Kashf Journal of Multidisciplinary Research
Vol: 02 - Issue 09 (2025)
P-ISSN: 3007-1992 E-ISSN: 3007-200X
https://kjmr.com.pk

AGRO-WASTE-BASED CEMENT SUBSTITUTION: SYNERGISTIC EFFECTS OF GREEN GRAM POD ASH AND EGGSHELL POWDER ON CONCRETE STRENGTH

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Article Info

Abstract

Cement production contributes nearly 7% of global CO_2 emissions, while the disposal of agricultural and food wastes poses significant environmental challenges. This study explores the use of green gram pod ash (GGPA) and eggshell powder (ESP) as supplementary cementitious materials (SCMs) in concrete. Cement was partially replaced at 5%, 10%, and 15% levels, and specimens were evaluated for slump, compressive strength at 7, 14, and 28 days, and water absorption. Results showed that early-age strength was lower in GGPA–ESP mixes compared to conventional concrete; however, by 28 days, the modified mix achieved higher compressive strength than the control. This improvement was attributed to the synergistic pozzolanic reactivity of GGPA and the calcium-rich composition of ESP. Water absorption results indicated higher initial porosity, though long-term durability is expected to improve with extended curing. The findings suggest that a 10% replacement level provides the most balanced performance in terms of strength, workability, and durability, making GGPA–ESP concrete suitable for sustainable applications. Beyond performance benefits, the approach reduces cement consumption, lowers carbon emissions, and valorizes agro-waste, aligning with circular economy principles. Nevertheless, further research is required on advanced durability properties, microstructural characterization, and life-cycle cost analysis to validate large-scale adoption. This study demonstrates the potential of combining GGPA and ESP as eco-friendly alternatives to Portland cement, contributing to the development of low-carbon, sustainable concrete.

Keywords:
Green gram pod ash (GGPA); Eggshell powder (ESP); Supplementary cementitious materials (SCMs); Sustainable Concrete Technology; Agro-waste valorization; Low-Carbon Construction.

1. INTRODUCTION

Countries everywhere are confronted with serious problems in the disposal of such surplus, such as millions of tons of accumulated agricultural waste. The present study seeks to address sustainable waste management issues through an analysis of agricultural waste incorporation into concrete production. This surge results in increased production of cement clinker characterized by high energy consumption and a substantial increase in CO2 emissions [1]. Concrete is a commonly used construction material, but its high cement content contributes to 7% of global CO2 emissions, releasing 90g of CO2 per 1000g of cement. Recent trends focus on reducing waste and promoting recycled materials for sustainable construction [2, 3]. Cement is valued for its strength and versatility, but its production requires high energy, contributing to significant environmental impacts[4]. To reduce these effects, the construction industry must explore alternative, sustainable materials to traditional Portland cement. One such solution lies in the strategic incorporation of alternative cementitious materials, such as pozzolans [5, 6]. Pozzolanic materials, primarily composed of siliceous or siliceous and aluminous elements, possess the unique ability to react with calcium hydroxide (CaOH2) released during cement hydration, forming essential cementitious properties [7, 8].

Open-field waste dumps create environmental pollution and spread infectious diseases in the air. The presence of rats and worms on an eggshell makes the shell contain organic particles, making them toxic, presenting them as a serious public health problem [9-11]. A lot of eggshell waste is produced by factories, residential areas, poultry farms, egg-laying farms and bakeries [12]. An eggshell contains 94% of calcium carbonate (CaCO3), 1% of calcium phosphate (Ca3(PO4)2), 1% magnesium carbonate (MgCO3) and 4% organic matter, which replaces limestone [13]. Also known as Vigna radiata by scientists, the green gram is widely known as the mung bean in India. Several Indian archaeological sites have provided evidence of carbonized mung beans. Mung beans are used not only as food but also as green manure and fattening stock. Most of this waste is burned and later becomes ash in landfills, thereby damaging the environment. To reduce adverse impacts on both environmental and health of humans, there is a need for black gram pod waste to be utilized as a value-added alternative use rather than being discarded with disregard. GGPA itself contains alumina; therefore, it can precipitate with calcium hydroxide to form additional cementitious materials [14, 15].

To promote sustainable construction, supplementary cementitious materials (SCMs) that partially replace cement while maintaining or enhancing concrete properties [16]. Green Gram Pod Ash (GGPA) and Waste Eggshells, rich in silica and calcium compounds, offer a promising eco-friendly alternative [17, 18]. Utilizing these agricultural and food wastes as SCMs can reduce environmental pollution, enhance mechanical strength, and improve durability. The effects of GGPA and waste eggshells on the mechanical and durability properties of concrete, contributing to the development of sustainable, cost-effective, and high-performance building materials [15, 19].

Table 1. Literature Review

Year	Author	Objective	Methods	Materials / Tools	Conclusions
2025	[16]	Assess sustainability challenges in green buildings and propose solutions.	Thematic analysis using SPSS.	Conceptual framework.	Green buildings can achieve sustainable growth; ROI also requires study.
2024	[15]	Evaluate GGPA as a partial cement replacement for concrete.	Mechanical, durability, and microstructural tests.	GGPA, OPC, aggregates, water.	8% GGPA improves strength, ductility, and sustainability.
2023	[19]	Assess ESP as a cement alternative and predict strength with ANN.	Mix design, mechanical tests, and ANN modeling.	ESP, cement, aggregates, water.	Up to 20% ESP enhances strength; ANN accurately predicts performance.
2022	[7]	Review biomass ashes as SCMs in sustainable construction.	Chemical, microstructural, and durability review.	Rice husk, wheat straw, sugarcane ash, etc.	Biomass ashes (10–20%) improve strength, durability, and sustainability.
2021	[1]	Evaluate spent garnet as a fine aggregate in cold mix asphalt.	Physio-mechanical, microstructural, and toxicity tests.	Spent garnet, asphalt binders.	AG garnet is suitable for CMA; MG garnet is less ideal.
2021	[12]	Assess the Indian cement industry's readiness for sustainability.	Self-assessment, survey, and real-time observation.	Survey data, assessment model.	Industry-ready but needs stronger water-related policies.
2020	[20]	Review ESP concrete performance at various levels.	Literature review of chemical, strength, and durability properties.	ESP, cement, aggregates, water.	10% ESP improves strength and durability; lower chloride/sulfate resistance.
2020	[5]	Assess the readiness of the Indian cement industry for sustainability.	Self-assessment, survey, observation.	Assessment model, survey data.	Industry is prepared but must enhance water-related sustainability policies.

Previous studies on SCMs highlight the potential of agro-waste ashes and eggshell-derived powders in enhancing the mechanical performance of concrete. Agricultural ashes such as rice husk, palm oil fuel ash, and wheat straw ash have demonstrated improvements in strength, ductility, and resistance to chemical attack at replacement levels of 8–20%, while also contributing to a reduction in the carbon footprint of cement production [7, 14, 21-23]. Similarly, ESP, rich in calcium carbonate, has been exhibited to increase early-age strength, reduce permeability, and enhance durability when used as a partial replacement of cement. Research indicates that ESP can substitute up to 20% of cement without significant performance loss [12, 19, 20]. Advanced predictive models such as Artificial Neural Networks (ANN) have also been applied to forecast the strength of ESP-based concrete, further validating its potential as a sustainable SCM [19]. Alongside this, recent studies on eco-friendly concrete demonstrate the role of fly ash, hemp, and other agricultural wastes in optimizing strength and workability for green construction [24, 25], while the use of local resources and clay minerals has been shown to support low-carbon, resource-efficient concrete mixes [26]. Collectively, these findings confirm that valorizing agricultural and food wastes contributes to sustainability while maintaining or enhancing concrete performance.

Despite the wide application of individual SCMs, the combined use of green gram pod ash (GGPA) and ESP remains largely unexplored. GGPA, containing silica and alumina, provides long-term pozzolanic activity, whereas ESP contributes calcium-rich compounds that complement pozzolanic reactions [15, 27]. However, no standardized mix design has been developed for this combination, and limited evidence exists on their synergistic behavior. Most prior research has emphasized short-term mechanical properties, with less attention to durability factors such as chloride resistance, carbonation, sulfate attack, or freeze–thaw cycles [19, 28, 29].

Addressing these gaps, the present study sets out three objectives: (i) to assess the mechanical performance of concrete including GGPA and ESP as partial cement replacements, (ii) to establish the optimal replacement levels for balanced strength, workability, and durability, and (iii) to explore their potential as low-cost, eco-friendly SCMs for sustainable construction. The significance of this research lies in reducing reliance on Portland cement, diverting agro-waste from landfills, and lowering CO_2 emissions while aligning with circular economy principles [27]. In addition, recent advances in sustainable construction, such as biochar-based concrete [21], wastewater-integrated concrete pavers [30], and agro-industrial waste blends [23], underscore the importance of multi-material approaches. By demonstrating the synergistic potential of GGPA and ESP, this study adds to the growing body of work on sustainable, high-performance, and environmentally responsible concrete for future construction practices.

2. MATERIAL AND METHODOLOGY

Ordinary Portland Cement (OPC, 43 grade) was employed as the main binder (Table 2, Fig. 1)due to its wide availability and adequate strength development [31]. 43 Grade Cement is used in both residential and commercial buildings because of its outstanding workability and durability. Because of its surplus strength, 43-grade offers sufficient strength without wasting material. After 28 days of curing, 43-grade OPC cement has a minimum compressive strength of 43 MPa.

Table 2. Chemical Properties of Ordinary Portland Cement (OPC)

Chemical Properties	Values
Water Absorption	2.60
Specific Gravity	-2.0%

Figure 1. Cement used in this study

Waste eggshells were gathered from bakeries and poultry sources, thoroughly washed, dried, and ground into fine powder. The chemical composition of ESP (Table 3, Fig. 2) revealed a high $CaCO_3$ content (~94%), making it a potential substitute for limestone in cement [23].

Table 3. Chemical composition of ESP and OPC

Elements	Ordinary Portland Cement (OPC)	Egg-shell Powder (ESP)
Calcium Oxide	60.10	52.100
Magnesium Oxide	2.10	0.060
Silica Dioxide	21.80	0.580
Alumina	6.60	0.060
Ferric Oxide	4.10	0.020
Sulphur Trioxide	2.20	0.620
Potassium Oxide	0.40	0.020
Sodium Oxide	0.40	0.150
Loss on Ignition	2.40	45.420
Chloride	-	-

Figure 2. Eggshell Powder Preparation

Green gram pod ash (GGPA) was prepared by controlled burning of agricultural residues, sieved through a 90 µm sieve, and found to contain reactive silica and alumina (Table 4, Fig. 3), which can contribute to pozzolanic reactions [15].

Table 4. Chemical Properties of Green Gram Pod Ash (GGPA)

Chemical Properties	Values
Water Absorption	2.10
Specific Gravity	2.0%

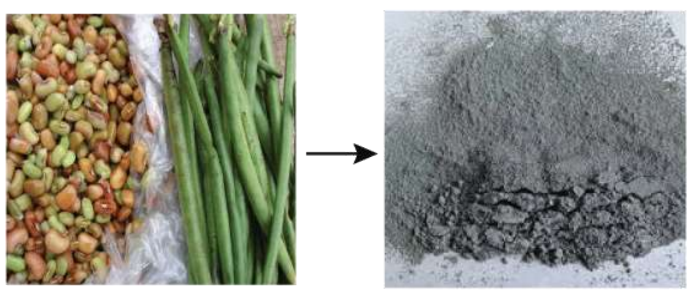


Figure 3. Green gram pod ash (GGPA)

Fine aggregate (sand) conforming to Zone II specifications (IS: 383) was used, with physical properties summarized in Table 5, Fig. 4. Coarse aggregates with a maximum size of 12.5 mm were sourced locally, and their gradation and physical characteristics (Table 6, Fig. 5) met IS:2386 standards [24, 25]. Potable tap water was used for mixing and curing.

Table 5. Fine Aggregate's Chemical Properties

Chemical Properties	Values
Water Absorption	1.820
Specific Gravity	2.580

Figure 4. Fine Aggregates

Table 6. Coarse Aggregate's Chemical Properties

Chemical Properties	Value
Moisture Absorption	1.0%
Specific Gravity	2.70
Fineness modulus	4.189
Aggregate Crushing	16.60%
Aggregate Impact	11.01%

Figure 5. Coarse Aggregate

Mix Design

The experimental program was planned to evaluate the potential of Green Gram Pod Ash (GGPA) and Eggshell Powder (ESP) as partial replacements for cement in concrete production. The control mix was prepared with a nominal ratio of 1:2:4 and a water–cement (w/c) ratio of 0.5, which is widely used for medium-strength structural concrete applications. Cement was incrementally replaced by GGPA and ESP at levels of 5%, 10%, and 15% by weight of cement. This approach allowed for comparison across different substitution levels while maintaining a consistent baseline mix.

The selected proportions for a batch of nine standard cube specimens are presented in Fig. 6, while the chemical composition of ESP and OPC is provided in Table 3. The sieve analysis and grading of coarse aggregates, which play a critical role in concrete density and strength, are shown in Table 6. The replacement ratios were designed in alignment with IS:10262 recommendations and previous studies on agricultural waste ashes and eggshell powders [15, 22].

For each mix, the quantities of materials were carefully calculated. For instance, a typical batch required 7.88 kg of cement, 0.46 kg of GGPA (5%), 0.92 kg of ESP (10%), 18.52 kg of sand, 37.04 kg of coarse aggregate, and approximately 5.6 liters of water (Fig. 6). This proportioning ensured adequate workability while avoiding segregation or bleeding. The rationale behind selecting 5–15% replacement levels was based on earlier findings that agro-waste ashes and ESP contribute positively up to moderate replacement levels, beyond which strength reductions often occur [15, 22].

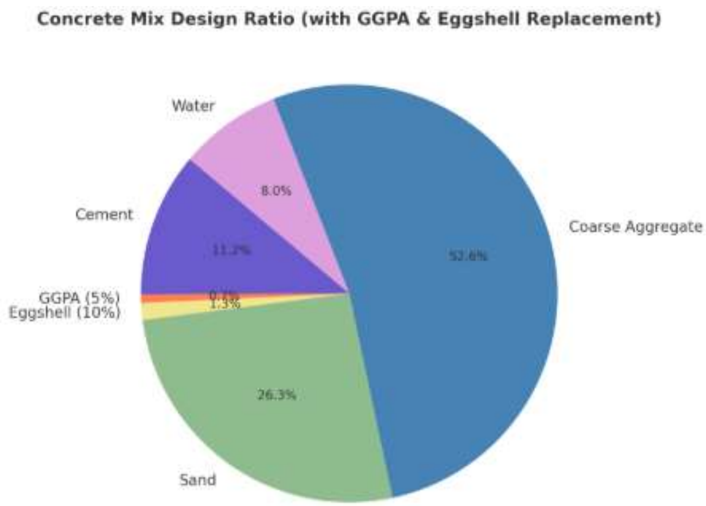


Figure 6. Concrete Mix Design Ratio (with GGPA and ESP Replacement)

Table 7. Sieve Analysis

Sieve Size	Weight retained (kg)	Cumulative weight retained (kg)	Cumulative % retained	Cumulative % Passing
19mm	1.519	1.519	30.380	69.620
12.5mm	2.143	3.662	73.240	26.760
9.3mm	1.301	4.963	99.260	0.740
4.75mm	0.037	5	100	0
Total	5		729.64	

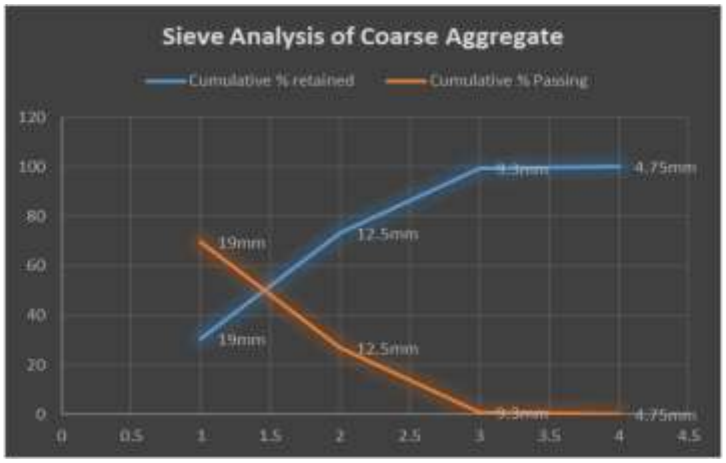


Figure 7. Sieve Analysis of Coarse Aggregate

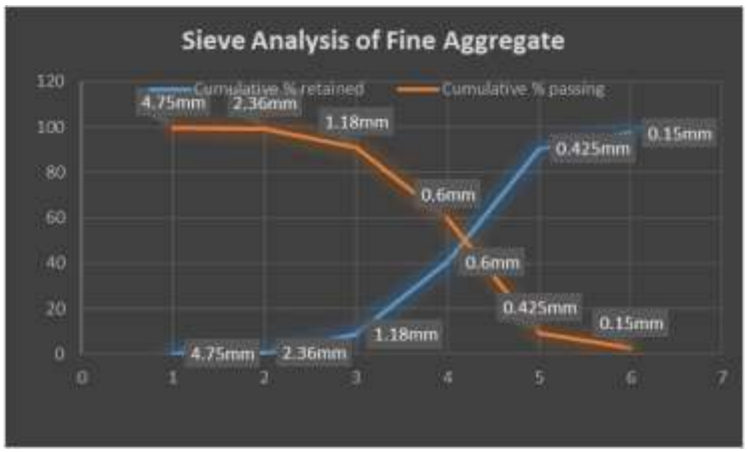


Figure 8. Sieve Analysis of Fine Aggregate

The materials used in this research study were cement, ESP, GGPA, fine aggregate (sand), coarse aggregate, and water.

- **Cement:** Ordinary Portland Cement (OPC, 43 grade) was selected due to its common use in residential and commercial construction. Its physical and mechanical properties provide reliable benchmarks, with a minimum 28-day compressive strength of 43 MPa [24].
- **Eggshell Powder (ESP):** Waste eggshells were gathered from local bakery shops, poultry farms, and food outlets. The shells were washed to remove organic contaminants, sun-dried, and ground into fine powder (Fig. 2). The chemical composition (Table 1) indicated a high $CaCO_3$ content (~94%), with minor proportions of $Ca_3(PO_4)_2$, $MgCO_3$, and organic matter [23].
- **Green Gram Pod Ash (GGPA):** Agricultural residues of green gram pods were dried and incinerated at controlled temperatures to obtain ash (Fig. 3). The material was sieved through a 90 µm sieve to achieve uniform fineness. Previous research confirmed the existence of silica and alumina in GGPA, both of which contribute to pozzolanic activity.
- **Fine Aggregate (Sand):** River sand that is locally accessible and complies with IS:383 specifications was used (Fig. 4). Its physical properties, including specific gravity (2.58) and water absorption

(1.82%), are listed in the material characterization section. Well-graded sand was chosen to ensure dense packing and improved particle interlocking (Figure 7).

- **Coarse Aggregate:** Crushed gravel with a maximum nominal size of 12.5 mm was employed (Fig. 5). Properties such as specific gravity (2.70), moisture absorption (1%), aggregate crushing value (16.6%), and impact value (11.01%) were determined in accordance with IS:2386. The coarse aggregates' sieve analysis is summarized in Table 7.
- **Water:** In accordance with IS:456, potable tap water devoid of contaminants or organic matter was utilized for both mixing and curing.

Methodology

Concrete was prepared using a laboratory-grade mechanical mixer. The dry materials (cement, ESP, GGPA, sand, and coarse aggregates) were homogenized for 3–5 minutes to ensure uniform blending (Figs. 10–12). Water was gradually added while mixing continued for an additional 5–10 minutes until a workable consistency was achieved. Workability was measured using the slump test (ASTM C143) [28] immediately after mixing.

Concrete was poured into steel cube molds of size 150 × 150 × 150 mm (Fig. 13). Compaction was achieved using tamping rods to minimize entrapped air. The specimens were demolded after 24 hours and cured under water at a constant temperature of 27 ± 2 °C (Fig. 14). Curing durations were set at 7, 14, and 28 days to monitor both early and long-term strength development.

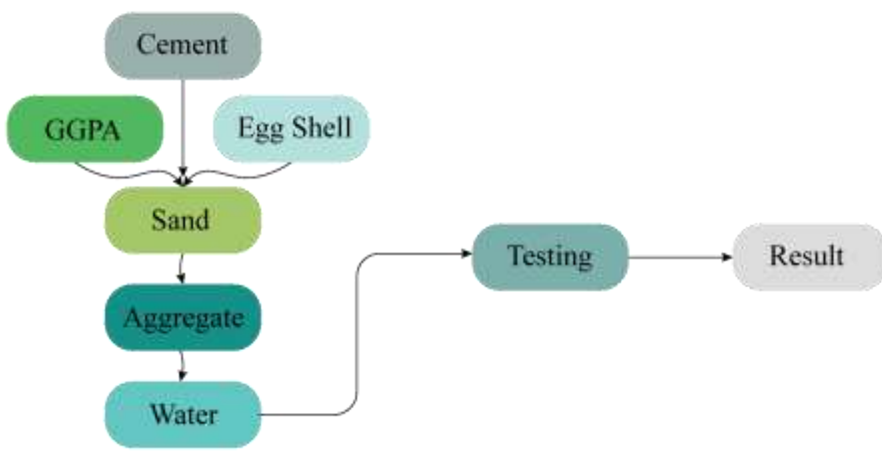


Figure 9. Methodology of the research Study

Testing Procedures

Workability (Slump Test): The workability of fresh concrete was assessed using the slump cone method as per ASTM C143. Slump values provided insights into the effect of ESP and GGPA on fresh concrete consistency. Previous studies indicated that fine particles of ESP improve cohesiveness, while porous GGPA particles may reduce flowability.

Compressive Strength Test: The compressive strength of concrete cubes was evaluated at 7, 14, and 28 days through Universal Testing Machine. The procedure followed ASTM C39 [29]. Three specimens were used in each test and the average strength was reported. This allowed comparison between control and modified mixes, highlighting the influence of replacement levels on strength development.

Water Absorption Test: Durability was preliminarily assessed through water absorption tests in accordance with ASTM C642 [20]. Water was used to immerse concrete specimens for 28 days and then weighed to determine mass gain (Fig. 13 and 14). Increased water absorption reflects higher porosity, while lower absorption indicates denser, more durable mixes.

Figure 10. Mixing GGPA and Sand in Course Aggregate

Figure 11. Mixing Eggshell Powder

Figure 12. Mixing Material

Figure 13. Casting of Concrete Cubes

Figure 14. Curing of Concrete Cubes

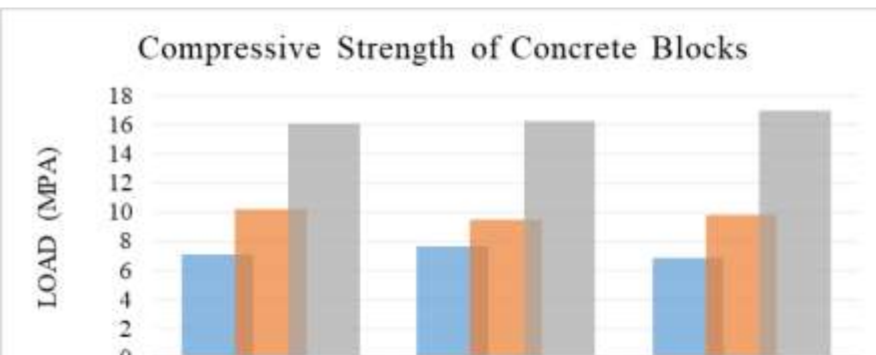
The testing program was designed to capture both mechanical and durability characteristics of GGPA–ESP concrete. Since agro-waste–based SCMs often influence early-age hydration and long-term pozzolanic reactions differently, testing at multiple ages was critical. In addition, curing was conducted under controlled conditions to minimize variability. The data collected provided a foundation for analyzing performance trends and drawing comparisons with conventional concrete.

The selection of tests was based on their relevance to practical construction performance. Compressive strength is still the most often used metric for evaluating concrete quality and structural capacity. Water absorption serves as an indirect indicator of durability, particularly resistance to permeability, carbonation, and sulfate attack. The slump test was essential for assessing field applicability, since highly sustainable mixes often face challenges in workability. By combining these tests, the study provided a balanced understanding of how GGPA and ESP affect both fresh and hardened concrete properties.

3. RESULTS AND DISCUSSION

The compressive strength performance of the mixes incorporating green gram pod ash (GGPA) and eggshell powder (ESP) showed distinct trends over curing periods of 7, 14, and 28 days. At 7 days, the control concrete achieved a strength of 9.75 MPa, while the GGPA–ESP blend exhibited only 7.7 MPa. Similarly, at 14 days the control reached 13.5 MPa compared to 10.2 MPa for the modified mix. This reduction at early ages can be attributed to the dilution effect caused by cement replacement, which reduces the immediate availability of calcium hydroxide for hydration [23]. However, by 28 days the scenario reversed, with the GGPA–ESP mix achieving 17.01 MPa, surpassing the 15 MPa recorded for the control (Fig. 15). This result highlights the delayed yet effective pozzolanic activity of GGPA and the filler effect of ESP, which collectively densify the concrete matrix. Previous research on rice husk ash, palm oil ash, and ESP has shown similar strength gain patterns, where early reductions in strength were compensated by enhanced long-term development through secondary calcium silicate hydrate (C–S–H) formation [15, 19]. Thus, the present study reaffirms that the combination of GGPA and ESP provides a synergistic effect that improves long-term strength performance.

The compressive strength findings also indicate that the optimal replacement level lies around 10%, where the balance between strength retention and sustainability is best achieved. Higher replacement levels risk excessive dilution of cementitious content, while lower levels may not fully capitalize on the pozzolanic potential of GGPA and the calcium-rich composition of ESP. This conclusion is consistent with earlier investigations on palm oil ash and bagasse ash, which recommended replacement levels between 8% and 15% for optimum strength [12, 20]. By surpassing the control mix at 28 days, the GGPA–ESP concrete demonstrates that hybrid agro-waste blends can perform comparably, if not better, than conventional cement-based concretes under proper curing conditions.



	1	2	3
7 Days	7.1	7.7	6.9
14 Days	10.2	9.5	9.8
28 Days	16.1	16.3	17

Figure 15. Compressive Strength (MPa) of Concrete Blocks

Water absorption tests revealed slightly higher absorption values for GGPA–ESP mixes compared to the control concrete. This result suggests greater initial porosity, which can be linked to the porous nature of agro-waste ashes and their high surface area [20]. Although this may appear to compromise durability at first, the pozzolanic reactions of GGPA and the fine filler effect of ESP are expected to refine pore structure over time. Studies on palm oil ash and eggshell powder reported similar trends, where higher water absorption at 28 days diminished significantly after longer curing periods of 56–90 days [31, 32]. Other eco-friendly concrete systems, such as biochar-based blocks [21] and wastewater-integrated pavers [30], also displayed increased early porosity yet developed superior resistance to permeability after extended hydration. The slightly higher water absorption recorded here is therefore not a permanent weakness, but rather a transitional phase before the pore structure becomes denser.

Workability results, measured through slump tests, indicated a modest reduction in flowability for mixes containing GGPA and ESP compared to the control. This reduction is largely attributable to the porous structure of GGPA, which increases water demand, and the irregular particle shapes of ESP, which disrupt fluidity [19]. Nonetheless, all mixes maintained workable consistencies suitable for casting without admixtures, proving their practicality for standard construction applications. Previous research on fly ash–hemp blends and bagasse ash–silica fume systems similarly reported reduced slump due to higher surface areas of waste particles. The fact that the mixes remained workable without chemical admixtures underscores their field applicability. However, to ensure consistent workability in large-scale applications, future studies could investigate the use of superplasticizers and water-reducing admixtures in combination with GGPA and ESP.

When compared against the wider body of literature, the findings of this study fall within recognized performance ranges of agro-waste–based SCMs. For example, ESP has consistently been shown to replace cement up to 20% without significant losses in strength or durability [20]. Similarly, biomass ashes such as rice husk and palm oil ash typically provide optimal performance at replacement levels between 8% and 20% [1]. The present study not only aligns with these benchmarks but extends the evidence base by validating the combination of ESP and GGPA, which has been largely unexplored to date. The synergistic effect observed here mirrors other hybrid waste systems such as fly ash–hemp and bagasse ash–silica fume, which outperformed single-material replacements [5]. This reinforces the argument that dual-waste combinations offer enhanced performance by balancing distinct chemical and physical contributions.

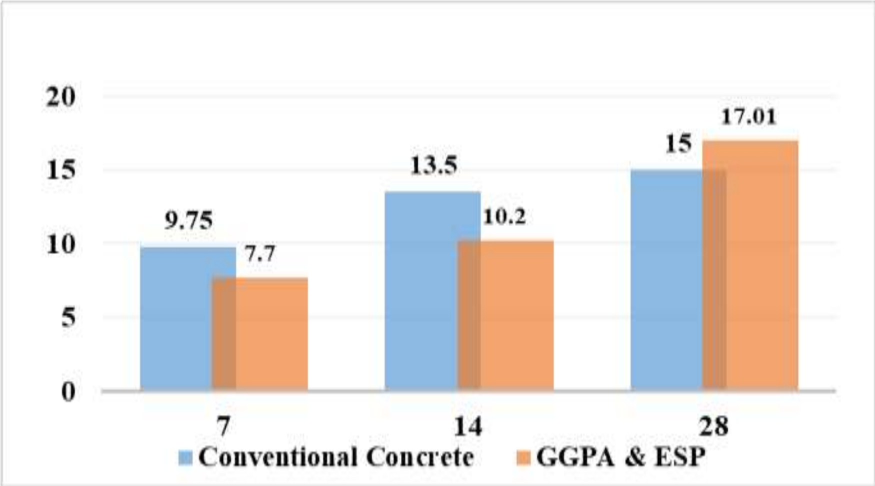


Figure 16. Comparative analysis of Conventional concrete Block with Study concrete blocks

The analytical explanation for the observed performance lies in the complementary mechanisms of GGPA and ESP. GGPA, being rich in silica and alumina, reacts with calcium hydroxide released during cement hydration to form secondary C–S–H gel. This reaction proceeds more significantly at later ages, explaining the delayed strength gain [15]. ESP, on the other hand, is composed primarily of calcium carbonate, which provides additional calcium ions for hydration and acts as a micro-filler. This accelerates hydration while also refining the pore structure [23]. Together, the combination enhances the long-term binding capacity of the matrix, creating a denser and stronger material. This synergy accounts for the fact that the 28-day strength of GGPA–ESP mixes exceeded that of the control, even though early-age results were lower. Similar mechanisms have been validated in microstructural studies of other SCM concretes, where scanning electron microscopy (SEM) and X-ray diffraction (XRD) confirmed the densification of the matrix through pozzolanic and filler effects [33].

Beyond mechanical and durability aspects, the environmental implications of this study are significant. Cement manufacture alone contributes nearly 7% of global CO_2 emissions, while agricultural and food wastes such as green gram pods and eggshells pose disposal challenges. Incorporating these wastes into concrete not only reduces cement demand but also diverts biodegradable waste from landfills, supporting circular economy principles [34]. The carbon footprint reduction and resource efficiency achieved through GGPA–ESP concrete mirror other sustainable innovations, such as biochar-based concrete [21], wastewater-integrated pavers [30], and low-grade clay mineral composites [24]. This confirms that agro-waste valorization offers dual benefits: enhanced technical performance and measurable environmental impact.

Despite these positive outcomes, several limitations of the study must be acknowledged. First, durability was only assessed through water absorption, which provides limited insight into long-term performance under aggressive environments. Comprehensive tests such as chloride ion penetration, sulfate resistance, carbonation depth, and freeze–thaw cycling are necessary to fully validate durability [34]. Second, the absence of microstructural analyses (SEM, XRD, FTIR) restricts understanding of hydration mechanisms at the microscopic level [33]. Third, variability in the chemical composition of GGPA and ESP, which depends on source and processing conditions, may affect reproducibility [23]. Finally, the reduced workability observed in GGPA–ESP mixes could limit large-scale adoption unless optimized with admixtures. These limitations highlight the need for future research to expand beyond mechanical tests and integrate advanced characterization techniques.

In synthesis, the results demonstrate several key findings. Compressive strength initially decreases due to cement dilution but surpasses control values by 28 days due to pozzolanic and filler effects. Water absorption is slightly higher, reflecting greater porosity, though this is expected to reduce with extended curing. Workability decreases modestly but remains within practical limits. The optimal performance is achieved at 10% replacement, balancing strength, workability, and durability. The combination of GGPA and ESP therefore produces synergistic effects superior to those of single-waste SCMs. Importantly, the environmental benefits of waste valorization strengthen the case for adoption in sustainable construction practices.

4. CONCLUSION

This research study assessed the efficacy of concrete containing green gram pod ash (GGPA) and eggshell powder (ESP) as partial substitutes for cement. The findings indicated that although the early-age compressive strength was inferior to that of traditional concrete, the long-term strength progression was markedly improved. By 28 days, the GGPA–ESP mix achieved higher compressive strength than the control, confirming the synergistic effect of silica-rich GGPA and calcium-rich ESP in promoting pozzolanic reactions. Water absorption tests indicated slightly higher porosity at early stages, though durability is expected to improve over extended curing periods.

The practical implication of these findings is that GGPA–ESP concrete can serve as an eco-friendly, low-cost alternative for sustainable construction, particularly in applications where long-term curing is feasible. By reducing cement consumption, diverting agro-waste from landfills, and lowering CO_2 emissions, this approach supports circular economy principles and aligns with global efforts toward sustainable construction.

However, the study was limited to compressive strength and basic durability testing. Further investigations should focus on advanced durability assessments, microstructural characterization, and life-cycle cost analysis to confirm industrial-scale viability. Future research may also explore the integration of GGPA and ESP with other SCMs to optimize performance across a wider range of applications.

Overall, the findings highlight the potential of GGPA and ESP as supplementary cementitious materials, demonstrating that agricultural and food wastes can be transformed into high-value resources for low-carbon, sustainable concrete.

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