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Psidium guajava (Guava Leaves) Ash and Eggshell Powder as a Alternative for Cement

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Abstract

This study evaluated the effectiveness of *Psidium guajava* leaf ash (GLA) and eggshell powder (ESP) as partial replacements for cement in mortar mixtures, aiming to develop a more sustainable construction material. Anchored on the pozzolanic reaction theory and the Input-Process-Output framework, the research employed a quantitative experimental design conducted in a controlled laboratory setting. Mortar specimens were prepared using three mixture variations eggshell-dominant, ash-dominant, and equal proportions and were tested using compressive strength measurements, estimated tensile and flexural strength calculations, water absorption tests, and one-way analysis of variance (ANOVA). The findings revealed that the eggshell-dominant mixture achieved the highest compressive strength, ranging from 0.798 MPa to 1.064 MPa, while the other mixtures exhibited no measurable compressive strength. This mixture also demonstrated moderate tensile and flexural performance and acceptable water absorption, indicating balanced mechanical properties and durability. Statistical analysis confirmed significant differences among the mixtures, establishing the eggshell-dominant formulation as the most effective. However, the study identified limitations in the performance of guava leaf ash when used alone or in equal proportions. The results highlight the potential of eggshell powder as a viable partial cement replacement, while further optimization is needed for guava leaf ash. This study aligns with SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) by promoting sustainable construction materials and waste utilization. The findings contribute to environmental and economic sustainability by reducing reliance on conventional cement, minimizing waste, and supporting cost-effective and eco-friendly construction practices.

Keywords: Cement Replacement, Eggshell Powder, Guava Leaf Ash, Mechanical Properties, Mortar Mixtures, Water Absorption

1. Introduction

The construction industry significantly contributes to environmental degradation, particularly through the high carbon emissions associated with Ordinary Portland Cement (OPC). The integration of agricultural waste materials such as *Psidium guajava* leaf ash (GLA) and eggshell powder (ESP) as supplementary cementitious materials (SCMs) presents a sustainable alternative. These materials exhibit pozzolanic and chemical properties that can enhance concrete performance while reducing environmental impact. This study examines the effectiveness of GLA and ESP as partial cement replacements, focusing on their mechanical properties and potential for sustainable construction applications.

1.1 Background of the Study on GLA and ESP as Cement Replacement Materials

OPC production accounts for approximately 7–8% of global anthropogenic CO_2 emissions and requires substantial energy and raw materials (Scrivener et al., 2019). This environmental burden has encouraged the use of SCMs derived from agricultural and industrial by-products to reduce clinker consumption and carbon emissions (Awoyera & Adesina, 2020). Agricultural ashes such as rice husk ash, corn cob ash, and bamboo leaf ash demonstrate pozzolanic properties that enhance concrete strength and durability by forming additional calcium silicate hydrate (C–S–H) (Neville, 2020). Similarly, *Psidium guajava* leaf ash (GLA), when calcined at approximately 600 °C, contains about 82.33% combined silica, alumina, and ferric oxide, exceeding ASTM C618 requirements (Adegbesan et al., 2020). This composition enables GLA to improve microstructure and reduce permeability. Eggshell powder (ESP), composed of approximately 95% calcium carbonate, contributes to cement hydration through nucleation and chemical reactions, enhancing early strength and matrix densification (Jaber et al., 2019; Ahn, 2019). Studies show that replacing 5–20% of cement with ESP can maintain or improve compressive and flexural strength while reducing costs (Khan et al., 2023). The combined use of GLA and ESP offers synergistic benefits: GLA provides pozzolanic reactivity, while ESP enhances hydration and structural density

(Adegbesan et al., 2020; Faridi et al., 2019; Jaber et al., 2019). This combination supports reduced clinker use and lower CO_2 emissions (Andrew, 2019; Ritchie & Roser, 2019).

1.2 Themes and Insights from Related Literature on Agricultural Waste-Based SCMs

Existing literature emphasizes the effectiveness of agricultural waste ashes as SCMs due to their high silica and alumina content, which promotes pozzolanic reactions (Mohammed et al., 2022). Studies on banana leaf ash and rice husk ash indicate improved compressive strength, reduced porosity, and enhanced durability at appropriate replacement levels (Islam et al., 2024; Stel'makh et al., 2024; Mohammed et al., 2022). Corn cob ash has also demonstrated increased long-term strength due to its silica content (Awal et al., 2019). GLA exhibits similar chemical properties, suggesting comparable performance (Adegbesan et al., 2020; Islam et al., 2024). However, limited empirical studies exist on its mechanical and durability performance, highlighting the need for further investigation (Khalid, 2023). ESP studies reveal improved hydration, strength, and microstructure due to its calcium-rich composition (Rathinavel et al., 2023; Sharma et al., 2024). Optimal replacement levels enhance compressive strength, though excessive amounts may reduce performance (Hama, 2019). ESP also improves density and reduces water absorption while supporting waste recycling (Paruthi, 2023; Rathinavel et al., 2023). Blended SCM systems combining silica-rich and calcium-rich materials show superior performance compared to single-material replacements (Muthukumar et al., 2018; Devi & Shankar, 2020).

1.3 Local, National, and Global Context of GLA and ESP Utilization

Globally, cement production remains a major environmental concern due to its contribution to greenhouse gas emissions (Scrivener et al., 2019). Locally, increasing egg consumption in the Philippines has resulted in significant eggshell waste, with per capita consumption reaching 13.74 kilograms annually (Department of Agriculture, 2023). Agricultural residues such as guava leaves are often discarded or burned, contributing to pollution and inefficient waste management (Domingo & Villanueva, 2024). Utilizing these materials as SCMs addresses both waste management and environmental sustainability challenges while supporting local resource utilization (Khalid, 2023). The adoption of agricultural waste in construction aligns with global efforts to reduce carbon emissions and promote sustainable infrastructure development (Sharma et al., 2024).

1.4 Theoretical or Conceptual Basis: Pozzolanic Reaction and IPO Framework

This study is grounded in the theory of pozzolanic reactions, where silica- and alumina-rich materials react with calcium hydroxide to form additional C–S–H, improving strength and durability (Neville, 2020; Mehta & Monteiro, 2014). ESP contributes calcium compounds that enhance hydration reactions and matrix stability (Ahn, 2019). The study also adopts the Input-Process-Output (IPO) model, where GLA, ESP, sand, and water serve as inputs; material preparation and mix formulation represent the process; and the resulting cement product and its mechanical properties constitute the output.

1.5 Research Gaps and Rationale for GLA–ESP Blended Cement

Despite evidence supporting agricultural ashes as SCMs, limited studies focus specifically on GLA's mechanical performance and optimal replacement ratios (Adegbesan et al., 2020; Khalid, 2023). Additionally, while ESP has been widely studied, its combined use with GLA remains underexplored. There is a need to determine the effects of varying proportions of GLA and ESP on flexural strength, tensile strength, and water absorption. Addressing these gaps will provide empirical data to validate their effectiveness as sustainable cement alternatives.

1.6 Alignment with Relevant Sustainable Development Goals (SDGs)

This study supports several Sustainable Development Goals by promoting environmentally responsible construction practices through the use of agricultural waste materials. It aligns with SDG 9 – Industry, Innovation and Infrastructure by advancing innovative alternatives to conventional cement, and SDG 11 – Sustainable Cities and Communities by contributing to the development of sustainable building materials. The study also addresses SDG 12 – Responsible Consumption and Production through the utilization of guava leaves and eggshells as waste-derived resources, supporting waste valorization and circular economy principles (Awoyera & Adesina, 2020). Additionally, it contributes to SDG 13 – Climate Action by reducing reliance on clinker-based cement, thereby lowering CO_2 emissions associated with cement production (Ritchie & Roser, 2019).

1.7 Importance of the Study to Multidisciplinary Sustainability

This research contributes to environmental sustainability by reducing carbon emissions and waste disposal issues, economic sustainability by lowering material costs and creating value from waste, and technological sustainability by advancing eco-friendly construction materials. It also supports community and policy sustainability by providing solutions for waste management and promoting sustainable practices among local governments and industries. Furthermore, the study benefits stakeholders such as the construction industry, local government units, farmers, and academic institutions by offering practical, cost-effective, and environmentally responsible alternatives to traditional cement (Khan et al., 2023).

2. Material and methods

2.1 Research Design

The study utilized a quantitative experimental research design to collect and analyze numerical data for testing hypotheses and identifying patterns (Bhandari, 2020). The experimental approach allowed the manipulation of independent variables, specifically the proportions of guava leaf ash and eggshell powder, to determine their effects on dependent variables such as compressive strength, tensile strength, flexural strength, and water absorption (Salmons, 2021). This design enabled controlled conditions to ensure accurate and reliable measurement of the effectiveness of the alternative cement mixtures.

2.2 Locale of the Study

The study was conducted in a controlled laboratory setting at Saint Louis School of Pacdal Inc., where appropriate equipment and facilities were available for material preparation, sample production, curing, and mechanical testing. The controlled environment ensured consistency in experimental procedures and adherence to safety protocols.

2.3 Respondents of the Study

This study did not involve human respondents, as it focused on material testing and experimental evaluation of cement mixtures. The units of analysis were mortar specimens produced using varying proportions of guava leaf ash and eggshell powder.

2.4 Sample and Sampling Procedure

The samples consisted of mortar cubes prepared using three different mixture proportions of guava leaf ash and eggshell powder. A purposive sampling approach was applied, where mixtures were intentionally designed to represent equal, ash-dominant, and eggshell-dominant compositions. The equal mixture used the same proportion of guava leaf ash and eggshell powder combined with fixed amounts of sand and water. The ash-dominant mixture contained a higher proportion of guava leaf ash than eggshell powder, while the eggshell-dominant mixture used a greater proportion of eggshell powder than guava leaf ash. Across all mixtures, the quantities of sand and water were kept constant to ensure consistency in workability and hydration. These variations allowed the study to systematically compare the performance of different material proportions and identify the most effective combination in terms of mechanical strength and durability.

2.5 Research Instrument

Data collection involved observation and laboratory testing. Observational methods were used to document changes in workability, setting behavior, and surface characteristics during preparation and curing. Mechanical performance was measured using a Compression Testing Machine (CTM) to determine compressive strength. Tensile and flexural strengths were estimated from compressive strength values using established empirical relationships (Neville, 2020; ACI Committee 318, 2020). Photographic documentation was also used to assess mixture uniformity and detect surface defects. Water absorption testing was conducted to evaluate porosity and durability. These instruments ensured accurate and reliable data collection for comparing the effectiveness of the mixtures.

2.6 Data Gathering Procedure

The data gathering process began with securing permission from the school administration to conduct the experiment and use laboratory facilities. Raw materials, including guava leaves and eggshells, were collected, cleaned, and prepared. Guava leaves were dried and burned to produce ash, while eggshells were washed, dried, crushed, and ground into fine powder. Proper preparation ensured uniform particle size and suitability for cement replacement (Mehta & Monteiro, 2020; Yerramala, 2021). The prepared materials were measured accurately and mixed with sand and water to produce mortar mixtures. Dry components were blended thoroughly before water was gradually added to achieve a consistent mixture. The mixtures were then poured into molds and compacted to remove air voids, ensuring uniform density (ASTM International, 2020). After initial setting, the samples were cured in water for seven days to allow hydration and strength development (Neville, 2020; Mehta & Monteiro, 2022). Following curing, compressive strength testing was conducted using a CTM, where each specimen was subjected to increasing load until failure. The maximum load was recorded to determine compressive strength. Tensile and flexural strengths were subsequently estimated from compressive strength values using standard relationships (ACI Committee 318, 2020). Water absorption testing was performed by measuring dry and saturated weights of specimens to assess porosity and durability (ASTM International, 2020). Throughout the procedure, safety measures such as wearing protective equipment and proper handling of materials were strictly observed.

2.7 Data Analysis Techniques

Compressive strength was calculated by dividing the maximum load by the cross-sectional area of the specimen, providing a measure of resistance to crushing forces (Aggarwal et al., 2023). Tensile and flexural strengths were estimated as percentages of compressive strength using empirical relationships commonly applied in concrete studies. Water absorption was determined by comparing the saturated and dry weights of specimens, expressed as a percentage. Lower absorption values indicated reduced porosity and improved durability (Huang Q., et al., 2021). To compare mixture performance, the mean was used to determine the average compressive strength of each group (Frost, 2023). Additionally, one-way analysis of variance (ANOVA) was applied to assess whether differences among mixtures were statistically significant. This method enabled comparison of group means and determination of whether observed differences were due to mixture composition rather than random variation (Bürger, 2023). The overall effectiveness of each mixture was evaluated based on compressive strength, estimated tensile and flexural strengths, and water absorption, with higher strength and lower porosity indicating better performance.

3. Results and Discussion

3.1 Mechanical Performance of GLA and ESP Cement Mixtures

3.1.1 Compressive Strength Performance of Mixture Variations

The results show that the eggshell-dominant mixture exhibited measurable compressive strength values ranging from 0.798 MPa to 1.064 MPa, with an average of 0.931 MPa (115.74–154.32 psi). In contrast, both the ash-dominant and equal mixtures recorded no measurable compressive strength after 7 days of curing, indicating complete lack of load-bearing capacity under the tested conditions. These findings indicate that increasing the proportion of eggshell powder significantly enhances compressive strength due to its high calcium carbonate content, which contributes to improved cementitious bonding and load-bearing capacity. Conversely, guava leaf ash alone or in equal proportion does not provide sufficient binding properties, likely due to limited hydration or insufficient reactive compounds. This confirms that eggshell powder plays a more critical role in early strength development compared to guava leaf ash.

3.1.2 Statistical Significance of Compressive Strength Differences (ANOVA)

The analysis revealed that the eggshell-dominant mixture achieved an average compressive strength of 0.931 MPa, while the ash-dominant and equal mixtures both recorded 0 MPa. Statistical testing produced an F-value of 49 and a p-value of 0.0051, which is below the 0.05 significance level. This result confirms that the differences in compressive strength among the mixtures are statistically significant, leading to the rejection of the null hypothesis. It demonstrates that mixture composition directly influences mechanical performance, with the eggshell-dominant formulation significantly outperforming the others. This validates the experimental observation that higher eggshell content improves compressive strength.

3.1.3 Tensile Strength Behavior of Mixtures

The results indicate that the eggshell-dominant mixture achieved a tensile percentage of 54.29%, which falls within the moderate performance range. Meanwhile, the other mixtures exhibited a higher tensile percentage of 62.69%, corresponding to a high-performance classification, although their absolute strength values remained low due to zero compressive strength. These findings suggest that while mixtures with higher guava leaf ash content appear relatively more flexible, their actual tensile strength is limited by insufficient structural integrity. The eggshell-dominant mixture, although slightly lower in tensile percentage, provides a better balance between strength and ductility. This indicates that eggshell powder contributes to improved structural performance, while guava leaf ash primarily influences flexibility rather than load-bearing capacity.

3.1.4 Flexural Strength Performance of Mixtures

The eggshell-dominant mixture demonstrated the highest flexural strength at 0.639 MPa, corresponding to a flexural percentage of 60.11%, classified as moderate performance. Another sample with lower compressive strength showed a flexural strength of 0.554 MPa but a higher flexural percentage of 69.41%, categorized as high performance. These results indicate that higher eggshell content improves bending resistance and structural rigidity due to enhanced bonding within the mortar. However, mixtures with relatively lower strength exhibit higher flexibility, as reflected in their higher flexural percentages. This demonstrates a trade-off between rigidity and ductility, with the eggshell-dominant mixture providing superior overall structural performance for applications requiring both strength and resistance to bending.

3.2 Durability Performance Through Water Absorption

The water absorption results show that the eggshell-dominant mixture recorded 5.46% absorption, while the ash-dominant mixture had 6.97%, and the equal mixture showed the highest absorption at 18.91%. These findings indicate that the eggshell-dominant mixture has lower porosity compared to the other variations, contributing to better resistance to moisture penetration. The ash-dominant mixture shows moderate durability, while the equal mixture demonstrates poor durability due to high porosity. This suggests that increasing eggshell powder improves both mechanical strength and water resistance, whereas higher guava leaf ash content negatively affects durability.

3.3 Overall Performance of Trial Mixtures

The results show that the eggshell-dominant mixture achieved the highest compressive strength at 0.931 MPa and the lowest water absorption at 5.46%, while the ash-dominant and equal mixtures recorded zero compressive strength and higher water absorption values. This overall performance confirms that the eggshell-dominant formulation is the most effective among the tested mixtures, as it provides both structural strength and acceptable durability. The results demonstrate that increasing eggshell powder enhances cementitious performance, while guava leaf ash alone or in equal proportion is insufficient for structural applications under the tested conditions.

4. Conclusion and Recommendations

The study determined the effectiveness of *Psidium guajava* leaf ash and eggshell powder as partial cement replacements by evaluating three mixture variations using compressive strength, estimated tensile and flexural strength, water absorption, and statistical analysis. The results showed that the eggshell-dominant mixture achieved the highest compressive strength, ranging from 0.798 MPa to 1.064 MPa with an average of 0.931 MPa, indicating improved load-bearing capacity due to the influence of eggshell powder. In contrast, the ash-dominant and equal mixtures exhibited no measurable compressive strength, demonstrating insufficient binding properties at the tested ratios. The eggshell-dominant mixture also showed moderate tensile and flexural performance and acceptable water absorption, indicating balanced mechanical properties and durability, while the equal mixture displayed poor durability due to high porosity. Statistical analysis confirmed that the differences among mixtures were significant, establishing the eggshell-dominant formulation as the most effective combination, while guava leaf ash alone was not effective under the given conditions.

Future studies should examine alternative replacement ratios, particularly lower proportions of guava leaf ash combined with eggshell powder, to determine optimal performance. Additional research should also consider longer curing periods beyond seven days to assess long-term strength development. Further mechanical testing, including direct tensile, flexural, and durability evaluations such as permeability and sulfate resistance, is recommended to provide a more comprehensive assessment. Improvements in processing methods for guava leaf ash, including controlled burning and finer grinding, should be explored to enhance its cementitious properties. The eggshell-dominant mixture may be considered for small-scale, non-load-bearing applications, while further investigation into environmental and economic feasibility is necessary to evaluate its broader application.

The study was limited to three mixture variations and a curing period of seven days, which restricts the evaluation of long-term strength development. The investigation focused only on selected mechanical properties, including compressive strength, estimated tensile and flexural strength, and water absorption, without conducting direct tensile or advanced durability tests. The use of guava leaf ash was restricted to specific preparation methods and proportions, which may have influenced its performance. Additionally, the findings are limited to small-scale laboratory conditions and may not fully represent large-scale structural applications or varying environmental conditions.

Compliance with ethical standards

The authors declare no conflict of interest and confirm that this study received no external funding. Permission to conduct the research was obtained from Saint Louis School of Pacdal Inc., and all procedures were carried out with voluntary participation and informed consent. Data were collected using non-invasive laboratory and observational methods, and no identifying information was recorded to ensure confidentiality. The researchers acknowledge the support of the institution and all individuals who contributed to the completion of this study.

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