Mechanical and Microstructural Characterization of Cold-Bonded Geopolymer Aggregates from Industrial and Agricultural By-Products for Sustainable Concrete Applications – Pages 63-77

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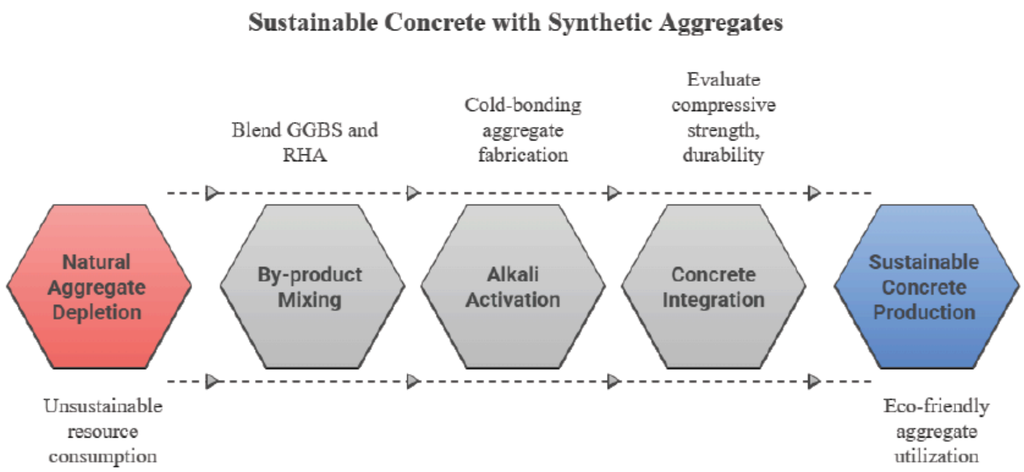
Abstract: The exhaustion of natural resources increases the demand for sustainable substitutes for use in concrete production is becoming prevalent. The present research evaluated the eco-production of synthetic aggregates by means utilizing industrial and agricultural by-products which are, ground granulated blast furnace slag (GGBS) and rice husk ash (RHA). The synthetic aggregates were developed by means of cold-bonding methods. By eliminating the high-temperature sintering stage typical of conventional lightweight aggregate production, the cold-bonding process achieves up to 90–95% energy savings and an estimated reduction of approximately 75 kg CO_2 per ton of aggregate and divert up to 1.2 tons of industrial/agricultural waste per ton of aggregate produced. The developed aggregates were used in concrete and workability was evaluated through slump test, and compressive strength was evaluated at 7, 14, and 28 days. The findings revealed that the optimum density, ideal strength and adequate microstructural characteristics were derived from using 90% GGBS and 10% RHA. This research emphasizes an eco-friendly alternative in the production of aggregates and provides practical strategies in conventional materials for sustainable concrete applications which ultimately replaces the construction practices into greener processes.

Graphical abstract



Keywords: Circular Economy, Waste Valorization, Low-Carbon Concrete, Geopolymer Aggregates, Cold-Bonding, Sustainable Construction, Industrial By-Products.

1. INTRODUCTION

Globally concrete is the most prevalent construction material, and its usage is projected to grow due to ongoing urbanization and infrastructure expansion. Coarse aggregates account for 60-70% of the concrete volume and are the most important concrete component in relation to the concrete's strength, durability, and structural performance. The aggregates are traditionally natural and are obtained from quarries and riverbeds. Unfortunately, this continued extraction of natural aggregates raises serious environmental concerns, resource depletion, and land use concerns that ultimately are unsustainable [1, 2]. Aggregate extraction and mining on the scale currently applied, destroys habitat, contributes to soil erosion, and uses more energy than any other element used in concrete, so it is critical to search for alternatives for the aggregates.

Simultaneously, the industrial and agricultural operations produce massive amounts of solid waste, a lot of which is underutilized or sent to landfills that can pose harmful environmental impacts. Ground Granulated Blast Furnace Slag (GGBS) is a by-product of the steel industry, while Rice Husk Ash (RHA) is a by-product from rice milling and they are both commonly produced in significant quantities in multiple sectors. GGBS and RHA have high concentrations of

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reactive oxides, such as silica and alumina, and therefore have potential applicability for use in cementitious and geopolymeric systems. Valorising of such waste supports circular economy development and sustainable construction practices while reducing impact on natural resources [1-3].

Geopolymer technology is a new form of technology that can be considered as a sustainable alternative to normal Portland cement (OPC) based on using aluminum silicate rich precursors activated with alkaline solutions that form binding gels. Th cold-bonded geopolymer aggregates (synthetic aggregate) can be produced at ambient temperatures. Geopolymer aggregates have a potentially significant energy-saving benefit relative to producing traditional sintered aggregates and can have significantly reduced carbon footprints for adapting them to everyday uses. With proper design, these geopolymer aggregates can be used to reliably provide the same physical and mechanical properties as natural aggregates, but with added functionality, such as similar to lower densities and improved durability. This presents a unique opportunity to address waste management issues as well as build construction sustainability [2, 3].

Unlike sintered lightweight aggregates that require firing at 800–1200 °C, the cold-bonding process relies on ambient-temperature geopolymerization to form mechanically robust aggregates, drastically reducing energy consumption and associated greenhouse gas emissions. This low-carbon process contributes to an estimated CO_2 reduction of approximately 75–80 kg per ton of aggregate, compared with traditional fired methods, while diverting significant waste volumes from landfills. Thus, the cold-bonding technique aligns strongly with the principles of the circular economy, advancing low-carbon, resource-efficient concrete technologies. Past studies have shown potential for synthetic aggregates made with fly ash, metakaolin, and other industrial by-products. However, limited studies have reported on the combined use of GGBS and RHA together, to some extent. GGBS provides calcium, alumina, and reactive silica which will help with strength and the geopolymers activation speed, while RHA provides the high silica content, which can refine pore structures in addition to providing improved durability. The two materials have been combined and activated with sodium hydroxide and sodium silicate for the production of aggregates that possess structural integrity and environmental worth; nevertheless, currently, there appears to be limited studies on the impact that different GGBS–RHA ratios may have on aggregate properties and concrete performance which represents a gap in knowledge that this study will address [1, 4-6].

The main goal of this research was to develop synthetic aggregates using varying proportions of GGBS and RHA through cold bonded geopolymerization, and determine their viability as natural aggregate substitution in concrete. The aggregate properties of specific gravity, bulk density, water absorption, impact resistance, and crushing value were systematically tested. Concrete cubes were prepared using synthetic aggregate by partially replacing natural aggregate. Workability and compressive strength were tested at 28 days. The study examined the most successful mix design and provide a preliminary assessment if these waste-derived aggregates were appropriate for use in structural concrete [7, 8].

The importance of this study not only from demonstrating technical feasibility but also from advancing sustainable practices in construction. The method successfully turns two waste streams into applicable construction products, thereby minimizing the use of virgin aggregates; decreasing total carbon dioxide emissions from processing materials; and reducing impacts on landfill, ecological conservation is increased in the long usage span. The use of lightweight synthetic aggregates in structural concrete also has added practical benefits in that it has a lower dead load and increased efficiencies in high rise and precast construction. Thus, this study contributes significantly to both green and environmental concerns with a potentially usable alternative material that meets structural requirements.

2. MATERIALS AND METHODS

To successfully produce synthetic aggregates and utilize them in concrete requires an involved experimental procedure, which commences with the selection of raw materials, preparation of binder solutions, and proportioning of the various constituents, and ends with the evaluation of physical, mechanical, and microstructural properties. This study utilized a systematic method that incorporated the lab-based synthesis of synthetic aggregates with standards for aggregate testing, and also the preparation and testing of concrete cubes with various proportions of natural and synthetic (and combinations of the two) aggregates. The cold-bonding process was employed to produce geopolymer aggregates under ambient conditions, thereby eliminating the need for high-temperature sintering. In contrast to conventional sintered aggregates that consume approximately 3.5–4.0 GJ of energy per ton, the cold-bonding method requires only minimal mixing and curing energy (≈0.2–0.3 GJ/ton), representing an energy saving of around 90–95%. This makes the process inherently low-carbon and suitable for large-scale sustainable production. The following section describes the materials used, the method for producing the aggregates, and the method of testing.

2.1. Raw Materials

The raw materials chosen for synthetic aggregate production were GGBS, RHA, and alkaline activators, more specifically sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). In addition, Ordinary Portland Cement (OPC), manufactured sand (M-sand), natural coarse aggregates, and potable water were used, in the preparation of concrete cubes to evaluate performance. GGBS is a by-product that results from iron production in a blast furnace. The GGBS was obtained from a local steel plant, was then dried to saturated surface dry (SSD) condition before use. The GGBS was substantially ground to have a specific surface area more than 350 m²/kg, as required by standards. In addition to satisfactory specific surface area, the GGBS was properly angular in shape and off-white in color; therefore, it was more than adequate to use as a precursor in a geopolymerisation reaction. Table **1** presents the physical properties of GGBS while Table **2** includes the chemical compositions of GGBS.

Table 1: Physical Properties of GGBS

Physical properties	Characteristics
Particle size	9.2 micron
Particle shape	Angular
Colour	Off-white
Specific gravity	2.9
Bulk density	1000-1300 kg/m3
Fineness	>350 m^2/kg

Table 2: Major Chemical Composition of GGBS

Chemical composition	Percentage (%)
CaO	40
SiO_2	35
Al_2O_3	13
$Mg(OH)_2$	8

Rice husk, an agricultural by-product, was collected from a local rice mill. The husks were burnt under controlled conditions to obtain ash with high silica content. To ensure uniform particle size, the RHA was sieved through a 600 μm sieve to remove unburnt residues. The physical properties of RHA are summarized in Table **3**. The greyish-black ash, with specific gravity ranging from 2.11 to 2.27, was selected for its high pozzolanic reactivity and potential contribution to the geopolymerization process.

Table 3: Physical Properties of RHA

Physical properties	Characteristics
Particle size	600 micron
Colour	Greyish black
Specific gravity	2.11-2.27

For the production of synthestic aggregates, sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) were used together using laboratory grade NaOH pellets which were dissolved in distilled water and made into an 8 M solution at 320 g of NaOH per litre of solution. Sodium silicate solution of silica and sodium oxide was mixed with NaOH at the ratio of 2.5:1 for preparing the geopolymer material as they used similar amounts in their previous studies which found setting proportions for producing geopolymers to give optimum compressive strength of geopolymer systems. The alkaline solution was made 24 hours prior to the mix to allow for complete dissipation and stabilisation of temperature.

53-grade OPC was used as the primary binder in the concrete mixes. Manufactured sand (M-sand) was used as the fine aggregate because it is manufactured by crushing rock, giving the range of angular particle shape, consistency of quality, and less damage to the environment compared to river sand. Natural aggregates were used for the control coarse aggregate, and synthetic geopolymer aggregates were the experimental variable. Potable water, free from any organic impurities, was used for mixing and curing the geopolymer specimens.

2.2. Preparation of Synthetic Aggregates

The synthetic aggregates were produced through cold bonding geopolymerization. Initially, the dry powders of GGBS and RHA were weighed in proportions of 95:5, 90:10, and 85:15 (by weight) is demonstrated in Table **4**.

Table 4: Proportioning of Raw Material for Synthetic Aggregate

Sample ID	GGBS (%)	RHA (%)	L/B
SA1	95	5	0.37
SA2	90	10	0.37
SA3	85	15	0.37

The dry powders were mixed together in a mortar mixer at 120 rpm for two minutes to achieve uniformity in the mixture. After 2 minutes, the alkaline solution (NaOH + Na_2SiO_3) was slowly added by maintaining the liquid to binder ratio (L/B) as 0.37, and wet mixing continued for five minutes, until uniformly mixed composites were achieved. The composite was placed in the mixer and underwent palletisation creating spherical aggregates of various sizes. The process of making synthetic aggregate is presented in Figure **1**.

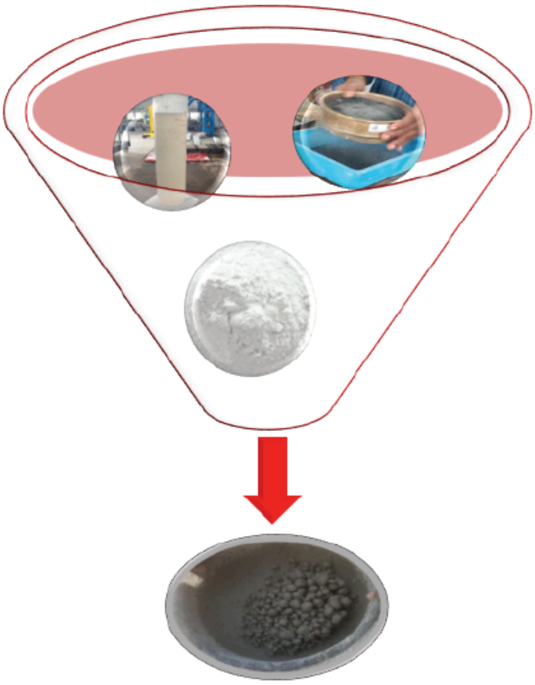


Figure 1: Process of palletisation.

The synthetic aggregates were formed and set for a total time of 24 hours under ambient conditions before curing in an oven at 100 °C for another 24 hours to promote geopolymerization. After the oven curing the aggregates were placed in ambient conditions until future testing [9,10].

2.3. Testing Procedure for Synthetic Aggregates

The synthetic aggregates produced from GGBS and RHA were systematically evaluated for physical, mechanical, and morphological characteristics.

2.3.1. Particle size Distribution of Aggregate

Particle size distribution of synthetic aggregates was measured in accordance with IS2386 (Part 1): 1963. A test portion was taken of approximately 2-3 kg of synthetic aggregates and through oven-drying to 105 °C to remove moisture, was made representative. The sample was placed on the top sieve of a sieve set measuring between 40 mm to 4.75 mm. The sieves were ordered from largest to smallest below the top sieve and then set on a sieve shaker and mechanically shaken for 10–15 minutes to ensure the particles were uniformly placed. The mass of aggregates retained per sieve was weighed, and the cumulative percent retained was calculated and from which a particle size distribution curve was generated to indicate suitability for concrete. The method is reproducible and standardized.

2.3.2. Specific Gravity

The specific gravity of synthetic aggregates was determined according to the IS 2386 (Part 3): 1963 standard. A 500-gram representative dry sample was weighed accurately. The measurement of volume displacement from the aggregates was conducted in a pycnometer, as seen in Figure **2**. FIrst, the pycnometer and water weight was determined. Then, the specific gravity was determined with the aggregates immersed in water in the pycnometer, with all air bubbles removed to avoid measurement error. Then the pycnometer, water, and aggregates total weight was determined and normal specific gravity was calculated using the standard formula where the normal specific gravity is the ratio of the dry weight of the aggregates to the weight of an equal volume of water. Three replicate measurements were conducted in order to obtain reliable values and accuracy [11, 12]. The integration of density and porosity of aggregates lead to a comprehensive understanding of concrete performance.

Figure 2: Specific gravity testing.

2.3.3. Water Absorption

Water absorption was investigated following IS 2386 (Part 3): 1963. The masses W_d of the oven dried samples were taken and then immersed in clean water, at room temperature, for 24 hours [13,14]. After immersion, the samples were surface dried with a damp cloth to remove surface water, without the loss of water in pores. The samples were then weighed again W_w Water absorption percentage was calculated using the equation (1).

$$\text{Water absorption (\%)} = \frac{W_w - W_d}{W_d} \text{ x } 100 \quad (1)$$

This measurement indicates a sample's porosity and internal water storage potential essential for concrete's workability and durability. A minimum of three tests were completed in triplicate to minimally quantitate reproducibility measures.

2.3.4. Bulk Density

Bulk density was measured in accordance with IS 2386 (Part 3): 1963. Oven dried aggregates were poured into a standard cylindrical container with a known volume in three layers. The aggregates were compacted with a tamping rod to remove any voids and the total mass of the aggregates in the container was recorded the bulk density was calculated as mass per volume. This characteristic provides information on the compactness of the aggregates and their weight classification confirming lightweight, intensive measure was repeated three time for ease of reliability.

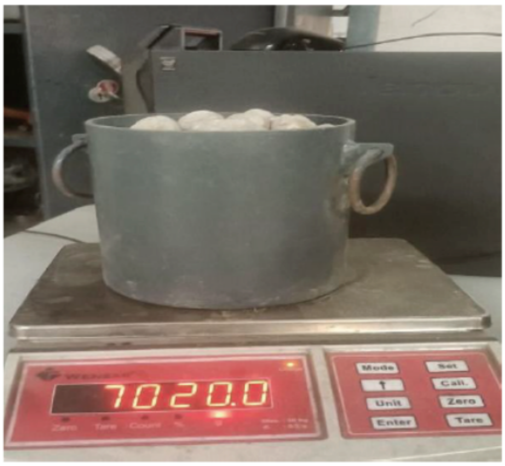


Figure 3: Bulk density testing.

2.3.5. Aggregate Impact Value (AIV)

The Aggregate Impact Value was performed as outlined in IS 2386 (Part 4): 1963, to assess the aggregates' resistance to sudden impact. Oven-dried aggregates that went through a 12.5 mm sieve and was held on the 10 mm sieve were loaded into the cylindrical mould. The assembly was subjected to 15 blows from the standard hammer, dropped from a height of 38 cm. The crushed material was sifted through a 2.36 mm sieve, and the mass of the fraction that passed through the 2.36 mm sieve was weighed. The pre-test and post-test test samples are shown in Figure **4** (a & b). The AIV was formulated as a percentage using the mass of fines through the total sample mass [15]. This test determines toughness and shock resistance, both of which are vital for concrete exposed to dynamic loading.

2.3.6. Aggregate Crushing Value (ACV)

Figure 5: Aggregate crushing test.

The Aggregate Crushing Value (ACV) was carried out in accordance with IS 2386 (Part 4): 1963 to determine mechanical strength under compressive load. Oven-dried aggregates that passed 12.5 mm sieve and retained on 10 mm sieve were placed in a cylindrical steel mould and subjected to compressive loading via a hydraulic compression testing machine. The load was applied gradually to the aggregates until we have 40% of the aggregates passing a 2.36 mm sieve. The aggregate crushing test is demonstrated in Figure **5**. The ACV was calculated to be the ratio between the mass of fines to total mass of the sample, expressed as a percentage [15]. This test determines

Figure 4: Aggregate impact testing **a**) the sample before and **b**) after test.

suitability for structural concrete and as high crushing strength demonstrates better performance under load.

2.3.7. Morphological Characteristic (SEM analysis)

This test is performed to study the morphological characteristics of aggregate particles in detail. The aggregates are first crushed into fine particles to prepare them for microscopic examination. These particles are then oven-dried to remove any residual moisture that could interfere with the analysis. After drying, the samples are placed into appropriate capsules and subjected to Scanning Electron Microscopy (SEM). This advanced technique provides high-resolution images, allowing for detailed observation of the surface texture, particle shape, and microstructural features of the aggregates.

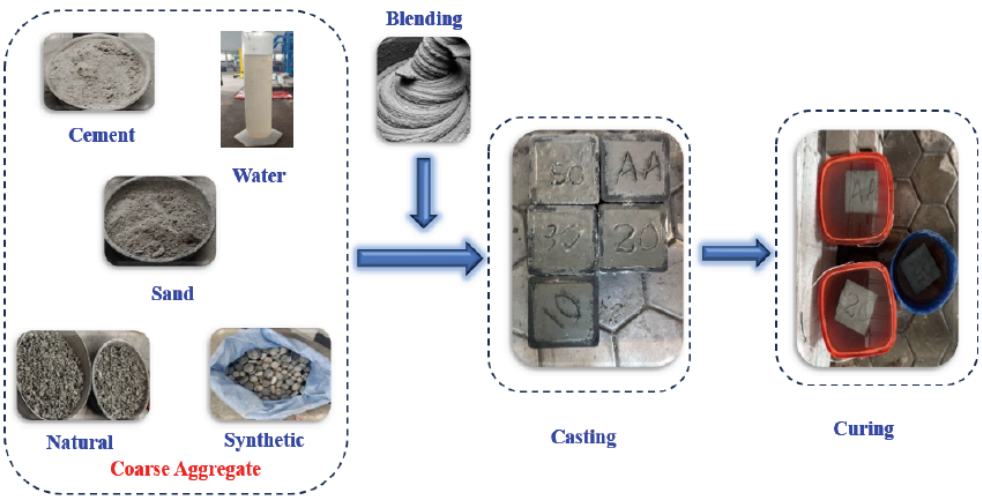
2.4. Preparation of Concrete Cubes

To assess the performance of the optimized synthetic aggregates, concrete cubes were cast in accordance with IS 10262:2019 for mix design with different proportions of synthetic aggregates. Of the combinations studied, the 90% GGBS and 10% RHA combination had the most favourable physical and mechanical properties when compared to others. The optimization was supported using detailed study of each aggregate physical, mechanical and microstructural properties. With this information, the synthetic geopolymer aggregate with a blend of 90% GGBS and 10% RHA, SA2, was presented as the best aggregate to use [8, 16]. Therefore, the optimized SA2 aggregate was utilized in the casting of concrete cubes using the M20 grade presented in Table **5**.

The materials were weighed, combined, mixed and poured into standard cube moulds. The cubes were built up in layers to remove air and get a level surface. After surface finishing and labelling, the cubes were placed in water for a given curing period, and then tested as required. This method developed in evaluating the ability of manufactured geopolymer aggregates in concrete. The mixing method required the cement, M-sand and aggregates to dry blend and progressively add water in a workable mix. The wet concrete was subjected to slump testing, and the standard cube size was determined to be 150 mm × 150 mm × 150 mm (150 mm). They were cast, compacted, surface levelled, and labelled - the process is provided in Figure **6**. After 24 hours, the cubes were removed from the mould and placed in water for curing periods of 28 days.

Table 5: Concrete Mix Proportions with Varying Proportion of Synthetic Aggregates

Mix ID	C	FA	SA	NA
CCN	17	30	0	53
CC0	17	30	53	0
CC1	17	30	47.7	5.3
CC2	17	30	42.4	10.6
CC3	17	30	37.1	15.9
CC4	17	30	26.5	26.5



Figures 6: Material Preparation, Casting, and Curing of Concrete Cubes.

2.5. Testing of Concrete

The fresh and hardened properties of concrete with synthetic aggregates were systematically assessed to check their performance suitability for structural use. Workability was assessed using the slump test following IS 1199: 1959. Freshly mixed concrete was placed in a typical conical slump mould, compacted, and the mould was carefully lifted allowing the concrete to settle as shown in Figure **7**. The vertical subsidence (slump) was measured in order to quantify workability.

Figures 7: Slump cone test.

Hardened concrete properties were assessed by conducting compressive strength tests in accordance with IS 516: 1959. Concrete cubes that were 150 × 150 × 150 mm in size were cast from each mix. The cubes were compacted using a tamping rod. After 24 hours, the cubes were demoulded and cured in water at 27 ± 2°C, until testing at the ages of 7, 14 and 28 days. Compressive strength tests were conducted with the aid of a calibrated compression testing machine with a controlled loading rate. The compression test setup is illustrated in Figure **8**. The results were analysed and compared to conventional concrete to understand the progressive strength development of concrete with synthetic aggregates. Testing at early ages was useful to understand initial binder reactivity and early-age microstructural densification; 28-day tests were pertinent for joint long-term performance and structural applicability. The average of three cubes per mix were reported to minimize variation. This direct testing protocol is representative of the guidelines in Indian Standards, and provides for reliable assessments of fresh concrete and hardened concrete properties, as indicated by compressive strength values confirming that the synthetic aggregate concrete was structurally and durably suited for use in medium-strength reinforced concrete.

3. RESULTS AND DISCUSSION

This experimental program resulted in a large body of data on the physical, mechanical, and morphological characteristics of synthetic aggregates, as well as how concrete prepared with the aggregates would perform. This section will present and discuss the results, commencing with the trial mixer results, followed by the synthetic aggregate characterization, and ending with the performance of concrete cubes. Per usual, each result will be interpreted in the context of previous work with the aim of providing confidence in the validity and originality of our work.

3.1. Physical Properties of Synthetic Aggregates

The synthetic aggregates were characterized by particle size distribution, specific gravity, water absorption, and bulk density.

3.1.1. Particle Size Distribution

Findings from the sieve analysis showed that most of the synthetic aggregates existed in the 20 mm size fraction which was within the grading limits of IS 383:2016 for large aggregates intended for use with concrete [17]. The particle size curve showed the aggregates had a good grading which might provide adequate packing density to reduce the void in concrete.

Figure 8: Testing of concrete cubes.

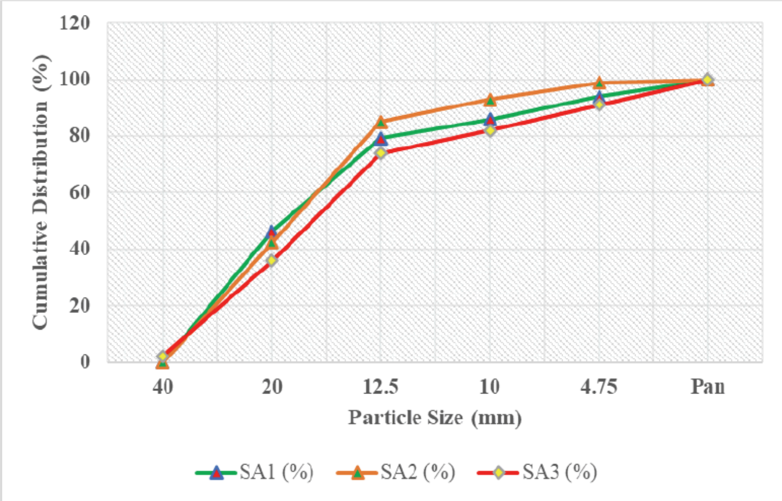


Figure 9: Particle Size Distribution of various synthetic aggregate.

The particle size distribution of three synthetic aggregates (SA1, SA2, and SA3) was analyzed through cumulative percent passing, as illustrated in Figure **9**. All aggregates exhibited a typical gradation curve with particle sizes from 40 mm to pan passing fines. SA2 showed the largest cumulative distribution almost everywhere in terms of particle size and seemed to have a relatively finer and more uniformly graded aggregate compared to SA1 and SA3. At the 20 mm sieve, SA2 cumulatively contained ~45% passing, while SA1 and SA3 slightly less at ~42% and ~36%, respectively. A similar trend was found at the 12.5 mm and 10 mm sieves, with SA2 again being higher, indicating SA2 had the greatest fine faction content. Following the 4.75 mm sieve, all aggregates showed near-total passing (~90 - 98%), suggesting most of the aggregate is generally in specifications for typical concrete grading requirements. In general, when comparing the overall texture of the aggregates, SA3 appeared to contain more coarser aggregates as it showed the least cumulative distribution at all of the coarser sieves, which could impact workability with a concrete mix given it's overall coarser proportion. In summary, the grading is showing that SA2 was very well-graded and should be able to obtain dense packing with in concrete, whereas SA1 and SA3, less so (coarser proportions), and may need to slightly alter mix designs to try to obtain better workability and strength.

3.1.2. Specific Gravity

The synthetic aggregates showed specific gravity values between 1.98 and 2.37 while the natural granite aggregates had a specific gravity value of 2.77 as shown in Figure **10** and the values below, the lesser specific gravity illustrates the value or potential to be used as a lightweight aggregate which will have great value in structural application with negligible direct costs associated with the aggregate weight. For example, when producing concrete for a multi-story building or precast element, the weight reduction from the aggregate can be beneficial to the overall design efficiency.

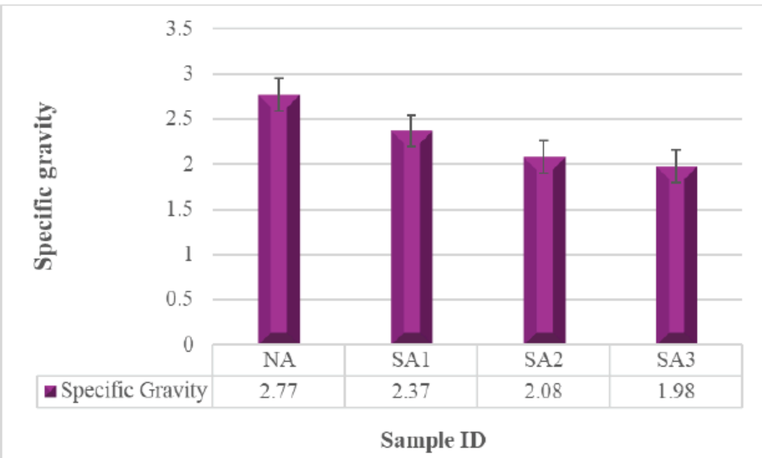


Figure 10: Graph of Specific Gravity Comparison

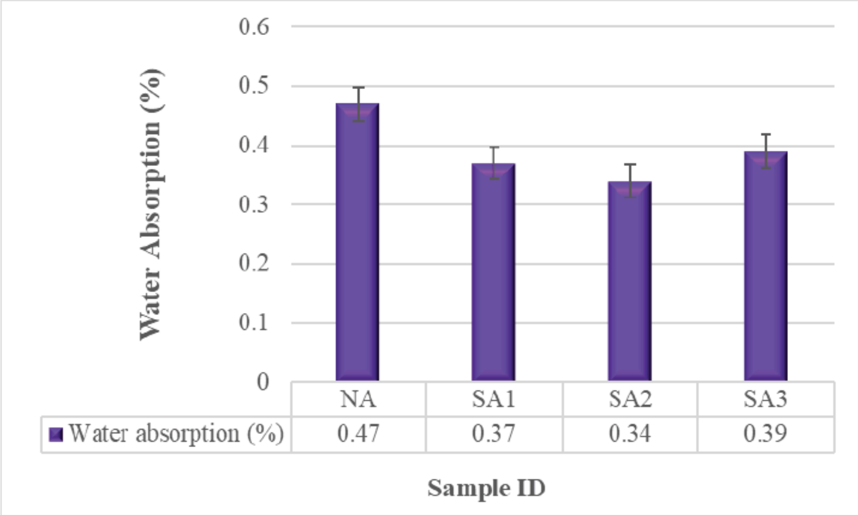


Figure 11: Water Absorption Comparison.

3.1.3. Water Absorption

Water absorption values for synthetic aggregates were between 0.34% to 0.39%, both lower than 0.47% for natural aggregates. This reflects better strength and lower porosity in synthetic aggregates likely due to a successful geopolymerization process and binder phase development. Low water absorption values are preferable as they decrease any additional water requirements needed for mixing and consequently improved durability.

3.1.4. Bulk Density

The bulk density of synthetic aggregates varied between 960 and 1020 kg/m³, significantly lower than the 1630 kg/m³ of natural aggregates, as illustrated in Figure **12**. This also supports the categorization of synthetic aggregates being lightweight. These lightweight properties have practical application in reducing loads on a structure but may alter workability due to modifying the voids between particles within the aggregate itself.

Collectively, the physical property results suggest that GGBS–RHA synthetic aggregates are lighter yet structurally competent alternatives to natural aggregates. These findings echo earlier studies on lightweight geopolymer aggregates, which also highlighted reduced density and adequate performance.

3.2. Mechanical Properties of Synthetic Aggregates

The mechanical strength of aggregates is a critical parameter that determines their ability to resist crushing and impact during handling, mixing, and service. Two tests, such as aggregate impact value (AIV) and aggregate crushing value (ACV), were conducted in accordance with IS 2386.

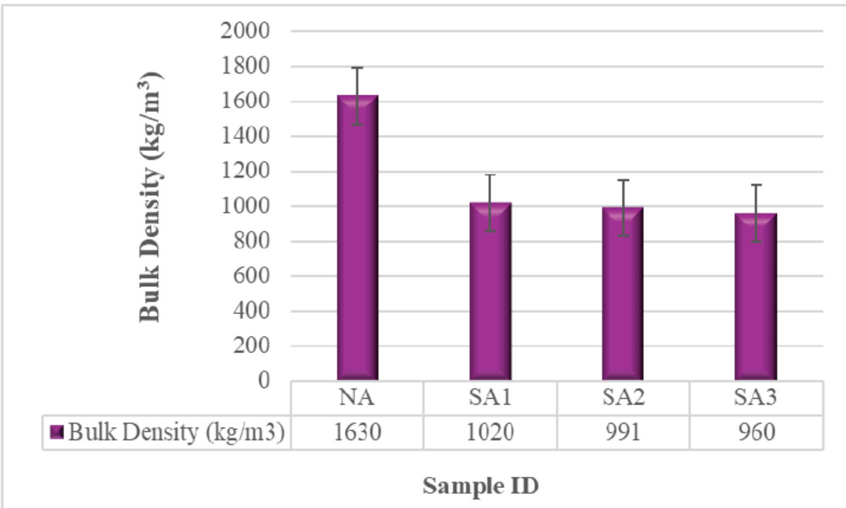
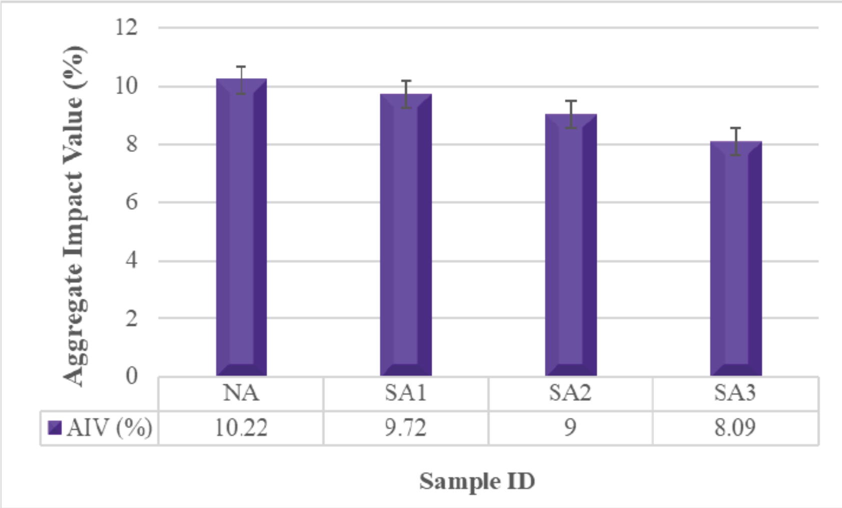


Figure 12: Bulk Density Comparison.



Figures 13: Impact Test Observations.

3.2.1. Aggregate Impact Value (AIV)

Synthetic aggregates were indicated as having an impact value of < 10 %, while natural aggregates had an impact value of 10.22 %_. And according to IS classification, an aggregate having an AIV of <10 % are considered to be very strong, even suitable for heavy-duty concrete pavements as shown in Figure **13**. Their performance is due to a geopolymeric gel matrix, which binds particles in the aggregates firmly, resulting in resistance to sudden impact loads [18-20].

3.2.2. Aggregate Crushing Value (ACV)

Synthetic aggregates had an ACV between 25.03% and 26.88%, whereas the ACV of the natural aggregates was 17%, as indicated by Figure **14**. While higher, these values remained acceptable limits for structural concrete per existing codes [18-20]. The small decrease in crushing resistance can be explained due to the porous nature of the microstructure of the RHA-based binder, but the compressive strength of the concrete was not affected significantly.

Overall, although synthetic aggregates may exhibit lower values for crushing resistance than natural granite, the impact resistance of synthetic aggregates offsets this limiting property so that it may be acceptable in a structural concrete application.

3.3 MORPHOLOGICAL CHARACTERISTICS-SEM ANALYSIS

The Scanning Electron Microscopy (SEM) analysis was carried out to examine the microstructure of natural aggregate and artificial geopolymer aggregates (NA, SA1, SA2, and SA3). In the natural aggregate sample, the SEM images reveal a well compacted matrix formed by multiple bonded particles. In contrast, the artificial geopolymer aggregates exhibit a more uniform distribution of materials.

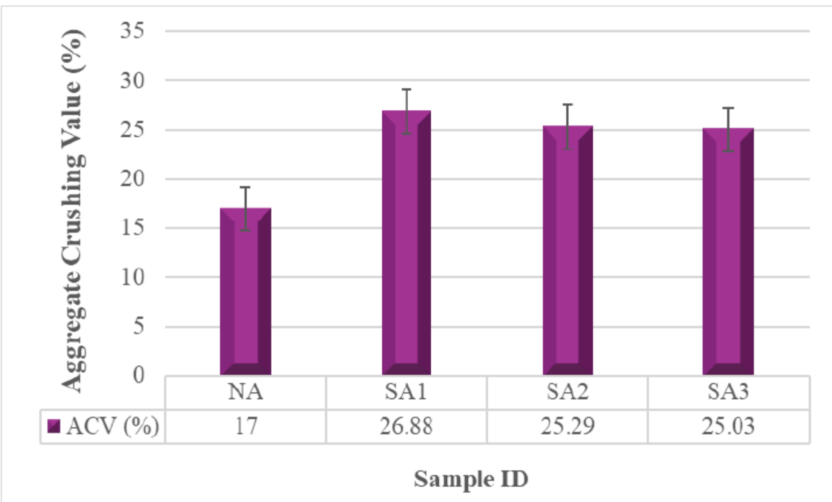


Figure 14: Crushing Value Graph.

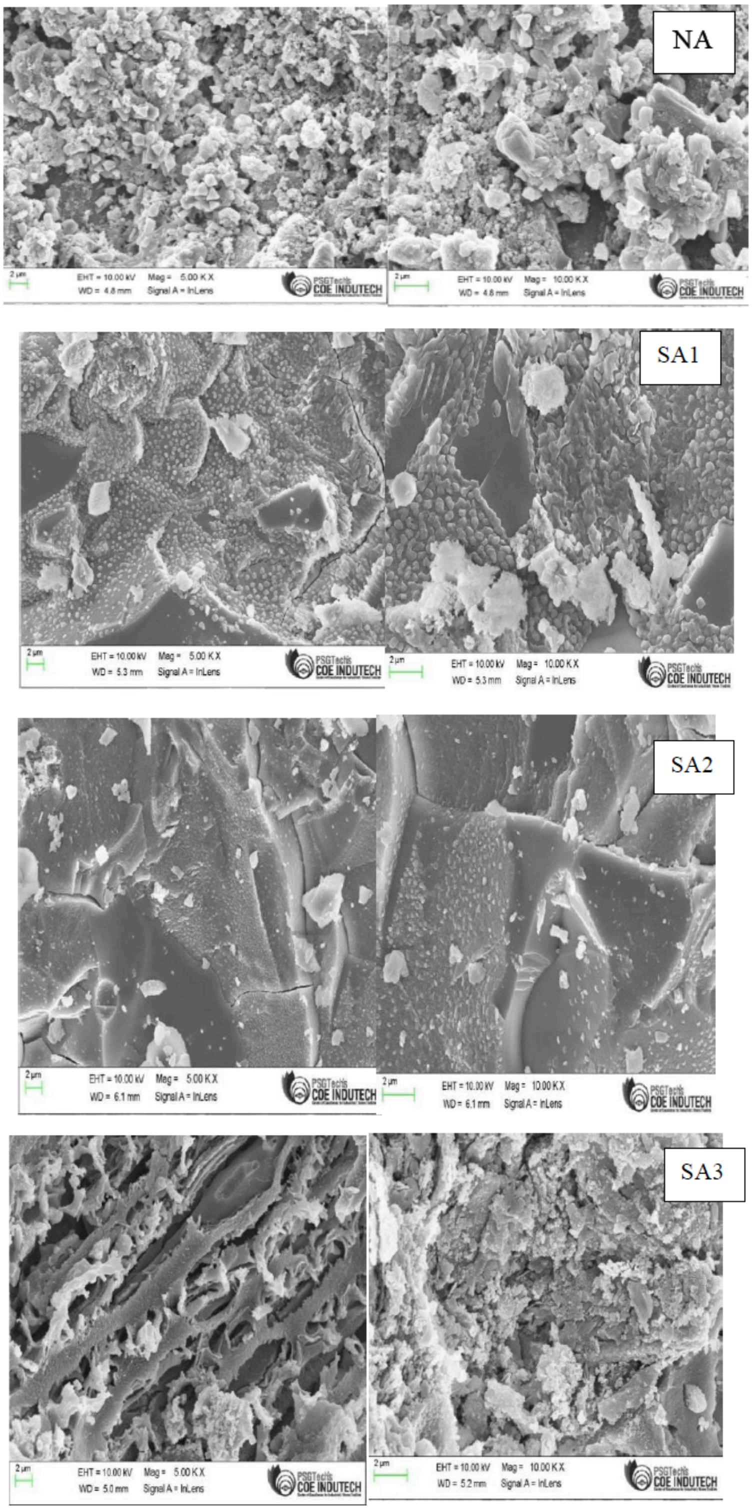


Figure 15: SEM image natural aggregate (NA), SA1, SA2 and SA3 respectively.

The images also provide insight into the porosity and binder formation within the samples. SA1 and SA2 samples appear to contain fewer aggregate particles and show minimal to no visible pores, indicating a denser structure. In comparison, SA3 contains a higher amount of aggregate material, likely due to its increased rice husk ash content. Additionally, visible cracks are present in the SEM images of SA1 and SA2, suggesting slight weaknesses in their structure. The presence of white patches across the images is attributed to the binders used during the preparation of the geopolymer aggregates. Overall, the SEM analysis effectively illustrates the internal structure, material distribution, and bonding characteristics of both natural and artificial aggregates. While the current study focuses on SEM-based morphological assessment, future work will incorporate X-ray Diffraction (XRD) analysis to identify crystalline and amorphous phases in the geopolymer matrix and further validate the microstructural interpretations.

3.4. Concrete Performance with Synthetic Aggregates

In order to test the practical applicability of synthetic aggregates, concrete cubes were manufactured using various percentages of replacements of natural aggregates (10%, 20%, 30%, 50%, and 100%). The cumulative performance of concrete was evaluated in relation to their workability and compressive strength performance.

The slump for all mixes was reported as being 60 mm, which delivers medium workability. The true slump demonstrated by both the control and experimental mixes indicates that synthetic aggregates did not have a negative impact on the behaviour of fresh concrete. The consistency relates to the relatively low absorption of synthetic aggregates and, thus, minimal variability was created.

The compressive strength test results for the different concrete mixes with various combinations of natural aggregate (NA) and recycled coarse aggregate (RCA) are presented in Figure **15**. The control mix containing only natural aggregate (CCN) achieved a compressive strength of 19.58 MPa. The mix containing only recycled aggregate where NA was 100% replaced with RCA (CC0) had a compressive strength of 23.47 MPa, which was likely impacted by mechanical interlocking, improved hydration due to the pores in the RCA that allows internal curing.

Once again, changing the mix designs revealed that compressive strength improved while partially replacing the NA. The CC1 mix that contained 47.7% RCA and 5.3% NA achieved the highest compressive strength at 24.25 MPa. This suggested that a specific balance of RCA and NA optimizes both microstructural densification and the aggregate Interfacial Transition Zone (ITZ) synergistically. However, compressive strength decreased beyond this optimum amount. The CC2, CC3, and CC4 mixes incorporated incoming RCA, while NA were decreased to 10.6%, 15.9%, and 26.5% respectively, ultimately measuring compressive strengths of 22.68 MPa, 21.1 MPa and 20.5 MPa.

The loss in strength with increased levels of RCA replacement may be related to the fact that recycled aggregates possess poorer mechanical properties than natural aggregates, as well as a greater level of water absorption from the RCA, which could negatively affect the effective water to cement ratio. Adhered mortar on recycled aggregates may also result in weak bonding in the ITZ and ultimately lower strength as well [21, 22].

Based on the research, the general conclusion is that partial replacement of natural aggregate (NA) with recycled aggregate (RCA), especially at approximately 5–10% NA replacement amounts (CC1) provides the best compressive strength performance overall. In most cases, these benefits diminish by increasing the RCA beyond this optimal proportion, and careful control of the RCA within the concrete is essential in order to achieve acceptable structural performance.

4. COMPARATIVE ANALYSIS AND SUSTAINABILITY PERSPECTIVE

The experimental results demonstrate a number of positive features of the synthetic aggregates using GGBS–RHA. They have a lower density with better water absorption, good impact resistance, and equal concrete compressive strength. The lightweight characteristics of the developed aggregates, with bulk densities between 960 and 1020 kg/m³, present significant sustainability advantages in structural applications. The use of such lightweight aggregates can reduce the self-weight of concrete elements by up

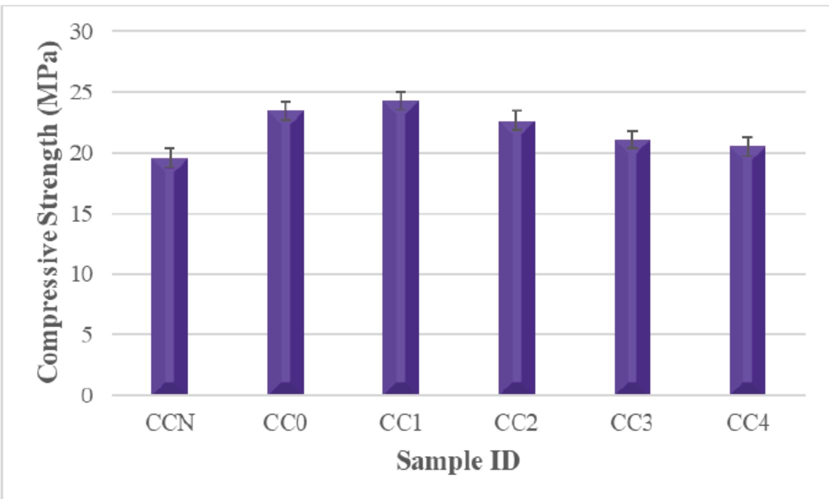


Figure 16: Compressive strength at 28 days.

to 25–30%, leading to 10–15% savings in reinforcement and foundation materials. This cascading benefit contributes to overall material efficiency, reduced embodied energy, and lower transport emissions. Consequently, the adoption of CBGAs can generate system-wide sustainability impacts extending beyond aggregate production to the entire structural design lifecycle.

From a life-cycle perspective, the cold-bonded geopolymer aggregate production process demonstrates significant environmental advantages compared with conventional aggregate manufacturing. Preliminary estimates indicate that producing one ton of cold bonded aggregates can achieve approximately 75 kg of CO_2 savings relative to sintered aggregates, primarily due to the elimination of high-temperature firing stages. The process also offers substantial energy reductions of up to 90–95%, as it operates under ambient conditions with minimal thermal input. Furthermore, each ton of cold bonded utilizes roughly 1.2 tons of industrial and agricultural by-products, including fly ash, GGBS, and rice husk ash, effectively diverting these waste materials from landfills while conserving virgin natural aggregates. Collectively, these outcomes illustrate the strong alignment of coldbonded with the principles of the circular economy and low-carbon construction, demonstrating their potential to contribute to waste minimization, resource conservation, and carbon footprint reduction. Incorporating such aggregates into concrete production presents a scalable and sustainable pathway toward carbon-neutral infrastructure development [23,24].

5. CONCLUSION

This research investigated the feasibility of producing artificial aggregates through geopolymerisation using RHA, and GGBS, supporting two purposes: firstly, the depletion of natural aggregates; secondly, the management of industrial, agricultural waste. The results of the investigation showed that the derived aggregate can be used in structural concrete, without any detriment in strength or workability, and demonstrated suitable physical and mechanical properties.

The results showed the performance of the aggregates depended heavily on the amount of RHA used which reduced compressive strength because of its porous structure and slower reaction kinetics, but moderate amounts, especially with the SA2 mix (90% GGBS + 10% RHA) had shown the most success. After 28 days of curing, the SA2 aggregate had a compressive strength of 30.25 MPa and was comparable with conventional concrete at 30.47 MPa. It is clear that a carefully proportioned GGBS-RHA aggregate blend could achieve similar structural performance to that of natural aggregates.

The key outcomes of the research can be summarized in points as follows:

- Optimized mix ratio (SA2) had hybrid strength, lower density, improved sustainability
- Bulk density values of 960 kg/m³ - 1020 kg/m³ and specific gravity from 1.98 to 2.37 indicated lightweight synthetic aggregates.
- Water absorption was generally lower than natural aggregates (0.34 – 0.39% vs. 0.47%) indicating dense microstructures and increased related durability potential.
- Impact resistance was fantastic, aggregate impact value was well below 10%, while crushing strength values (25 – 27%) were within limits.
- Fresh concrete workability was unchanged, slump values remained consistent around 60 mm for all mixes, compressive strength agreed with natural aggregate concrete at all curing times.

These findings have notable sustainability benefits. The use of industrial by-products, such as GGBS, and agricultural residues, such as RHA, diverts waste from landfill, reduces quarrying of natural aggregates, and lowers the carbon emissions associated with high-temperature aggregate manufacture. Furthermore, the lightweight nature of these aggregates; makes them attractive in applications where reduced dead load is desirable for reducing substructure size, such as high-rise buildings, precast elements and infrastructure.

In future studies, the durability of these materials should be investigated further through long-term durability studies that include aggressive exposure conditions (*e.g.*, sulphate attack, freeze–thaw cycles, chloride ingress, and alkali–silica reactivity). Life-cycle assessments and cost–benefit analyses on a larger scale will further clarify the economic and environmental potential of the materials. Advanced characterization approaches such as X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), and thermal gravimetric analysis (TGA), might deepen understanding of the mechanisms of reactions and contribute to engineering scale residue use. The use of other potential residue sources, for example, red mud and bagasse ash among others, also has the potential to broaden the applicability of the method.

Beyond the technical performance, the process embodies the principles of waste valorization and circular resource use, effectively converting industrial and agricultural residues into valuable construction materials. Looking ahead, the findings contribute directly to the advancement of global sustainability goals, particularly UN SDGs 9 (Industry, Innovation, and Infrastructure), 11 (Sustainable Cities and Communities), and 12 (Responsible Consumption and Production). The continued optimization and scaling of such cold-bonded geopolymer systems can play a transformative role in the transition toward low-carbon and resource-efficient construction.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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