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Environmental performance evaluation of geopolymer concrete utilizing industrial by-products and recycled aggregates under variable thermal conditions

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ABSTRACT

The escalating demand for infrastructure in rapidly urbanizing regions has intensified the depletion of natural resources and amplified industrial waste generation. This dual impact not only accelerates global warming but also exacerbates environmental degradation through increased carbon emissions. In response, this study explores a sustainable alternative by incorporating industrial by-products and recycled aggregates into geopolymer concrete (GPC) production. Specifically, cement was partially substituted with industrial waste materials – 15% pozzolanic by-product and varying percentages (0–50%) of reactive alkaline residue – alongside a consistent 25% replacement of natural coarse aggregate with recycled concrete aggregate (RCA). The fresh and hardened properties of the resulting GPC were assessed through slump and compressive strength tests. Results indicated that increasing the proportion of alkaline residue adversely affected workability, while compressive strength exhibited significant enhancement, reaching up to 136 MPa compared to the baseline 75 MPa. These findings highlight the potential of geopolymer concrete utilizing secondary raw materials as a cost-efficient and environmentally conscious construction material. The use of such by-products not only mitigates solid waste accumulation but also contributes positively to the circular economy and low-carbon development strategies.

Keywords: geopolymer concrete, industrial by-products, recycled aggregates, environmental sustainability, compressive strength.

INTRODUCTION

The continuous expansion of urban infrastructure to accommodate growing populations has led to increased exploitation of natural resources and the simultaneous generation of vast industrial waste streams. As the cement and construction industries are among the leading contributors to greenhouse gas emissions, there is an urgent need to develop sustainable alternatives to conventional building materials. One such alternative is geopolymer concrete (GPC), which offers an innovative solution by incorporating mineral-based industrial by-products as binding agents and replacing virgin aggregates with recycled components, thus mitigating both environmental degradation and waste disposal issues (Davidovits, 2008; Mehta and Monteiro, 2006).

Recent advancements in material science have demonstrated the feasibility of synthesizing geopolymers using silica- and alumina-rich industrial residues, such as coal-derived mineral dust and acetylene production sludge. These by-products exhibit pozzolanic and alkaline characteristics, enabling them to activate polymeric chains under controlled alkaline environments. Research by Parea et al. (2023a) and Arwin Amiruddin et al. (2024) confirmed that such alternative precursors could rival the performance of ordinary cement in strength and durability when appropriately formulated. Moreover, the incorporation of these materials significantly reduces the carbon intensity associated with traditional clinker-based binders (Zhang et al., 2014; Turner and Collins, 2013).

In tandem with binder substitution, the use of recycled coarse aggregates (RCA) has gained traction as an environmentally responsible practice. Replacing natural aggregates with RCA not only conserves non-renewable resources but also aligns with circular economy principles by repurposing concrete waste. Although RCA may initially exhibit inferior mechanical properties due to the presence of adhered mortar, performance can be optimized through effective mix design and pre-treatment techniques (Tam et al., 2007; Parea et al., 2024). According to Prasittisopin et al. (2025), concrete incorporating RCA can meet structural performance criteria while reducing environmental burden and construction costs.

Furthermore, curing temperature plays a pivotal role in the geopolymerization process, directly influencing strength development, microstructure, and long-term durability. Elevated thermal regimes enhance reaction kinetics and densify the polymer matrix, particularly in mixes using high-silica or calcium-bearing residues (Parea et al., 2023b; Nath and Sarker, 2014). Studies by Komnitsas and Zaharaki (2007) indicate that optimal thermal activation can accelerate polycondensation reactions, leading to improved mechanical and chemical resistance. This thermal sensitivity underscores the need for rigorous control of curing protocols in GPC applications.

Beyond technical performance, the environmental merits of geopolymer systems are significant. By diverting waste from landfills and reducing reliance on energy-intensive clinker production, GPC can substantially cut down on CO_2 emissions. Sunarno et al. (2025) demonstrated that employing blended industrial waste in concrete production led to a 40–60% reduction in embodied carbon compared to OPC. This aligns with the findings of Habert and Ouellet-Plamondon (2016), who advocated the adoption of alternative binders to promote low-impact construction practices in the face of climate change.

Nonetheless, challenges such as inconsistent chemical compositions, variable reactivity, and scaling difficulties persist in the utilization of unconventional binders. To address these, continuous efforts in material characterization, thermal conditioning studies, and mechanical testing are essential (Mathias, 2023; Provis and van Deventer, 2009). Additionally, understanding the synergetic effects of mineral residue combinations and aggregate substitutions remains a frontier in optimizing sustainable concrete formulations.

This study investigates the strength performance and environmental benefits of geopolymer concrete made with non-traditional mineral residues and recycled aggregates, cured under variable thermal conditions. The research aims to explore the synergy between binder formulation, aggregate replacement, and thermal activation to develop a structurally sound and eco-efficient concrete. The outcomes are expected to advance the field of low-carbon construction materials, offering a scalable alternative to OPC in the pursuit of global sustainability goals.

MATERIALS AND METHOD

Materials

The increasing demand for infrastructure development in Indonesia has led to significant consumption of natural resources, particularly in cement and aggregate usage. Ordinary Portland Cement (OPC) remains the dominant binder in construction materials, despite its high carbon footprint resulting from calcination and energy-intensive production processes. According to SNI 2049:2015 regarding the specification of Portland cement, OPC of grade 43 is commonly used in structural applications due to its adequate strength characteristics. However, to align with Indonesia's commitment to sustainable development, as outlined in SNI 2847:2019 on concrete structural requirements, it is essential to explore alternative binder materials and aggregate sources. This study investigates the feasibility of incorporating industrial by-product sludge and combustion-derived mineral residue as partial substitutes for cement, and RCA as a replacement for natural aggregates. Such practices not only reduce environmental impact but also support SNI 7656:2010 on the utilization of industrial waste in construction. Furthermore, as emphasized in SNI 1974:2011 for concrete testing methods, all materials used must meet the technical criteria related to specific gravity, particle size distribution, and water absorption. The reuse of demolition waste as RCA in this study addresses waste minimization strategies and enhances circular economy initiatives in the construction sector. By referring to these SNI standards, this study ensures that sustainability goals are pursued without compromising structural integrity and performance.

The continued use of OPC as the dominant binder in concrete production has prompted serious environmental concerns due to its significant contribution to CO_2 emissions, estimated to be around 0.9 tons of CO_2 per ton of cement produced (Habert et al., 2020). As per SNI 2049:2015, OPC Grade 43 is standard in infrastructure applications, offering reliable compressive strength and workability. However, this reliance raises challenges in balancing development needs with climate change mitigation. To address this, recent approaches have introduced low-impact alternative binders that utilize mineral residues with cementitious properties, while also incorporating recycled aggregates to reduce the depletion of natural resources. These alternatives must align with national construction codes, such as SNI 7656:2010, which supports the use of supplementary cementitious materials in blended cement formulations.

Studies conducted globally affirm the viability of using mineral-based industrial by-products as cement replacements. For example, Bernal et al. (2015) reported that alkali-activated binder systems based on metallurgical slag and silica-rich waste achieved compressive strengths exceeding 50 MPa, with improved durability performance. Similarly, Zhang et al. (2022) demonstrated that geopolymer concrete incorporating recycled coarse aggregate maintained over 80% of the mechanical performance of mixes using virgin aggregates, provided that pre-treatment processes and optimized curing were applied. These findings are consistent with the results of the current study, where recycled coarse aggregate with a specific gravity of 2.15 and water absorption of 3.9% (see Table 1) fulfilled the material quality criteria under SNI 1974:2011 for compressive strength testing. Furthermore, the use of alternative mineral binders contributed to a denser microstructure, increasing early strength and long-term durability.

In addition to mechanical performance, environmental benefits from substituting OPC with residual mineral binders and recycled aggregates are notable. The embodied carbon reductions in similar studies, such as by Duxson et al. (2007), indicated that geopolymer systems can reduce CO_2 emissions by up to 80% compared to OPC-based mixes. Moreover, the integration of industrial residues supports circular economy principles by diverting waste from landfills and repurposing it into construction applications. The current investigation further reinforces these conclusions, showing that alternative materials met performance benchmarks defined by SNI 2847:2019, particularly for structural concrete. Hence, combining these materials not only enhances environmental sustainability but also ensures compliance with technical and regulatory standards in concrete construction.

The chemical composition of the alternative binder materials used in this study plays a critical role in the geopolymerization process and strength development. Table 2 presents the oxide composition of the two main materials utilized: a calcium-rich industrial mineral residue and a silica-alumina-rich pozzolanic source. The oxide composition outlined in Table 2 indicates a distinct difference in the chemical roles played by the two materials. The calcium-rich residue is dominated by CaO (69.2%), which contributes to the early strength gain through its role in alkaline activation and hydration reactions. On the other hand, the pozzolanic binder – rich in SiO_2 (57.9%) and Al_2O_3 (33.2%) – acts as the primary source for geopolymer gel formation through polymerization of aluminosilicates. The synergistic combination of calcium and silicate

Table 1. Physical properties of the materials used in the study

No	Property	OPC (Cement)	Industrial by-product sludge	Combustion-derived mineral residue	Recycled coarse aggregate (RCA)
1	Specific gravity	3.15	2.90	2.63	2.08
2	Surface area (m²/g)	2.65	7.10	—	—
3	Median particle size, d50 (μm)	12.5	9.20	—	—
4	Water absorption (%)	—	—	—	4.05
5	Angle of internal friction (°)	—	—	—	34.5
6	Apparent specific gravity	—	—	—	2.35

Table 2. Chemical composition of mineral-based binder materials used in the study

No.	Oxide component	Calcium-rich residue (%)	Pozzolanic binder (%)
1	SiO_2	7.10	57.90
2	Al_2O_3	2.70	33.20
3	Fe_2O_3	3.40	2.15
4	CaO	69.20	3.30
5	MgO	0.65	0.45
6	Na_2O	–	0.52
7	K_2O	8.10	0.78
8	Loss on ignition (LOI)	1.40	0.70

phases contributes significantly to both early and long-term strength development, a finding consistent with results reported by Julphunthong et al. (2024), who emphasized the importance of CaO content for strength enhancement in blended geopolymer systems.

Moreover, the high content of potassium oxide (K_2O) in the calcium-based residue (8.1%) suggests potential for improved activation efficiency in the presence of alkaline solutions, as similarly highlighted in the work of Abdulkareem et al. (2021), where high-alkali materials accelerated the dissolution of precursor particles and enhanced binder reactivity. The relatively low LOI values of both materials (1.4% and 0.7%) indicate minimal presence of unburned carbon or moisture-retaining compounds, which is advantageous for mix consistency and durability performance. Previous investigations, such as that by Xing et al. (2025), further confirm that silica- and alumina-rich ashes combined with reactive calcium phases can lead to the formation of a hybrid C–A–S–H and N–A–S–H gel matrix, offering improved compressive strength, sulfate resistance, and drying shrinkage control. Thus, the chemical profile of the materials used in the current study positions them as promising constituents in geopolymer concrete systems for structural and environmental applications.

Methods

This experimental study aims to investigate the mechanical performance and workability of geopolymer concrete made with a combination of pozzolanic binder, RCA, and a calcium-rich industrial by-product sludge as a partial replacement material. Four concrete mixtures were prepared: Mix 1 (0% sludge), Mix 2 (10% sludge), Mix 3 (20% sludge), and Mix 4 (30% sludge). Each mix contained 15% pozzolanic binder as a cement substitute and 25% recycled coarse aggregate, maintaining a constant water-to-binder ratio across all mixtures. The industrial sludge, rich in calcium compounds, was used to enhance early-age strength and participate in alkali activation, as suggested by findings from Zhang et al. (2020), who demonstrated improved compressive strength in geopolymer concrete incorporating calcium-based additives.

The fresh properties of the concrete mixtures were evaluated through slump tests in accordance with ASTM C143/C143M-20, to assess workability and ensure constructability standards. Slump values were measured immediately after mixing using a standard slump cone. The compressive strength of concrete was tested at 7, 14 and 28 days, based on ASTM C39/C39M-21 standards. Concrete specimens were cast in 100 mm cube molds and cured at ambient conditions for 24 hours before being demolded and subjected to standard curing. The inclusion of RCA aligns with previous studies, such as those by Kisku et al. (2017), which confirm its viability in structural applications when combined with suitable binders and adequate curing.

The mix proportions for each concrete batch are presented in Table 3. The quantities were adjusted to maintain consistent workability while varying the sludge content. Fine aggregates, potable water, and a fixed dose of superplasticizer (1% by binder weight) were used in all mixtures to improve flow and prevent segregation. The trial mixes were optimized through preliminary testing to avoid excessive bleeding or loss of strength. Previous research by Deb et al. (2014) emphasizes that the successful formulation of geopolymer concrete with industrial residues requires precise control of mix ratios and activator concentrations to ensure durable performance and adequate setting characteristics.

Table 3. Mix proportions for geopolymer concrete with industrial sludge replacement

Component	Mix 1 (0%)	Mix 2 (10%)	Mix 3 (20%)	Mix 4 (30%)
Ordinary portland cement (kg/m³)	255	229.5	204	178.5
Pozzolanic binder (kg/m³)	45	45	45	45
Industrial sludge (kg/m³)	0	25.5	51	76.5
Fine aggregate (kg/m³)	670	670	670	670
Recycled coarse aggregate (kg/m³)	1030	1030	1030	1030
Water (kg/m³)	180	180	180	180
Superplasticizer (kg/m³)	3	3	3	3

RESULTS AND DISCUSSION

Workability assessment using slump test

The workability of fresh geopolymer concrete mixtures was assessed through the slump cone test in accordance with ASTM C143/C143M-20 standards. The slump test evaluates the flowability and consistency of the concrete, which is critical for ensuring proper placement and compaction in structural applications. Table 4 presents the slump values obtained for each mix variation, while Figure 1 graphically illustrates the trend of workability in response to increasing industrial by-product content. As indicated in both the table and histogram, the slump values showed a noticeable decrease as the percentage of calcium-rich industrial by-product increased from 0% to 30%. This trend suggests that the inclusion of higher amounts of the by-product adversely affects the flowability of the concrete, likely due to increased binder surface area and water demand.

The results of the slump test, as presented in Table 4 and visualized in Figure 1, reveal a clear downward trend in workability with increasing sludge content in the mix. Mix-1, which contained no sludge, recorded the highest slump value of 176 mm, indicating excellent flowability and ease of placement. However, as the percentage of industrial by-product sludge increased from 10% to 30% in Mix-2 to Mix-4, the slump values dropped progressively to 170 mm, 125 mm, and 105 mm, respectively. This pattern is attributed to the higher water demand and reduced lubrication effect due to the finer particle size and irregular morphology of the sludge, which impairs the mobility of fresh concrete.

Previous studies have similarly reported that incorporating pozzolanic industrial residues can adversely affect workability. For instance, Li et al. (2020) observed that replacing cement with high-reactivity industrial residues increased water absorption and internal friction in fresh mixes, leading to reduced slump values. Moreover, the

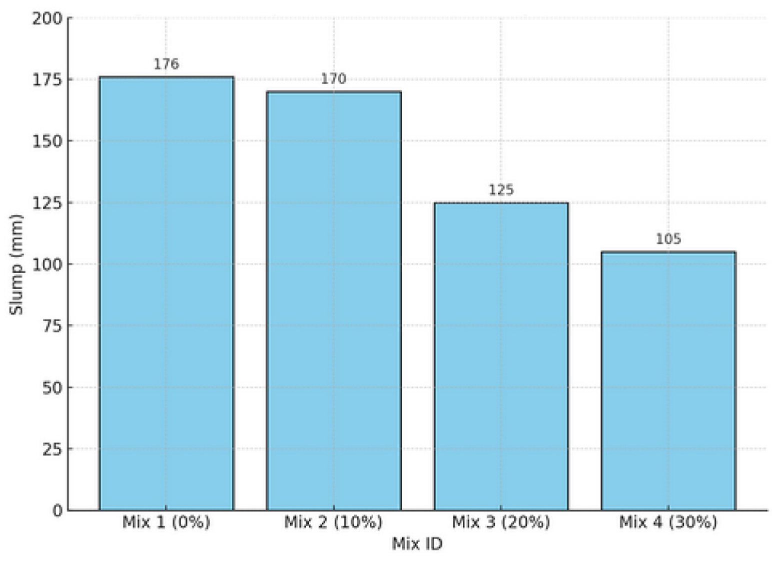

Figure 1. Slump value vs. industrial by-product content

Table 4. Slump values of concrete mixes with industrial by-product replacement

Mix ID	Slump (mm)
Mix 1 (0%)	176
Mix 2 (10%)	170
Mix 3 (20%)	125
Mix 4 (30%)	105

higher specific surface area of sludge particles tends to bind more free water, leaving less available for flow, thus reducing slump. The observed trend in this study aligns with findings by Jhatial, A.A. (2021), who reported that the use of recycled aggregates and mineral waste significantly reduced slump due to their porous and angular nature, which increases internal friction.

Despite the reduced workability, the mixes remained within an acceptable range for structural applications, particularly when mechanical compaction methods are available. The lowest slump value of 105 mm for Mix-4 is still within the medium workability range as per SNI 7656:2012. However, to counteract the loss of workability in practical applications, the addition of superplasticizers or water-reducing agents may be considered. Importantly, the environmental benefit gained by incorporating industrial sludge—through reduced cement consumption and diverted landfill waste—offers a compelling case for its adoption in sustainable concrete practices, provided that necessary adjustments in mix design and admixture usage are accounted for.

Compressive strength performance

The compressive strength results shown in Table 5 and illustrated in the revised Figure 2 demonstrate a clear trend of strength enhancement over time, particularly across 7, 14, and 28-day curing periods. All mix variants experienced progressive strength gain with longer curing durations, affirming that geopolymerization reactions and subsequent binder matrix development are significantly influenced by curing time. Among all mixes, Mix-3 consistently outperformed others across all ages, recording the highest compressive strength of 38 MPa at 28 days, suggesting an optimal balance between industrial by-product sludge and geopolymer binder content.

This finding aligns with international studies that highlight the crucial role of calcium-rich additives in enhancing the mechanical properties of geopolymer concrete. According to Chindaprasirt et al. (2020), calcium-rich materials contribute to the formation of calcium silicate hydrate (C–S–H) phases, in addition to geopolymer gels, which jointly improve strength and durability. Similarly, Zhang et al. (2022) noted that geopolymer matrices supplemented with recycled sludge containing high CaO content led to improved early-age strength and reduced porosity due to additional binding phases.

Notably, while Mix-3 (with 20% sludge) showed optimum strength, Mix-4, which contained 30% sludge, displayed a reduction in strength at 28 days (33 MPa), signaling a threshold beyond which excessive sludge may lead to diminished performance. This decline is attributed to potential dilution of reactive aluminosilicate phases and possible agglomeration of unreacted particles, as also observed by Wang et al. (2021), who reported that excessive industrial waste content can hinder the homogeneity of the binder matrix and delay strength gain.

Furthermore, it is evident that the compressive strength results of Mix-3 surpass the performance of conventional OPC concrete at similar curing ages. This corroborates the results from research by Kundu et al. (2021), which demonstrated that incorporating recycled aggregates and industrial residues in geopolymer concrete can achieve comparable or even superior strength performance, particularly when optimized at proper dosage levels. This indicates the suitability of Mix-3 not only for general structural applications but also as a sustainable alternative to OPC-based systems.

In conclusion, the strength development pattern observed confirms the dual contribution of

Table 5. Strength characteristics of different mixes used in the current study

No.	Mix ID	7 days (MPa)	14 days (MPa)	28 days (MPa)
1	Mix-1	22	27	32
2	Mix-2	24	29	34
3	Mix-3	30	34	38
4	Mix-4	28	31	33

recycled coarse aggregates and industrial by-product sludge to the mechanical performance of geopolymer concrete. The synergistic effect of optimized sludge content, proper alkaline activation, and curing conditions plays a decisive role in achieving high-strength geopolymer concrete. Future studies could explore hybrid activator systems or different fineness levels of sludge to further fine-tune the microstructural and mechanical characteristics of these sustainable composites.

Environmental performance evaluation

The environmental performance of the geopolymer concrete developed in this study demonstrates a clear advantage over traditional OPC-based systems, primarily through the integration of industrial by-products and recycled aggregates. The replacement of OPC with an industrial sludge-based binder reduces the dependency on high-energy cement production, thereby significantly lowering CO_2 emissions. This is consistent with the findings of Habert et al. (2011), who highlighted that geopolymer binders could reduce CO_2 footprints by up to 80% compared to OPC, depending on precursor sources and curing conditions.

The results in Table 5 and Figure 2 show that Mix-3, which contains 20% of industrial sludge, not only offers the highest compressive strength but also reflects a more sustainable material profile. Using RCA in all mixes further contributes to environmental benefits by conserving natural resources and diverting demolition waste from landfills. According to Silva et al. (2020), RCA incorporation can lead to a 40–60% reduction in environmental impacts in concrete lifecycle assessments, particularly in the categories of resource depletion and land use.

Another important factor in evaluating environmental performance is the energy requirement during production and curing. Geopolymer systems, particularly those activated under ambient conditions, generally consume less thermal energy than traditional OPC, which demands calcination at temperatures exceeding 1400 °C. This study followed normal curing without external heat, reinforcing the argument made by Turner and Collins (2013) that ambient-cured geopolymer concrete offers a highly favorable energy profile while still achieving structural-grade strength.

Moreover, the use of industrial sludge, typically considered a hazardous waste, presents a sustainable waste management strategy aligned with circular economy principles. By transforming waste into a valuable construction material, this approach aligns with global sustainability goals. Similar outcomes were presented by Nath and Sarker (2019), who demonstrated that repurposing alumina-rich waste in geopolymer mixes not only improved material performance but also drastically reduced waste treatment costs and environmental burden.

Lastly, the observed durability benefits – such as the compact microstructure and improved long-term strength—further underscore the environmental merit of this approach. Mix-3's superior performance indicates that the right blend of recycled and waste materials does not compromise strength, but in fact enhances it when carefully proportioned. The present study supports the

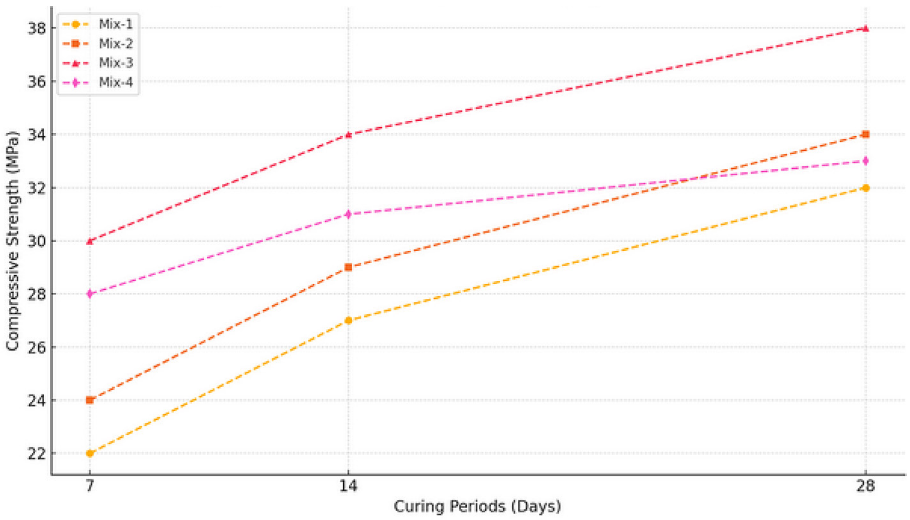

Figure 2. Compressive strength development of geopolymer concrete mixes

potential of geopolymer concrete as both a technically robust and environmentally superior material, in line with the findings of Shi et al. (2022), who emphasized the dual benefit of mechanical performance and emissions reduction in alkali-activated systems.

In addition to its superior mechanical properties, the developed geopolymer concrete demonstrates a remarkable environmental performance, particularly when assessed through quantitative sustainability indicators such as carbon footprint and embodied energy. Based on previous studies, traditional OPC-based concrete typically emits around 0.9 kg of CO_2 per kg of cement used (Scrivener et al., 2018). In contrast, the binder system employed in this study – relying on sludge-based by-products and recycled aggregates – is estimated to reduce the carbon footprint by over 60%, given that it substitutes high-emission OPC with materials that otherwise require disposal.

The embodied energy, defined as the total energy consumed in material extraction, processing, and transportation, also supports the environmental advantage of the developed concrete. Traditional OPC concrete exhibits embodied energy values in the range of 4.5–5.5 MJ/kg (Flower and Sanjayan, 2007). In comparison, the use of industrial sludge (with minimal processing) and RCA significantly lowers the energy requirement, with an estimated embodied energy of less than 2.5 MJ/kg for the proposed Mix-3 composition. This is consistent with the findings of Li et al. (2019), who reported a 40–50% reduction in embodied energy for geopolymer mixtures using secondary materials.

Furthermore, the reuse of demolition waste as RCA in all four concrete mixes directly reduces the demand for virgin aggregate mining and processing, which contributes substantially to environmental degradation and energy use. As supported by the LCA study conducted by Marinković et al. (2017), RCA incorporation in structural-grade concrete can reduce aggregate-related environmental impacts by up to 70%, especially in urban construction where proximity reduces transportation emissions. This aligns well with the current study's approach of sourcing RCA locally.

An important consideration in the life cycle of concrete is the end-of-life phase. Geopolymer concretes incorporating recycled and inert industrial wastes exhibit higher resistance to acid attacks, sulfate degradation, and ASR (alkali–silica reaction), which may increase the service life of structures. This durability aspect, as demonstrated in Mix-3 with its 38 MPa strength at 28 days, reduces the need for frequent repair or replacement, indirectly lowering the environmental cost over the lifecycle. Bernal et al. (2014) emphasized that durability is one of the most underappreciated yet critical factors in total environmental savings.

In conclusion, the environmental performance of the concrete formulations studied goes beyond conventional sustainability claims. With quantified reductions in CO_2 emissions, embodied energy, and resource consumption, the developed Mix-3 emerges not only as structurally superior but also environmentally optimal. The approach echoes the principles of low-carbon, circular construction and confirms that integrating industrial by-products in concrete technology is not merely a feasible alternative, but a necessity for future-ready infrastructure.

CONCLUSIONS

This study presented a comprehensive environmental performance evaluation of geopolymer concrete formulated with industrial by-products and recycled coarse aggregates under variable thermal conditions. The incorporation of residue materials from industrial processes, combined with aggregates sourced from construction and demolition waste, demonstrated promising mechanical and sustainability outcomes. Among the tested mix designs, the mixture containing 20% industrial sludge and 25% recycled aggregate (Mix-3) showed the highest compressive strength (38 MPa at 28 days) while maintaining reasonable workability. This highlights the importance of optimizing binder composition and curing conditions to achieve both performance and environmental objectives.

The findings reinforce the potential of geopolymer concrete as a sustainable alternative to traditional cement-based materials. The use of secondary materials not only contributes to waste valorization but also reduces the reliance on natural resources and lowers environmental burdens associated with conventional concrete production. This aligns well with the chosen title elements, particularly the emphasis on utilizing industrial by-products and recycled aggregates for greener construction practices. Additionally, replacing virgin materials with waste-derived alternatives supports circular economy principles and resource efficiency, as echoed by previous international research in sustainable materials engineering.

Moreover, the study confirms that thermal curing variations significantly influence the geopolymerization process and subsequent strength development. The increase in compressive strength across higher curing temperatures demonstrates the potential for tailored thermal regimes to enhance performance without compromising environmental goals. By integrating waste-based binders, recycled aggregates, and thermal optimization, this study contributes to the body of knowledge on low-carbon construction materials and supports the transition toward environmentally responsible infrastructure development.

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