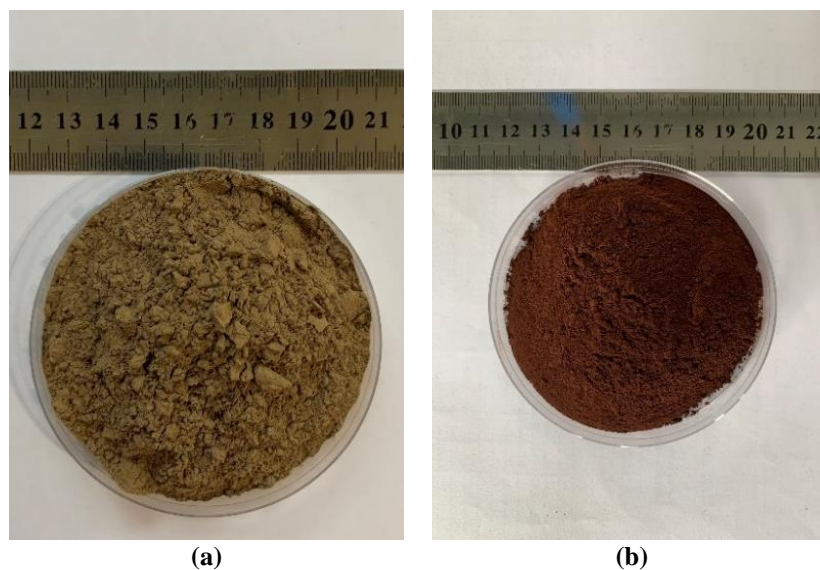


Fig. 1: Materials of geopolymer mortar (a) Fly ash; (b) Red mud

Red mud, a byproduct generated in Bayer process of aluminium production from bauxite in Kuantan, Pahang was utilized as a secondary material to enhance the geopolymer matrix. Its high iron oxide (Fe₂O₃) content contributes to its reddish colour and impacts reactivity. To improve usability, the red mud was ground

using a ball mill and sieved through a 150 μm mesh to achieve a suitable particle size distribution. Despite its lower reactivity, blending with fly ash improves its geopolymerization potential.

The alkali activator system comprised sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃). NaOH pellets were dissolved in distilled water to create a 12 M solution ensuring complete dissolution and temperature stabilization before mixing with Na₂SiO₃. The combined alkali activator system played a critical role in initiating the geopolymer reaction.

River sand, locally sourced from UTHM Pagoh was selected as the fine aggregate. A sieve analysis ensured particle sizes were within the required range for optimal mortar performance contributing to good workability and strength development. The grading curve in Fig.2 demonstrated that the sand met JKR specifications for fine aggregate in concreting applications.

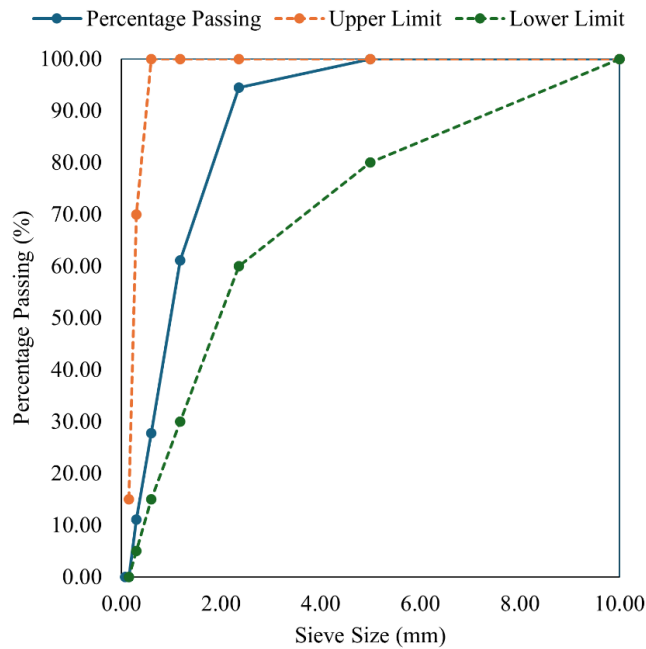


Fig. 2: Sieve analysis for fine aggregate (river sand)

Water played a dual role in this study—distilled water was used for dissolving alkali activators while tap water facilitated the hydration process. Proper mixing ensured uniform distribution of materials, while water content was carefully controlled to maintain the right water-to-solid ratio essential for geopolymerization and curing processes. These carefully selected materials and preparation steps were crucial for achieving a robust geopolymer mortar with desired strength and durability characteristics.

2.2 Mix Proportions

The mortar mixture consists of fly ash, red mud, sodium hydroxide, sodium silicate, fine aggregates and water. This study utilized various mix proportions of fly ash (100%, 98%, 96%, 94%, 92%, 90%) and red mud (0%, 2%, 4%, 6%, 8%, 10%) to determine the optimal blend ratio for enhanced performance. Table 1 shows the complete mix proportions, detailing the percentage of each material in the fly ash-red mud geopolymer mortar blend. The mix proportions were adopted from a previous study [12].

Table 1: Detail of geopolymer mortar mix proportion (kg/m³)

Percentage of Fly Ash (%)	Percentage of Red Mud (%)	Proportion in kg/m ³					
		Fly Ash	Red Mud	NaOH Solution	Na ₂ SiO ₃ solution	Sand	Water
100	0	700	0	82	206	1290	70
98	2	686	14	82	206	1290	70
96	4	672	28	82	206	1290	70
94	6	658	42	82	206	1290	70
92	8	644	56	82	206	1290	70

90	10	630	70	82	206	1290	70
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2.3 Casting and Curing

Initially, the fine aggregates were mixed with the dry fly ash and red mud according to the mix proportions specified. The alkali activator solution consisting of sodium hydroxide and sodium silicate was then gradually added to the dry ingredients. Water was also incorporated to achieve the specified water-to-binder ratio. The mixture was continuously stirred for 1 to 2 minutes to ensure a homogeneous consistency. Due to the rapid setting characteristics of the geopolymer mortar, the mixing process was carried out promptly after adding the alkali activator to avoid premature hardening.

Once the mixture was well-blended, it was poured into 50 mm x 50 mm x 50 mm silicone moulds. To ensure the moulds were free of air pockets, each mould was pounded 60 times. The moulds were checked to ensure that the cubes were uniform in size and shape with smooth even surfaces. After the casting process, the specimens were allowed to rest for 24 hours before being transferred to an oven for the initial curing phase.

For curing, a combination of oven and room temperature methods was employed. The specimens were first placed in an oven at 65°C for 24 hours with plastic covering to maintain moisture and prevent drying. After the initial oven curing, the samples were left at room temperature for further curing periods of 7, 28 and 56 days. The compressive strength of the specimens was evaluated after 7, 28 and 56 days of curing while thermal conductivity measurements were conducted after 28 days. This methodical approach to casting and curing ensured the proper setting and development of strength in the geopolymer mortar specimens allowing for reliable testing and analysis.

2.4 Testing

In this study, there are various tests conducted to evaluate the properties and performance of geopolymer mortar incorporating fly ash and red mud blends including characterization using X-ray fluorescence (XRF), X-ray diffraction (XRD), scanning electron microscopy (SEM) as well as testing for density, compressive strength and thermal conductivity.

XRF analysis was performed to determine the chemical composition of the fly ash and red mud as shown in Table 2. The results indicated a high content of silica (SiO_2), alumina (Al_2O_3) and iron oxide (Fe_2O_3) important for the geopolymerization process [13]. The presence of trace elements was also identified influencing the reactivity of these materials.

Table 2: Oxide composition percentage of fly ash and red mud

Oxide	Percentage (%)	
	Fly Ash	Red Mud
SiO_2	51.700	1.636
Al_2O_3	29.100	1.348
CaO	8.840	0.179
Fe_2O_3	4.760	95.752
P_2O_5	1.700	0.474
K_2O	1.600	-
SO_3	1.500	0.163
TiO_2	0.720	0.127
SrO	0.109	-
AsO_3	-	0.189
CuO	-	0.090

Fig.3 shows the XRD analysis revealed the crystalline and amorphous phases present in the raw materials. Fly ash predominantly consisted of amorphous phases while red mud exhibited crystalline structures such as hematite and gibbsite, influencing geopolymer properties [14].

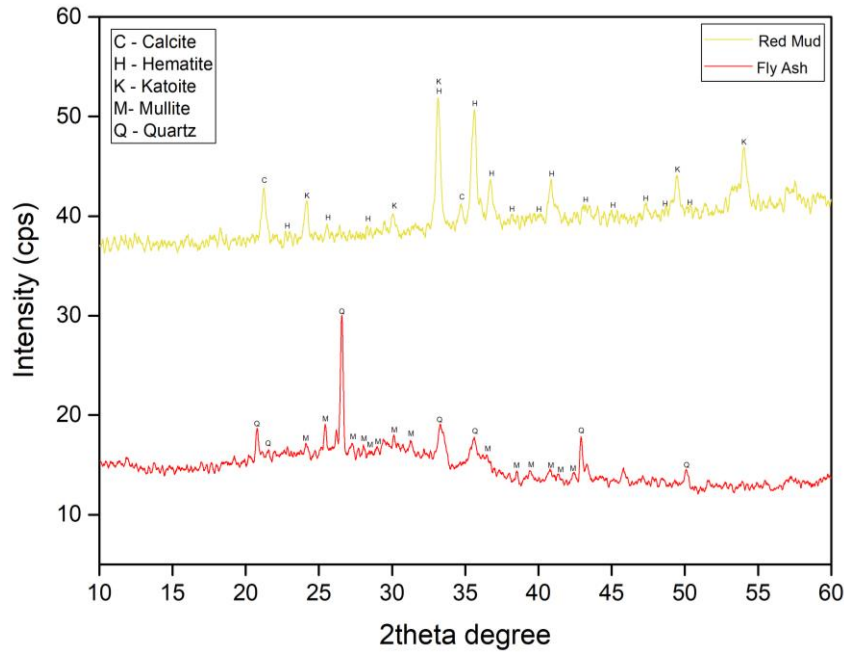


Fig. 3: X-Ray diffraction pattern of fly ash and red mud

SEM analysis examined the morphology of the particles shown in Fig.4. Fly ash particles were spherical and smooth indicates better reactivity whereas red mud particles exhibited irregular shapes and rough textures affects the overall microstructure of the geopolymer matrix [15].

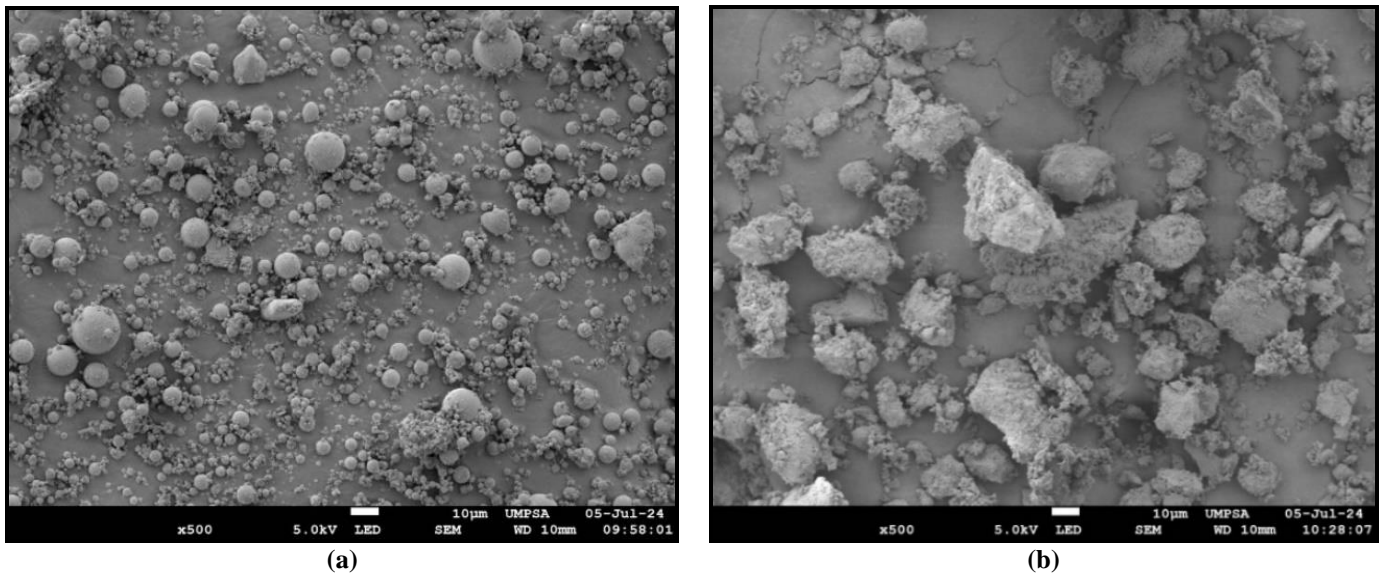


Fig. 4: SEM image of (a) Fly ash; (b) Red mud

Density testing determined the compactness of the geopolymer mortar revealing values ranging from 1.8 to 2.2 g/cm³ depending on blend ratios and curing conditions. Improved densities correlated with enhanced material consolidation [16].

Compressive strength tests on 50 mm cube specimens at 7, 28 and 56 days demonstrated that the inclusion of red mud alongside fly ash significantly influenced strength development. The mortar achieved compressive strengths ranging from 25 MPa to 40 MPa highlighting its potential for structural applications [17].

Thermal conductivity testing revealed values between 0.210 and 0.280 W/mK, demonstrating the material's thermal resistance potential suitable for applications in extreme environments [18]. The incorporation of fly ash and red mud enhanced both the thermal insulation and mechanical performance of the geopolymer mortar.

3. Results and Discussion

3.1 Density

The density test of geopolymer mortar was conducted before compressive strength testing to determine consistency in mix proportions and curing processes as these factors significantly influence material performance. Density is a crucial indicator as it correlates with compaction and void content, impacting structural integrity, thermal properties and design suitability [19]. The density of geopolymer mortar was calculated using mass per unit volume with testing conducted at 7, 28 and 56 days under room temperature and oven curing conditions at 65°C.

Results in Fig.5 illustrates density of geopolymer mortar cured at room temperature and oven (65 °C). It indicated that specimens cured in an oven exhibited higher densities than those cured at room temperature due to accelerated geopolymerization and uniform microstructure development. At room temperature, slower geopolymerization and greater water retention resulted in lower densities during early curing stages, though gradual increases were observed between 7 and 28 days as reactions matured. Conversely, oven curing accelerated aluminosilicate dissolution and polymerization, promoting compact structures with stable densities across all durations [20].

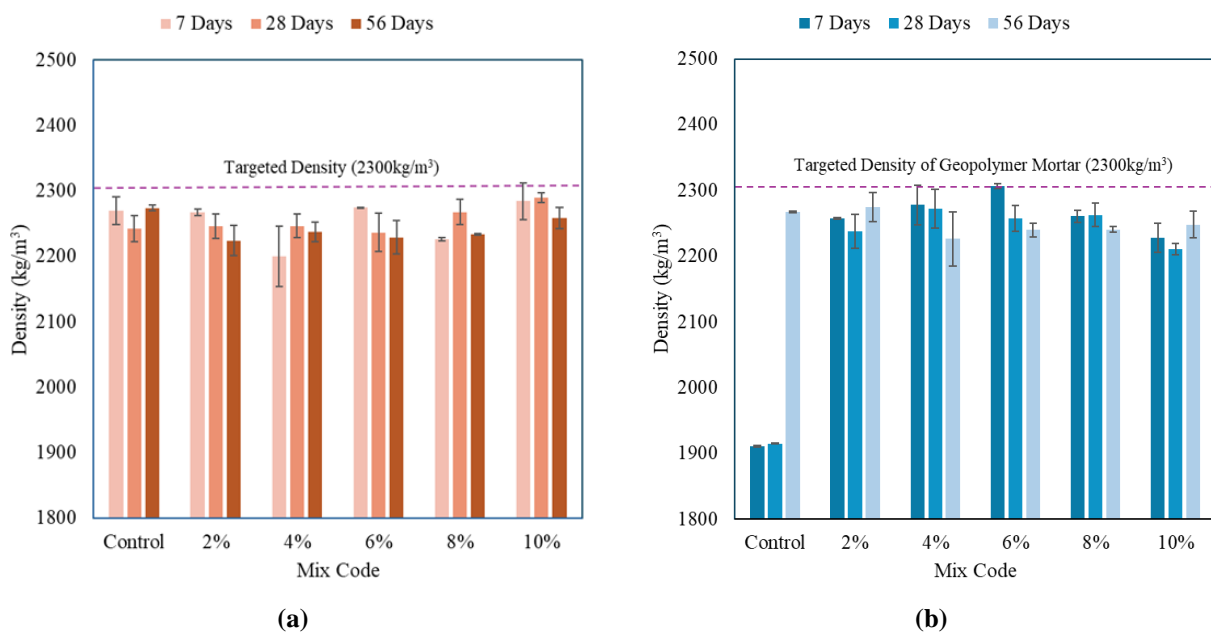


Fig. 5: Density of geopolymer mortar cured at (a) Room temperature; (b) Oven (65 °C)

The inclusion of red mud (RM) significantly affected density outcomes. The 6% RM mixture achieved the highest density (2306.32 kg/m³) likely due to optimal geopolymer gel formation and reduced void content [21]. In contrast, the 0% RM mixture exhibited the lowest density (1911.20 kg/m³) due to absence of RM result in poorer particle packing leading to a structure with more voids and lower compaction, thus reducing density.

Despite oven curing producing higher densities than room temperature, none of the curing methods achieved the target design density of 2400.00 kg/m³. Water loss during curing including evaporation of activator and extra water, contributed to lower final densities by creating porosity within the geopolymer structure. The study highlights the critical role of curing methods and red mud proportions in optimizing geopolymer mortar density and achieving desirable performance characteristics.

3.2 Compressive Strength

Compressive strength of geopolymer mortar at different curing ages reviewed by two different types of curing methods where room temperature is shown in Fig.6 (a) while oven shown in Fig.6(b). The compressive strength of geopolymer mortar was tested using 132 cube specimens (50 mm × 50 mm × 50 mm) cured under room temperature and oven conditions at 65°C for 7, 28 and 56 days. The study examined the effects of red mud (RM) proportions (0% to 10%) on compressive strength and its role as a binder replacement in the geopolymerization process. Results in Fig.6 indicate that oven-cured specimens consistently outperformed room

temperature-cured samples due to accelerated and more uniform geopolymerization at elevated temperatures [22].

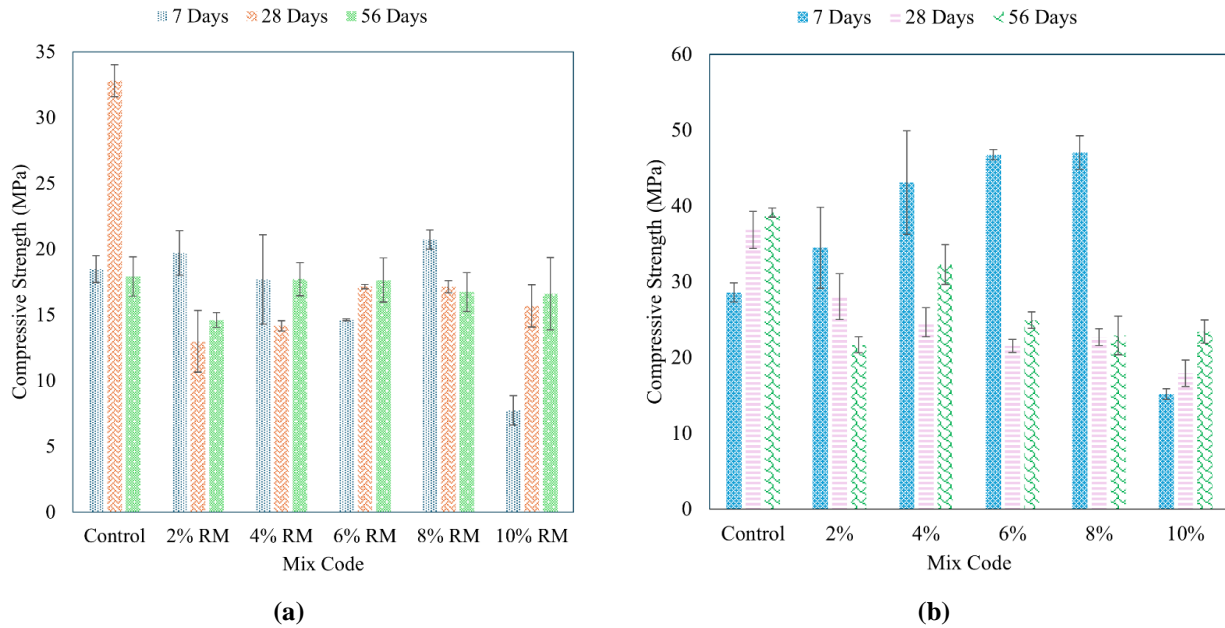


Fig. 6: Compressive strength of geopolymer mortar cured at (a) Room temperature; (b) Oven (65 °C)

Room temperature curing showed a slower reaction, leading to lower early-age strength development. The control mix (0% RM) achieved 32.80 MPa at 28 days, whereas RM mixtures showed declining strength trends as RM content increased particularly for 10% RM (7.73 MPa at 7 days). Optimal strength improvement was observed at 8% RM suggesting favorable geopolymerization conditions for this mix ratio. Conversely, oven curing produced a peak compressive strength of 47.04 MPa at 7 days for 8% RM attributed to enhanced reaction kinetics and cohesive microstructure formation.

Excessive RM content (10%) resulted in lower compressive strength (15.17 MPa) due to matrix integrity issues. Strength gains were rapid during the first 14 days but stabilized thereafter, aligning with hydration product accumulation and densification [23]. The 6% RM mix achieved a compressive strength of 46.74 MPa after 7 days under oven curing highlighting its suitability for applications requiring rapid strength development and consistent performance.

3.3 Thermal Conductivity

Thermal conductivity testing was conducted on 36 geopolymer mortar samples cured for 7, 28 and 56 days using room temperature and oven curing (65°C) methods at the Building Service Laboratory, UTHM. The study aimed to develop geopolymer mortar with low thermal conductivity for enhanced thermal insulation, supporting energy-efficient building design and durability. Achieving lower thermal conductivity aligns with SDG 11 by promoting sustainable building materials with reduced environmental impact. The results of thermal conductivity of geopolymer mortar cured at different temperatures demonstrated in Fig.7.

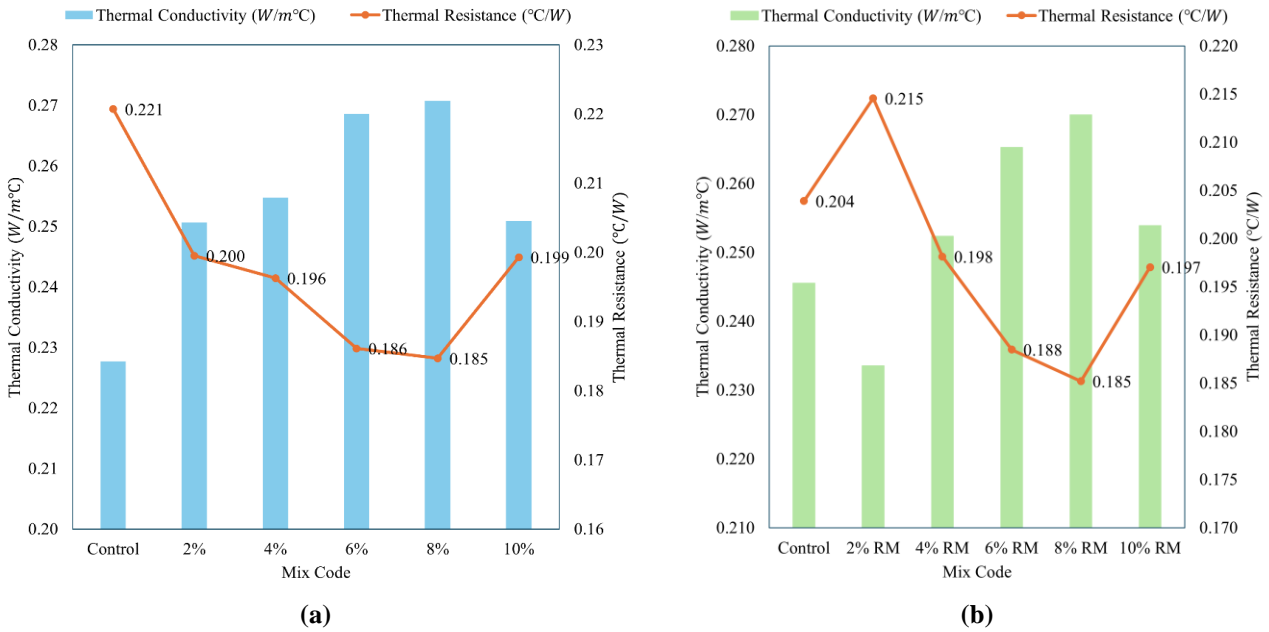


Fig. 7: Thermal conductivity of geopolymer mortar cured at (a) Room temperature; (b) Oven (65 °C)

The results show a consistent increase in thermal conductivity with red mud (RM) addition up to 8% RM followed by a decrease at 10% RM due to unreacted particles and voids disrupting heat transfer. The highest thermal conductivity values were recorded at 8% RM (0.271 W/m°C at room temperature, 0.270 W/m°C in oven curing). In contrast, the control mix (0% RM) exhibited the lowest thermal conductivity (0.228 W/m°C at room temperature). Oven curing produced more uniform and slightly higher conductivity values due to improved densification and particle bonding compared to room temperature curing.

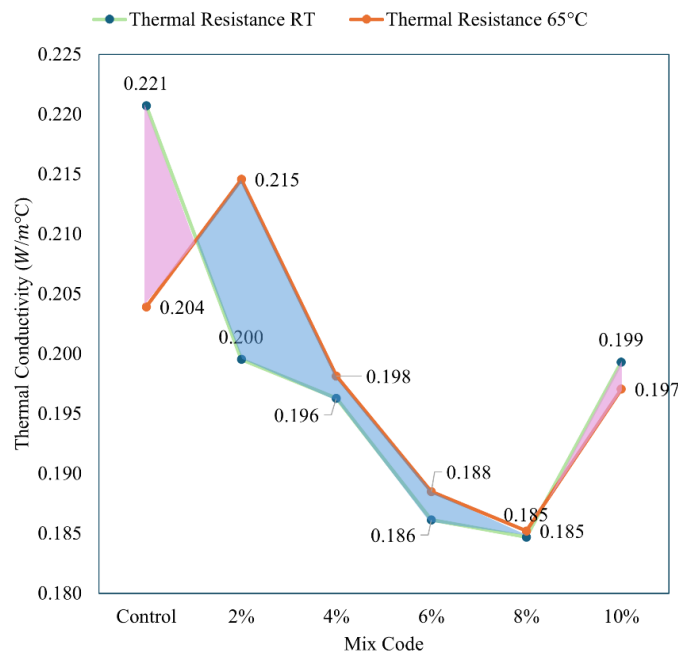


Fig. 8: Thermal Resistance of Geopolymer Mortar Cured at Room Temperature and Oven (65 °C)

Thermal resistance in Fig.8 showed an inverse relationship with RM content with the control mix having the highest resistance (0.221 °C/W) and 8% RM showing the lowest (0.185 °C/W). Despite its lower thermal resistance, the 8% RM mix proved optimal for insulation due to efficient geopolymerization and consistent thermal performance. This mix is particularly suitable for energy-efficient applications in Malaysia's hot and

humid climate such as roofs and walls while the 10% RM mix demonstrated stable performance for environments requiring consistent thermal behaviour.

3.4 Correlation Between Compressive Strength and Density

Fig.9 illustrates the correlation between compressive strength and density among all the mixed proportions cured at room temperature and oven (65 °C). The correlation between compressive strength and density for geopolymer mortar samples yielded a notably strong relationship with a good correlation ($R^2=0.7997$) which is nearly one. This indicates that density serves as a reliable predictor of compressive strength demonstrating a direct positive trend. The dataset showed increasing compressive strength values from 26.163 MPa to 41.497 MPa as density increased from 1910.4 kg/m³ to 2281.44 kg/m³. These findings suggest that optimizing density can significantly enhance the mechanical performance of geopolymer mortar underscoring its potential for structural applications requiring high strength and durability.

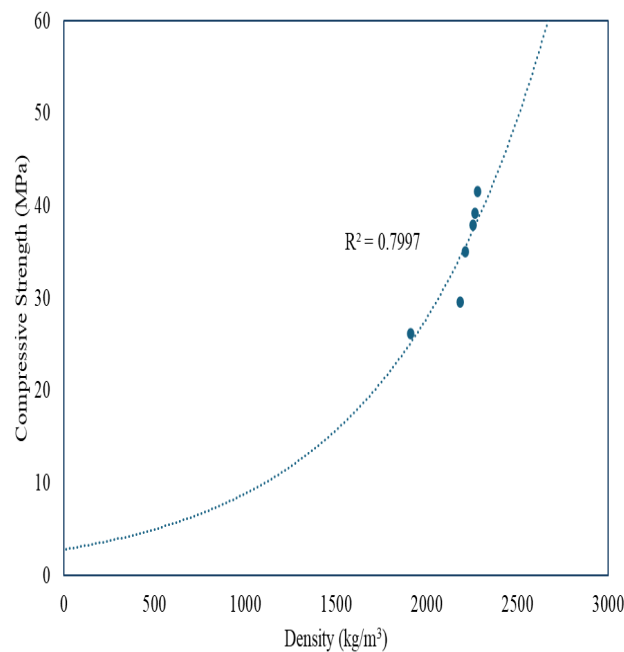


Fig. 9: Correlation between compressive strength and density cured at room temperature and oven (65 °C)

3.5 Correlation Between Thermal Resistance and Density

The correlation between density and thermal resistance at 28 days featured in Fig.10 that provide insights into the performance of geopolymer mortar with (a) 10% and (b) 4% RM content. Among the varying red mud (RM) content, the 10% RM mix exhibited the strongest correlation between density and thermal resistance ($R^2 = 0.970$), indicating that a higher RM content improves thermal resistance by reducing porosity. This makes it ideal for applications requiring high thermal insulation properties such as building envelopes in tropical climates like Malaysia.

In contrast, the 4% RM mix showed the weakest correlation ($R^2 = 0.497$) suggesting inconsistent thermal performance due to poor particle distribution of RM. This irregularity in the material matrix results in unpredictable thermal behaviour making it less suitable for reliable thermal insulation applications.

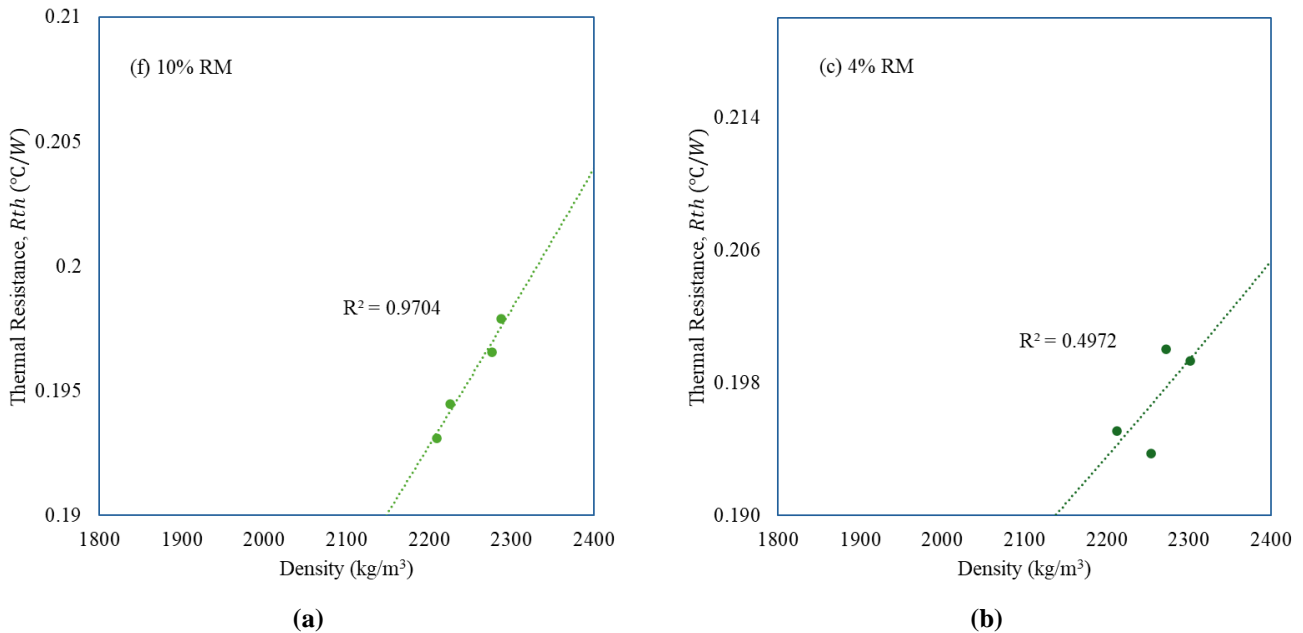


Fig. 10: Correlation between Thermal Resistance and Density cured at Room Temperature and Oven (65°C) (a) 10% RM; (b) 4% RM

4. Conclusion

Based on this study's experimental results and data analysis, it can be concluded that red mud significantly contributes to geopolymer concrete strength development. This study focused on evaluating the effects of red mud proportions and curing temperatures on the compressive strength of geopolymer mortar and identifying the optimum red mud proportions for enhanced performance. The results demonstrated that red mud significantly impacts compressive strength with varying proportions (2%, 4%, 6%, 8% and 10%) exhibiting a non-linear relationship. The compressive strength initially increased at 6% and 8% red mud (with oven curing) before decreasing at higher proportions. Elevated curing temperatures (65°C) proved to be more effective than room temperature in enhancing geopolymerization, leading to higher compressive strength.

The optimum red mud proportion was found to be 6% RM with oven curing offering the best balance between strength and sustainable construction practices. Beyond this proportion, excess red mud disrupted the microstructure and reduced strength. The findings contribute to a more consistent and reliable approach for high-performance, fast-strength development in construction ensuring sustainable and efficient use of industrial by-products.

5. Recommendations

Based on the findings of this study, several recommendations are made to enhance the performance of red mud-based geopolymer mortar. First, refining the mix proportions of red mud and other supplementary materials, particularly at higher red mud contents ($>8\%$) should be considered to improve compressive strength and durability. SEM and XRD analyses are suggested for further investigation of material behavior at these higher proportions. Second, exploring alternative curing methods, such as steam curing or ambient curing with additives, could improve the feasibility of large-scale applications, as elevated temperatures (65°C) were shown to positively affect strength development. Lastly, the addition of superplasticizers, nano-silica or other performance-enhancing additives is recommended to improve the workability, strength and thermal resistance of geopolymer mortar containing red mud.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results and manuscript preparation.

References

Journal

- [1] Scrivener, K. L., & Snellings, R. (2022). The rise of Portland cements. *Elements: An International Magazine of Mineralogy, Geochemistry, and Petrology*, 18(5), pp. 308-313.
- [2] Portland Cement Association. (2024). How Cement is Made. Retrieved on April 26, 2024, from <https://www.cement.org/cement-concrete/how-cement-is-made>
- [3] Setiawan, A. A., Hardjasaputra, H., & Soegiarso, R. (2023). Embodied carbon dioxide of fly ash based geopolymer concrete. *IOP Conference Series Earth and Environmental Science*, 1195(1), 012031. <https://doi.org/10.1088/1755-1315/1195/1/012031>
- [4] Jake Hoffman (2021). CO2 Emissions from Global Cement Production. Stanford University: Master's Project Report.
- [5] Olivia Frost. (2023). INSIGHTS FROM INDUSTRY. Sustainability Challenges in the Cement Industry. Retrieved on April 23, 2024, from <https://www.azom.com/article.aspx?ArticleID=22883>
- [6] Mijarsh, M. J. A., Abdullah. M. Zeyad, Otman M. M. Elbasir, Johari, M. A. M., Ahmad, Z. A. & Mohamed O. M. Mashri. Influence of cement content on the compressive strength and engineering properties of palm oil fuel ash-based hybrid alkaline cement. Ph.D. Thesis. Civil Engineering Department, Faculty of Engineering Al-Merghab University Al-Khums, Libya, Civil Engineering Department Jazan University Jazan, Saudi Arabia, Civil Engineering Department High Institute of Science and Technology Qaser bin Gashear, Libya, School of Civil Engineering, Engineering Campus Universiti Sains Malaysia Nibong Tebal, Penang, Malaysia & Civil Engineering Department College of technical and sciences Baniwaled, Libya ; 2020.
- [7] Jwaida, Z., Dulaimi, A., Mashaan, N. & Mydin, M. A. O. (2023). *Geopolymers: The Green Alternative to Traditional Materials for Engineering Applications*. Retrieved on April 26, 2024, from [doi: 10.3390/infrastructures8060098](https://doi.org/10.3390/infrastructures8060098)
- [8] Peiliang, C. & Yaqian, C. (2021). Advances in geopolymer materials: A comprehensive review. Retrieved on April 26, 2024, from [doi: 10.1016/j.jtte.2021.03.004](https://doi.org/10.1016/j.jtte.2021.03.004)
- [9] Swain, B. (2022). Red mud: An environmental challenge but overlooked treasure for critical rare earth metals. *MRS Bulletin*, 47(3), 289–302. <https://doi.org/10.1557/S43577-022-00300-X>
- [10] Zeng, H., Lyu, F., Sun, W., Zhang, H., Wang, L. & Wang, Y. (2020). Progress on the Industrial Applications of Red Mud with a Focus on China. Retrieved on April 26, 2024, from [doi: 10.3390/min10090773](https://doi.org/10.3390/min10090773)
- [11] Qureshi, H. J., Ahmad, J., Majdi, A., Saleem, M. U., Fuhaid, A. F. A. & Arifuzzaman, M. (2022). A Study on Sustainable Concrete with Partial Substitution of Cement with Red Mud: A Review. Retrieved on April 26, 2024, from [doi: 10.3390/ma15217761](https://doi.org/10.3390/ma15217761)
- [12] A. Kusbiantoro, M. Nuruddin, N. Shafiq and S. Qazi, 2012. The effect of microwave incinerated rice husk ash on the compressive and bond strength of fly ash based geopolymer concrete. *Construction and Building Materials*, 36, pp.695-703.
- [13] Davidovits, J. Geopolymers: inorganic geopolymeric new materials. *Journal of Thermal Analysis*. 1991. 37: 1633-1656.
- [14] Provis, J. L., & Bernal, S. A. (2014). Geopolymers and related Alkali-Activated materials. *Annual Review of Materials Research*, 44(1), 299–327. <https://doi.org/10.1146/annurev-matsci-070813-113515>
- [15] Zhang, Z., Huo, Z., Yang, Z., Wang, X. & Xia, J. (2013). Curing Condition and NaOH Concentration on the Mechanical Properties of Fly Ash Based Geopolymer Mortars. *International Journal of Sustainable Construction Engineering and Technology*, 14(11.), pp. 279-286.
- [16] Kong, D. L., & Sanjayan, J. G. (2008). Damage behavior of geopolymer composites exposed to elevated temperatures. *Cement and Concrete Composites*, 30(10), 986–991. <https://doi.org/10.1016/j.cemconcomp.2008.08.001>
- [17] Palomo, A., Grutzeck, M., & Blanco, M. (1999). Alkali-activated fly ashes. *Cement and Concrete Research*, 29(8), 1323–1329. [https://doi.org/10.1016/S0008-8846\(98\)00243-9](https://doi.org/10.1016/S0008-8846(98)00243-9)
- [18] Gupta, B., Ishwarya, G., & Singh, B. (2017). Porous geopolymer insulating core from a metakaolin/biomass ash composite. *Materials Today: Proceedings*, 4(2), 2210–2215. <https://doi.org/10.1016/j.matpr.2016.10.029>
- [19] Othman, R., Jaya, R. P., Muthusamy, K., Sulaiman, M., Duraisamy, Y., Abdullah, M. M. a. B., Przybył, A., Sochacki, W., Skrzypczak, T., Vizureanu, P., & Sandu, A. V. (2021). Relation between Density and Compressive Strength of Foamed Concrete. *Materials*, 14(11), 2967. <https://doi.org/10.3390/ma14112967>

- [20] Vitola, L., Pundiene, I., Pranckeviciene, J., & Bajare, D. (2020). The impact of the amount of water used in activation solution and the initial temperature of paste on the rheological behaviour and structural evolution of Metakaolin-Based geopolymer pastes. *Sustainability*, 12(19), 8216. <https://doi.org/10.3390/su12198216>
- [21] Ozcelikci, E., Kul, A., Gunal, M. F., Ozel, B. F., Yildirim, G., Ashour, A., & Sahmaran, M. (2023). A comprehensive study on the compressive strength, durability-related parameters and microstructure of geopolymer mortars based on mixed construction and demolition waste. *Journal of Cleaner Production*, 396, 136522. <https://doi.org/10.1016/j.jclepro.2023.136522>
- [22] Yun Ming, L., Hussin, K., Al Bakri Abdullah, M. M., Binhussain, M., Musa, L., Khairul Nizar, I., Ghazali, C. M. R., & Heah, C. Y. (2012). Effect of Curing Regimes on Metakaolin Geopolymer Pastes Produced from Geopolymer Powder. Retrieved on May 24, 2024, from [doi: 10.4028/www.scientific.net/amr.626.931](https://doi.org/10.4028/www.scientific.net/amr.626.931)
- [23] Wang, Y., & Zhen, Z. (2024). Properties of Red-Mud-Modified basic magnesium sulfate cement. *Materials*, 17(16), 4085. <https://doi.org/10.3390/ma17164085>