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Development of sustainable cementitious composites using agricultural waste and seashells

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This study investigates the development of sustainable cementitious composites by partially replacing ordinary portland cement (OPC) with agricultural waste ashes such as rice husk ash, groundnut shell ash, coconut shell ash, and bamboo leaf ash, along with seashell ash. The aim is to minimize environmental impact and promote low-carbon construction practices. The raw materials were cleaned, calcined, and characterized using XRF and FESEM analyses to assess their chemical composition and microstructure. Experimental results revealed that a 70% OPC and 20% agro-waste + seashell ash blend exhibited optimal performance, achieving a 28-day compressive strength of 0.71 MPa and a tensile strength of 0.507 MPa, suitable for non-structural applications such as paving blocks and tiles. The high silica and calcium oxide content enhanced pozzolanic reactivity and matrix densification. These composite reduced CO_2 emissions by up to 15%, provided effective waste valorization, and offered cost efficiency. The findings highlight its potential as an eco-friendly, sustainable alternative to conventional cement for future green infrastructure.

Keywords: Agricultural waste, Cementitious composites, CO_2 emission reduction, Pozzolanic materials, Seashell ash, Sustainable construction

Introduction

Cement has been a fundamental binder in concrete and other construction-related applications for nearly two centuries. Over this period, its usage has grown immensely due to the increasing demand for infrastructure, urbanization, and industrialization. However, this growth has led to substantial environmental challenges. Cement manufacturing is currently responsible for 8-10% of global CO_2 emissions, a figure that highlights the severity of its contribution to climate change. Projections indicate that as cement demand continues to rise, the associated CO_2 emissions will further escalate, creating a critical need for alternative and sustainable construction materials. Reducing the environmental burden of cement production requires the incorporation of agricultural and industrial by-products into cementitious systems, providing not only waste management solutions but also eco-friendly construction practices[1].

In recent years, there has been a significant push toward developing sustainable construction materials that mitigate the adverse environmental impacts of traditional building practices. One widely explored strategy is the partial replacement of cement with ashes derived from agro-wastes, including rice husk ash, corn cob ash, palm oil fuel ash, bamboo leaf ash, wood waste ash, groundnut shell ash, sugarcane bagasse ash, and coconut husk ash[2]. These agro-wastes, generated in millions of tonnes annually, are often disposed of through landfilling or open burning, which further exacerbates environmental degradation. By utilizing these wastes in construction, not only are disposal issues resolved, but greenhouse gas emissions linked to cement production are also significantly reduced. The pozzolanic properties of these materials improve concrete performance while simultaneously reducing the reliance on energy- and carbon-intensive cement[2].

Agro-industrial wastes such as silica fume (SF), ground granulated blast furnace slag (GGBS), rice husk ash (RHA), bagasse ash (BA), fly ash (FA), and coconut-based waste ash (CBWA) are particularly promising due to their high silica content. Over integration into cementitious composites over the past few decades has demonstrated multiple advantages.

These include enhanced strength, durability, and resistance to environmental degradation, reduced construction costs through lower cement consumption, and environmental benefits achieved by curbing CO_2 emissions[3,4]. In addition, the incorporation of these materials aligns with circular economy practices by creating value from wastes that would otherwise contribute to pollution.

In addition to conventional cement-based systems, alkali-activated binders (AABs) have emerged as viable low-carbon alternatives. Alkali activation enables industrial and agricultural wastes to transform into cementitious compounds with minimal ecological impact. The fresh properties of alkali-activated systems such as setting time, workability, and temperature requirements can be tailored to specific applications by adjusting mix design and processing conditions. Alkali-activating materials (AAMs), including sodium hydroxide (NaOH), sodium silicate (Na_2SiO_3), potassium hydroxide (KOH), calcium hydroxide ($Ca(OH)_2$), and sodium carbonate (Na_2CO_3), provide the necessary alkaline environment for polymerization reactions, yielding low-carbon binders[5]. Despite their potential, the practical adoption of AABs faces challenges, such as handling corrosive and viscous alkaline solutions and the need for heat curing to accelerate reactions. Ongoing research into blended alkaline solutions and ambient temperature curing methods aims to overcome these barriers and enhance industrial feasibility.

Globally, approximately 2.01 billion tonnes of waste and 4.1 billion tonnes of cement are produced annually, with projections showing steady growth in both sectors. Nearly 44% of this waste originates from agricultural and the food industry, while 56% comes from industrial and miscellaneous sources[6]. Agricultural activities alone generate massive quantities of residues each year, such as 70 million tonnes of rice husk ash, 40 million tonnes of olive mill waste, 45 million tonnes of sugarcane bagasse ash, and 30.5 million tonnes of corn stalk ash[7]. These figures highlight the immense potential of utilizing such residues as supplementary materials in cementitious composites. By integrating agro-waste into construction, industries can effectively reduce landfill burdens, improve waste management practices, and reduce environmental footprints[8].

Moreover, research indicates that combining agro-waste with chemical admixtures or employing specialized production techniques can significantly enhance the mechanical and durability properties of the resulting composites. For example, blending rice husk ash with sugarcane bagasse ash has demonstrated synergistic improvements in compressive strength and durability. This has led to the increasing recognition of high-performance concrete (HPC), which incorporates agro-waste materials to achieve superior performance in terms of strength, durability, and resistance to chemical attacks[9]. HPC also demonstrates lower embodied energy and environmental impacts compared to conventional concrete, further promoting its adoption in sustainable construction.

The widespread availability of agro-industrial wastes makes them suitable for diverse construction applications. These materials can be effectively employed in non-structural applications such as footpaths, plastering, interlocking pavers, and grouting. When available in larger quantities, agro-waste can also be integrated into structural applications through alkali-activated systems or partial replacement of natural aggregates, enhancing mechanical strength and durability[10]. These approaches not only provide cost savings but also contribute to low-carbon construction technologies, aligning with global sustainability goals.

The increasing demand for cement in construction has led to rising CO_2 emissions, necessitating the search for sustainable alternatives. Agricultural and industrial by-products such as rice husk ash, sugarcane bagasse ash, groundnut shell ash, and coconut shell ash exhibit strong pozzolanic properties, making them promising partial replacements for cement. Seashells, rich in calcium carbonate, provide additional cementitious benefits when calcined. Together, these wastes enhance strength, durability, and sustainability of concrete while addressing waste disposal challenges. This study demonstrates that integrating agro-waste and seashells into cementitious composites significantly reduces environmental impact and supports the development of eco-friendly, cost-effective construction materials.

Experimental Section

Raw materials

Agricultural Wastes

Agricultural residues such as rice husk, groundnut shells, coconut shells, and bamboo leaves (Fig. 1a-d) were selected owing to their high silica and alumina content and their proven pozzolanic activity.

- Rice Husk Ash (RHA): Produced through controlled combustion of rice husk[11]. Rich in amorphous silica (85-95%), RHA improves compressive strength, durability, and microstructural integrity of cement[12].
- Groundnut Shell Ash (GSA): Obtained by burning groundnut shells under control conditions. Contains silica, alumina, and calcium oxide, contributing to strength and long-term durability[13].
- Coconut Shell Ash (CSA): Lightweight and porous, CSA improves workability, reduces density, and enhances pozzolanic reactivity through additional calcium silicate hydrate (C-S-H) formation[14].
- Bamboo Leaf Ash (BLA): Rich in amorphous silica (70-80%), BLA improves setting time, chemical resistance, and durability of cement composites[15].

Seashells

Seashells (Fig. 1e) are the waste materials that are rapidly accumulating on seashores and landfills, causing an environmental problem of their own. The utilization of seashells in concrete helps in seashell waste management and in producing cost-efficient concrete[11]. Seashells, primarily composed of calcium carbonate ($CaCO_3$), were collected, cleaned, dried, and calcined at high temperatures to obtain calcium oxide (CaO). Seashell ash improves the binder phase by enhancing hydration reactions and providing additional C-S-H formation.

Ordinary portland cement (OPC)

Commercial OPC (53 Grade) conforming to IS 12269:2013 was used as the primary binder for baseline comparisons.

Preparation of cementitious composites

The preparation of raw materials involved systematic cleaning, grinding, and thermal treatment to enhance their cementitious properties. Agricultural waste washed first to remove dirt and other impurities, followed by drying to eliminate moisture. Similarly, seashells were thoroughly cleaned to remove organic matter and salts. The dried materials were then finely ground using ball mills to increase their surface area and reactivity. To activate their pozzolanic potential, agricultural wastes were calcined in a muffle furnace at temperatures ranging from 600-800°C, producing amorphous silica-rich ash. Seashells were subjected to calcination at 800-900°C, which transformed calcium carbonate ($CaCO_3$) into highly reactive calcium oxide (CaO), a key component in hydration reactions.

For experimental evaluation, optimized mixes were prepared by partially replacing Ordinary Portland Cement (OPC) with agro-waste and seashell ash at proportions of 0%, 10%, 15%, and 20%. A constant water-to-cement ratio of 0.40 was maintained to ensure a balance between workability and strength. Cement mortar cubes were cast in accordance with standard IS specifications and demolded after 24 h. The specimens were then cured in water for 7, 14, and 28 days to study the hydration process and strength

Fig. 1 — Photographs of (a-d) agricultural wastes and (e) seashells

development over time. This systematic methodology ensured reliable testing of the sustainable cementitious composites has shown below Fig. 2.

Characterization of cementitious composite

In this study, comprehensive characterization techniques were employed to analyze the properties of agricultural waste ash and seashell-derived materials before their incorporation into cementitious composites. Chemical composition of cementitious composite was determined using X-Ray Fluorescence (XRF) **(**Make: PANalytical Epsilon3XLE**)** to quantify major oxides such as SiO_2, CaO, and Al_2O_3. Microstructural analysis using Field Emission Scanning Electron Microscopy (FESEM/EDS) (Make: JSM-6390LV; JEOL, Tokyo, Japan) provided insights into particle morphology and elemental distribution. These characterization studies ensured a clear understanding of the materials' pozzolanic activity and suitability as supplementary cementitious components.

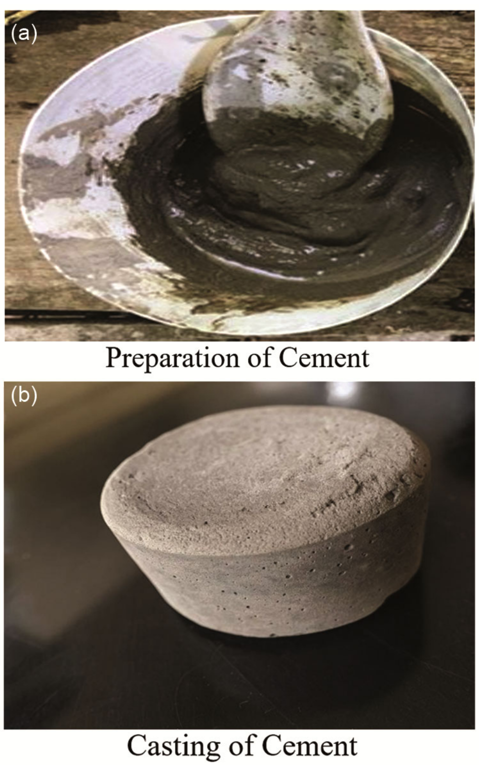

Fig. 2 — Synthesized sustainable cementitious composites using agricultural waste and seashells

Results and Discussion

The present study focused on evaluating the performance of sustainable cementitious composites developed by partially replacing OPC with agricultural waste ashes (rice husk ash, coconut shell ash, bamboo leaf ash, and groundnut shell ash) and seashell ash[15]. Table 1 summarizes the ash formation from agricultural waste. The ash produced from agricultural waste;a groundnut shell, rice husk, coconut shells, bamboo leaves yield% are 26.5%, 22.1%, 23.1%, 28.4%, respectively. The optimized best cementitious composition obtained as 70% Portland cement (OPC) with agro-waste and seashell ash at proportions of 20%. The experimental program included compressive strength, tensile strength, and durability assessments at different curing periods (3, 7, and 28 days). The results provide valuable insights into the mechanical and environmental performance of these composites in comparison to conventional cement[16].

Chemical and physical properties of cementitious composite

Chemical properties

The XRF analysis has been carried for cementitious composite and elemental composition listed in the given Table 2. The cementitious composite prepared with different proportions of agricultural waste + seashells from 10% to 30% and CPC (70%) and these composites are analysed with XRF spectroscopy. The CPC has been derived with various elemental composition is SiO_2, Al_2O_3 and CaO, respectively. It is also observed similar elemental composition for cementitious composites derived from CPC, agricultural waste and seashells, respectively. The % elemental composition has been varied between CPC and cementitious composites. Among all the proportions of cementitious composites, 20% cementitious composites elemental composition are more or less similar to CPC. The similar compositions had been addressed by Rahman *et al*.[16] and Ganesan *et al*.[18]. Thus, a 20% cementitious composite is good for constructions and releases the less CO_2 emissions.

The microstructural characteristics of the cementitious composite containing 70% CPC and

Table 1 — Ash formation details of agricultural materials

Sr. No	Raw materials	Temperature (°C)	Time (h)	Yield (%)
1.	Groundnut shell[15]	650-750	1 to 2 h	26.5
2.	Rice Husk[15]	650-750	1 to 2 h	22.1
3.	Coconut shell[16]	650-750	1 to 2 h	23.1
4.	Bamboo leaves[17]	650-750	1 to 2 h	28.4

Table 2 — XRF analysis of cementitious composite with various proportions of CPC and agricultural waste + seashells

Sample/ Element	%SiO_2	%Al_2O_3	%CaO
Commercial Portland cement (CPC)	92.59	0.30	0.04
CPC-70% and agricultural waste+seashells-10%	84.91	0.09	0.25
CPC-70% and agricultural waste+seashells-20%	90.87	0.09	0.38
CPC-70% and agricultural waste+seashells-30%	89.06	0.12	0.24

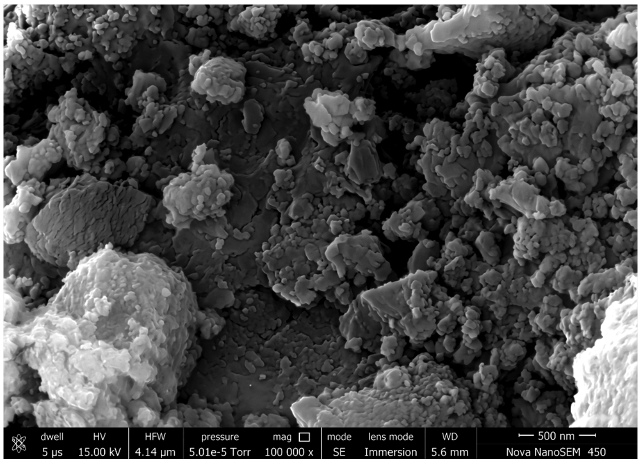

Fig. 3 — Microstructural image of cementitious composites (CPC-70% and agricultural waste+seashells-20%)

20% agricultural waste with seashells were examined using FESEM analysis. As shown in Fig. 3, the composite exhibits a compact and heterogeneous morphology with fine agglomerated particles uniformly dispersed within the cementitious matrix. The incorporation of bio-derived fillers leads to significant densification of the matrix, as evident from the reduced pore volume and fewer visible micro-voids compared to the control CPC sample[16].

Elemental composition analysis of the composite confirms the predominance of silica (SiO_2: 90.87%), followed by minor constituents of alumina (Al_2O_3: 0.09%) and calcium oxide (CaO: 0.38%). The high SiO_2 content is attributed to the presence of agricultural waste materials, which contribute to the formation of a silicate-rich network, enhancing the pozzolanic reactivity within the system. Meanwhile, the CaO derived from seashells acts as a reactive source for calcium silicate hydrate (C–S–H) formation, improving the overall matrix cohesion and strength development[18].

The rough and irregular surfaces of the agricultural waste particles, along with the angular morphology of seashell fragments, facilitate mechanical interlocking and effective load transfer within the composite. These morphological and compositional features collectively contribute to improved particle packing, reduced crack propagation, and enhanced mechanical integrity[18]. Therefore, FESEM and elemental analyses together confirm that the inclusion of agricultural waste and seashells effectively modifies the microstructure, yielding a denser, more homogeneous, and durable cementitious composite.

Physical properties

The compressive strength of cementitious composites increased steadily with curing age, reflecting effective hydration and pozzolanic reactions. At 3 days, the strength was relatively low due to slower hydration of waste-derived materials. However, by 28 days, the composite achieved a compressive strength of 0.71 MPa, which is adequate for non-structural applications such as paving blocks, tiles, and precast units. The improvement over time demonstrates the beneficial role of amorphous silica present in rice husk and bamboo leaf ash, which reacts with calcium hydroxide to form additional calcium silicate hydrate (C-S-H) gel. Similarly, seashell ash, rich in CaO, contributed as filler and provided gradual strength gain. It was observed that replacement levels beyond 30% led to dilution of cementitious compounds, lowering strength. Therefore, an optimum replacement of 20–30% appears most effective[18].

Concrete inherently exhibits lower tensile strength compared to compressive strength. The split cylinder test performed at different curing ages showed a gradual increase in tensile strength, with a maximum of 0.507 MPa at 28 days. This indicates that the composites had sufficient resistance to crack initiation and propagation, which is vital for durability in real applications. The presence of coconut shell and groundnut shell ash was particularly beneficial in enhancing bonding, reducing microcracks[19], and improving dimensional stability. Although the tensile strength remained lower than that of commercial OPC-based concrete, it was acceptable for lightweight, non-load-bearing applications where tensile stresses are minimal.

Effect of agricultural waste ashes

The pozzolanic nature of agricultural waste ashes significantly influenced the performance of the composites. Rice husk ash, with its high amorphous silica content, enhanced microstructural integrity and resistance to chemical attack. Bamboo leaf ash contributed to improved early strength and reduced permeability. Coconut shell ash and groundnut shell ash acted as effective fillers, refining pore structure and reducing shrinkage[20]. Collectively, these materials reduced the overall density of the composites, making them lightweight and suitable for specific construction purposes such as panels, pavements, and blocks.

Role of seashell ash

Seashells, predominantly composed of calcium carbonate ($CaCO_3$), were calcined to obtain CaO, which actively participated in hydration reactions. The addition of seashell ash enhanced long-term strength development and acted as a cost-effective alternative to limestone-based clinker[20]. However, high replacement levels reduced early strength due to delayed hydration. This highlights the importance of optimizing replacement percentages to balance both early and long-term performance. The utilization of seashells also provides an eco-friendly solution to marine waste management, preventing landfill accumulation and coastal pollution.

Environmental and economic implications

Cement production is a major contributor to global CO_2 emissions, releasing approximately 0.9 tons of CO_2 per ton of cement. By partially substituting cement with agricultural waste and seashells, the carbon footprint of the composites was reduced by up to 15%, representing a significant step towards sustainable construction[21]. Moreover, the process provides a dual benefit of waste valorization agricultural residues and seashells, often discarded or openly burned, are converted into high-value materials. Economically, the use of locally available waste reduces raw material and transportation costs, making the composites an affordable option for developing regions[22-25].

Comparison with conventional cement

A comparison between commercial cement and the sustainable composite revealed several advantages. Conventional cement involves extensive mining, higher energy consumption, and significant CO_2 emissions, whereas the sustainable cement utilized local waste, required lower thermal energy, and showed reduced environmental impact[26-27]. Although the strength of the developed composites was slightly lower than OPC-based materials, their performance was adequate for non-structural and semi-structural applications. With further optimization through chemical admixtures or nano-modifications, these composites can achieve even higher strength and durability[28].

The results demonstrate that sustainable cementitious composites have potential applications in tiles, bricks, pavements, partitions, and precast blocks where compressive strength requirements are moderate[29]. Their lightweight nature also makes them attractive for non-load-bearing structures. In addition, the improved thermal insulation properties offered by agro-waste ashes can contribute to energy-efficient buildings[30-32].

Conclusion

The study demonstrated the successful development of sustainable cementitious composites using agricultural waste ashes and seashell-derived materials as partial replacements for Ordinary Portland Cement (OPC). The optimal mix containing 70% OPC and 20% agro-waste + seashell ash exhibited favorable chemical composition, microstructural uniformity, and mechanical performance. A 28-day compressive strength of 0.71 MPa and tensile strength of 0.507 MPa confirmed its suitability for non-structural applications such as tiles and pavers. The pozzolanic reactivity of rice husk, bamboo leaf, coconut shell, and groundnut shell ashes enhanced C–S–H formation, while seashell ash supplied reactive CaO, improving strength and durability. Environmentally, the composites achieved up to a 15% reduction in CO_2 emissions and offered a sustainable waste management solution. Economically, the use of locally available residues reduced production costs. Overall, this approach promotes low-carbon, eco-friendly construction, aligning with global sustainability goals and providing a viable pathway for greener building materials.

Conflict of Interest

The authors declare no conflict of interest.

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