# Strength characteristic and life cycle cost of sustainable bio-patch repair geopolymer mortar using rice husk ash as an alternative silica and alumina source

*Pinta* Astuti[1*], *Muhammad Sakti* Isnaini[1], *Sachio Dwi* Ammar[1], and *Adhitya Yoga* Purnama[2]

[1]Department of Civil Engineering, Universitas Muhammadiyah Yogyakarta, Indonesia
[2]Department of Civil Engineering, Vocational College, Universitas Gadjah Mada, Indonesia

**Abstract.** Rapid development in construction has increased cement use, raising $CO_2$ emissions. Geopolymers offer an eco-friendly alternative, reducing reliance on cement. This study examines rice husk ash (RHA), a pozzolanic material, as a binder. Three alkali activator variations (AA40%, AA45%, AA50%) were tested for mechanical properties, focusing on compressive strength. The mix design was optimized and cured at 70°C and room temperature. The AA40% variation showed the highest compressive strength of 8.14 MPa. RHA-based geopolymer mortar supports UN SDGs 9, 12, and 13, showing a significantly lower 30-year life cycle cost (IDR 4,125,000 vs. IDR 6,225,000 for Portland cement). It reduces agricultural waste, lowers carbon footprints, and offers long-term economic benefits, highlighting its potential as a sustainable building material.

## 1 Introduction

The construction sector in Indonesia is experiencing an annual growth rate of approximately 7-8%, indicative of the rising demand for infrastructure and facilities to support the country's population. However, this expansion presents significant environmental challenges, particularly due to the extensive use of cement in construction [1], [2]. Cement production is a major source of carbon dioxide emissions, contributing substantially to greenhouse gas emissions [3]. As global concrete consumption increases, so does the demand for cement, driven by the need for essential human infrastructure [4]. This trend highlights the pressing need to address the environmental impacts of cement production. Mitigating these effects requires the adoption of sustainable construction practices, such as developing and utilizing alternative eco-friendly materials, improving the efficiency of cement production processes, and promoting green building standards [5], [6]. By focusing on sustainable practices, Indonesia can continue its infrastructural development while reducing the environmental footprint of its construction industry. Various construction engineering experts are striving to mitigate environmental damage caused by

* Corresponding author: pinta.astuti@ft.umy.ac.id

carbon dioxide ($CO_2$) emissions. This is evidenced by the increasing use of alternative materials designed to produce environmentally friendly construction materials without compromising structural performance. Numerous innovations in alternative materials are being explored to replace cement as a binder in geopolymers, including fly ash, rice husk ash, sugar cane bagasse, and eggshells, all of which contain silica (Si) and alumina (Al) compounds [5], [7]. The development of these environmentally friendly materials represents a significant step towards innovations that can combat global warming. These new materials are being incorporated into geopolymer mixtures, offering a promising alternative to traditional cement. Geopolymer innovation has the potential to reduce $CO_2$ emissions by approximately 80%, significantly decreasing the reliance on cement in conventional concrete [8], [9].

Due to its high silica content, rice husk ash (RHA) is recognized as a valuable supplementary cementitious material (SCM) in concrete production [10], [11]. RHA, with silica content ranging from 87% to 97%, acts as an excellent pozzolanic material. When RHA reacts with calcium hydroxide in concrete, it forms additional calcium silicate hydrate (C-S-H), crucial for enhancing concrete's strength and durability [12], [13]. Incorporating rice husk ash (RHA) into concrete enhances durability by reducing permeability and increasing resistance to chemicals and corrosion. The pozzolanic reaction improves mechanical properties, including strength. RHA also lowers the environmental impact by decreasing the need for cement, thus reducing $CO_2$ emissions from cement production [14]. RHA has the ability to substitute a certain amount of cement in concrete mixtures, usually ranging from 5% to 20% by weight. This substitution not only improves the characteristics of concrete, but also provides an eco-friendly option by making use of agricultural waste. High-performance concrete (HPC) relies on the use of RHA to achieve exceptional strength and durability [15], [16]. High-performance concrete (HPC) with RHA has been successfully used in high-rise buildings, bridges, and essential infrastructure, promoting sustainable construction. Reusing agricultural waste, like RHA, helps reduce the construction industry's environmental footprint and supports circular economy principles [17]. But there is no report on the use of RHA as the binder material for bio-patch repair geopolymer mortar. As many demand related to the use of patching method in the degradated concrete structure in some fields due to corrosion damage [18]. Patching method is the famous method to be combined by the cathodic protection system due to its effectivity [19], [20]. This research aims to investigate the feasibility and performance of RHA-based geopolymers as patching mortars, potentially leading to more durable, sustainable, and eco-friendly construction materials.

## 2 Material and methods

This research employs an experimental method to analyze the potential of rice husk ash (RHA) as a substitute in mortar mixtures. The study tests RHA at 40%, 45%, and 50% replacement levels for cement, combined with NaOH and $Na_2SiO_3$. Compressive, split tensile, and flexural strengths are measured. Fine aggregate from Mt. Merapi sand and RHA from Pajangan, Bantul District, Yogyakarta, sieved to No. 200, are used. Tap water prepares the mortar, with NaOH activating the alumino-silicate reaction and $Na_2SiO_3$ speeding up polymerization. A superplasticizer improves fluidity. The pozzolanic substance's chemical composition is analyzed using specific gravity and X-ray fluorescence (XRF). Rice husks, crushed and burned at 700°C to 900°C, are sieved to achieve fine ash. This ash (Figure 1), meeting the No. 200 sieve standard, is used in geopolymer mortar production, demonstrating the viability of RHA as an eco-friendly construction material.

**Fig. 1.** Rice husk ash used in this experiment

The mix design computation entails a meticulous examination of rice husk ash, sand, water, and superplasticizer components for a volume of 1 m³. This test employs mix design calculations to ascertain the most advantageous composition for constructing the test specimens. The outcomes of these computations are shown in Table 1, showcasing the subsequent deviations: (a) 60% to 40%, (b) 55% to 45%, and (c) 50% to 50%. In addition, an additional amount of water is added, equivalent to 25% of the volume of the alkali activator. According to SNI 1974:2011, testing geopolymer mortar compressive strength involves several steps. Prepare test specimens and immerse them for 28 days. Measure, weigh, and place specimens on the compressive testing machine, then apply load until failure. Document results and calculate compressive strength. This study used 5 cm³ cubic mortar specimens made from rice husk ash, sand, water, NaOH, $Na_2SiO_3$, and superplasticizer. Nine specimens, with variations in alkali activator content (40%, 45%, 50%), were cured at 70°C for 24 hours and then at room temperature for 27 days. Each specimen variation was tested three times.

**Table 1.** Mix proportion of the specimens

| Material | 40% of Alkali Activator (AA40%) | 45% of Alkali Activator (AA45%) | 50% of Alkali Activator (AA50%) |
|---|---|---|---|
| Fine aggregate (grams) | 1680 | 1680 | 1680 |
| Rice husk ash (RHA) (grams) | 432 | 396 | 360 |
| NaOH (grams) | 44,8 | 50,4 | 56 |
| $Na_2SiO_3$ (grams) | 80 | 176,4 | 196 |
| Water (grams) | 59.7 | 90 | 100 |
| Superplasticizer (grams) | 6.0 | 6 | 6 |

## 3 Result and discussions

The compressive strength test was carried out in accordance with SNI 1974:2011, which describes the phases of compressive strength testing for geopolymer mortar. The purpose of the test was to determine the compressive strength values of geopolymer mortar. The result of the test was presented in Figure 2. It was determined that the average compressive strength ranged from 2.88 MPa to 8.18 MPa, with 8.18 MPa being the highest value.

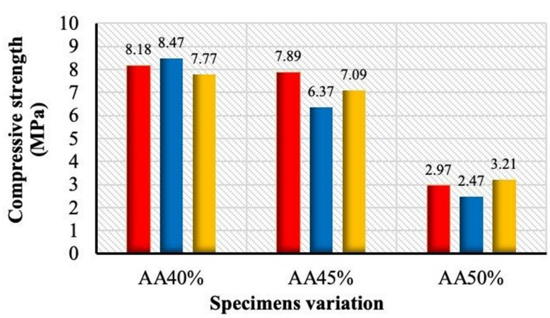


**Fig. 2.** The result of compressive strength test

Based on the findings, it seems that the variant consisting of sixty percent rice husk ash exhibited the maximum compressive strength. Given that it contains a larger amount of binder and alkali activator, notably rice husk ash, in comparison to the other two versions, this may be ascribed to the fact that it is more effective. Previous research found that this material had greater concentrations of silica ($SiO_2$) and calcium (CaO) as a consequence of how it was constructed [21], [22]. A major amount of the compressive strength of the mortar is attributed to the presence of silica, which is a key component of rice husk ash. When silica is hydrated and interacts with water, silica gel is created. It is because silica gel has excellent binding characteristics and has the ability to fill the pores of mortar, so increasing the density of the substance. The appearance of the specimens after the compressive strength test was depicted in Figure 3.

**Fig. 3.** The appearance of the specimens after the compressive strength test

The incorporation of rice husk ash (RHA) into geopolymer mortar balances sustainability with the contemporary building industry's needs. With a compressive strength of 8.18 MPa, RHA-based geopolymer mortar is suitable for non-structural applications such as stonemasonry, plastering, and flooring. Utilizing RHA offers significant environmental benefits by reducing agricultural waste, lowering $CO_2$ emissions compared to traditional Portland cement, and contributing to a circular economy. The life cycle cost (LCC) analysis of RHA-based geopolymer mortar, converted into Indonesian Rupiah (IDR), demonstrates its economic and environmental advantages, supporting various United Nations' Sustainable Development Goals and fostering sustainable construction practices.

RHA, an inexpensive agricultural by-product, requires transportation and processing, while alkali activators (NaOH and $Na_2SiO_3$) add to the initial costs. Both RHA-based and traditional mortars have comparable costs for superplasticizers and aggregates. Processing equipment and skilled labor for RHA also contribute to the initial expenses. Energy consumption for curing RHA-based mortars at 70°C for 24 hours is higher than for traditional mortars. However, RHA-based mortars may achieve efficiency during mixing and application, offsetting initial energy costs. Geopolymer mortars, including those with RHA, are generally more durable and chemically resistant, leading to lower maintenance costs over their lifespan compared to traditional mortars. This durability translates to fewer repairs and replacements, resulting in significant long-term savings. RHA-based mortars are more environmentally friendly, incurring lower disposal costs and less environmental remediation. They can often be recycled more easily than traditional mortars, potentially generating revenue from recycling.

The total LCC over 30 years for RHA-based geopolymer mortar is significantly lower (IDR 4,125,000) compared to traditional Portland cement mortar (IDR 6,225,000). Despite higher initial investments in alkali activators and curing energy, the reduced maintenance and disposal costs, along with environmental benefits, make RHA-based geopolymer mortar economically viable. RHA-based geopolymer mortar aligns with sustainable development goals by reducing agricultural waste and lowering carbon footprints. It offers significant economic benefits, with the initial costs offset by long-term savings, making it an attractive alternative for eco-friendly construction. The results reinforce RHA's potential as a valuable component in sustainable building materials, advocating for broader adoption and further research into optimizing these materials for various construction applications.

## 4 Conclusion

The study shows that RHA-based geopolymer mortar is a promising, sustainable building material. It aligns with UN Sustainable Development Goals 9, 12, and 13 by reducing waste, improving resource efficiency, and cutting greenhouse gas emissions. Over 30 years, its life cycle cost (IDR 4,125,000) is significantly lower than that of Portland cement mortar (IDR 6,225,000). Despite higher initial costs for alkali activators and curing energy, the lower maintenance and disposal costs, along with environmental benefits, make it economically viable. The findings highlight RHA's potential as an eco-friendly construction material, encouraging broader adoption and further research.

## References


[1] M. A. Jungclaus, S. L. Williams, J. H. Arehart, and W. V. Srubar, "Whole-life carbon emissions of concrete mixtures considering maximum CO2 sequestration via carbonation," *Resour Conserv Recycl*, vol. 206, p. 107605, Jul. 2024, doi: 10.1016/J.RESCONREC.2024.107605.

[2] D. Sinkhonde and T. Bezabih, "On the computational evaluation of carbon dioxide emissions of concrete mixes incorporating waste materials: A strength-based approach," *Cleaner Waste Systems*, vol. 8, p. 100149, Aug. 2024, doi: 10.1016/J.CLWAS.2024.100149.

[3] K. L. Scrivener, V. M. John, and E. M. Gartner, "Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry," *Cem Concr Res*, vol. 114, pp. 2–26, Dec. 2018, doi: 10.1016/j.cemconres.2018.03.015.

[4] Y. Xu, Z. Yao, J. Wang, W. Xue, X. Liu, and Z. Ding, "Acoustic emission characteristics and damage constitutive model of high-performance concrete of freezing shaft under hydro-mechanical coupling," *Journal of Building Engineering*, vol. 93, p. 109876, Sep. 2024, doi: 10.1016/J.JOBE.2024.109876.

[5] Md. Zia ul haq, H. Sood, R. Kumar, P. Chandra Jena, and S. Kumar Joshi, "Eco-friendly approach to construction: Incorporating waste plastic in geopolymer concrete," *Mater Today Proc*, Sep. 2023, doi: 10.1016/j.matpr.2023.09.037.

[6] M. R *et al.*, "Performance of recycled Bakelite plastic waste as eco-friendly aggregate in the concrete beams," *Case Studies in Construction Materials*, vol. 18, p. e02200, Jul. 2023, doi: 10.1016/j.cscm.2023.e02200.

[7] M. K. A. Talib, S. N. H. Arifin, A. Madun, M. F. M. Dan, and F. Pakir, "Effect of Rice Husk Ash (RHA) as a Pozzolan on the Strength Improvement of Cement Stabilized Peat," *Journal of Advanced Research in Applied Mechanics*, vol. 114, no. 1, pp. 83–93, 2024.

[8] P. Dashti, S. Ranjbar, S. Ghafari, A. Ramezani, and F. M. Nejad, "RSM-based and environmental assessment of eco-friendly geopolymer mortars containing recycled waste tire constituents," *J Clean Prod*, vol. 428, p. 139365, Nov. 2023, doi: 10.1016/J.JCLEPRO.2023.139365.

[9] R. Afriansya, E. A. Anisa, P. Astuti, and M. D. Cahyati, “Effect of polypropylene fiber on workability and strength of fly ash-based geopolymer mortar,” *E3S Web of Conferences*, vol. 429, p. 05006, Sep. 2023, doi: 10.1051/e3sconf/202342905006.

[10] Y. Hou, K. Yang, S. Yin, X. Yu, L. Wang, and X. Yang, “Enhancing the physical properties of cemented ultrafine tailings backfill (CUTB) with fiber and rice husk ash: Performance, mechanisms, and optimization,” *Journal of Materials Research and Technology*, vol. 29, pp. 4418–4432, Mar. 2024, doi: 10.1016/J.JMRT.2024.02.068.

[11] M. M. Hirose Carlsen and Y. Saito, “Phase diagram of SiO2 crystallization upon rice husk combustion to control silica ash quality,” *Waste Management*, vol. 182, pp. 55–62, Jun. 2024, doi: 10.1016/J.WASMAN.2024.04.009.

[12] K. Hamcumpai *et al.*, “High-strength steel fibre-reinforced geopolymer concrete utilising recycled granite waste and rice husk ash,” *Constr Build Mater*, vol. 433, p. 136693, Jun. 2024, doi: 10.1016/J.CONBUILDMAT.2024.136693.

[13] S. K. Chelluri and N. Hossiney, “Performance evaluation of ternary blended geopolymer binders comprising of slag, fly ash and brick kiln rice husk ash,” *Case Studies in Construction Materials*, vol. 20, p. e02918, Jul. 2024, doi: 10.1016/J.CSCM.2024.E02918.

[14] X. Yuan, W. Xu, A. H. AlAteah, and S. A. Mostafa, “Evaluation of the performance of high-strength geopolymer concrete prepared with recycled coarse aggregate containing eggshell powder and rice husk ash cured at different curing regimes,” *Constr Build Mater*, vol. 434, p. 136722, Jul. 2024, doi: 10.1016/J.CONBUILDMAT.2024.136722.

[15] R. C. Kaze, A. Naghizadeh, L. Tchadjie, Ö. Cengiz, E. Kamseu, and F. U. Chinje, “Formulation of geopolymer binder based on volcanic-scoria and clay brick wastes using rice husk ash-NaOH activator: Fresh and hardened properties,” *Sustain Chem Pharm*, vol. 40, p. 101627, Aug. 2024, doi: 10.1016/J.SCP.2024.101627.

[16] J. Zou, X. Ma, M. Zhao, Q. Guan, D. Chen, and Y. Chao, “Ternary geopolymer synthesized using self-made rice husk ash-based water glass for removing Cu2+ and Cr3+ from wastewater,” *Mater Lett*, vol. 367, p. 136556, Jul. 2024, doi: 10.1016/J.MATLET.2024.136556.

[17] S. Feng, C. Ge, Q. Sun, W. Zheng, G. Li, and C. Hu, “Valorization of agriculture waste: Preparation of alkoxysilanes from mixed rice straw and rice husk ash,” *Chemical Engineering Journal*, vol. 495, p. 153377, Sep. 2024, doi: 10.1016/J.CEJ.2024.153377.

[18] K. Kawaai, T. Nishida, A. Saito, and T. Hayashi, “Application of bio-based materials to crack and patch repair methods in concrete,” *Constr Build Mater*, vol. 340, p. 127718, Jul. 2022, doi: 10.1016/J.CONBUILDMAT.2022.127718.

[19] P. Astuti, R. S. Rafdinal, D. Yamamoto, and H. Hamada, “Corrosion rate of deteriorated steel bar protected by sacrificial anode cathodic protection,” 2023, p. 050010. doi: 10.1063/5.0110419.

[20] P. Astuti, R. S. Rafdinal, D. Yamamoto, and H. Hamada, “Natural Localized Corrosion of Steel Bar in 44-Years Old Cracked RC Beam Structures Exposed to Marine Tidal Environment,” 2024, pp. 371–381. doi: 10.1007/978-981-99-6018-7_27.

[21] P. Astuti, R. Afriansya, E. A. Anisa, S. D. Puspitasari, and A. Y. Purnama, “The potential use of agriculture pozzolan waste as supplementary cementitious materials by integrating with biomass,” 2022, p. 040017. doi: 10.1063/5.0104926.

[22] T. Lee and J. Lee, “Setting time and compressive strength prediction model of concrete by nondestructive ultrasonic pulse velocity testing at early age,” *Constr Build Mater*, vol. 252, p. 119027, Aug. 2020, doi: 10.1016/J.CONBUILDMAT.2020.119027.