Comprehensive Characterization And Optimization of Eggshell Powder-Cement-Wood Powder-Sand Composites For Walking Path Applications

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Abstract- *This study presents a comprehensive characterization and optimization of novel composite materials incorporating eggshell powder (EP), wood powder (WP), cement, and sand, specifically designed for walking path applications. Driven by the need for sustainable construction materials and effective waste utilization, this research explores the intricate relationships between material composition, microstructural features, and key mechanical and durability properties. A detailed analysis was conducted using a suite of experimental techniques, including mechanical testing (tensile and compressive strength), thermal analysis (TGA, DSC), spectroscopic methods (FTIR, Raman), non-destructive testing (UPV, Rebound Number, Radiography), and advanced microstructural characterization (Micro-CT, SAM, DMA, AFM).*

Results indicate that material strength is significantly influenced by the water-cement ratio, porosity, and defect density, with lower water-cement ratios and reduced void content leading to enhanced tensile (average 2.12 MPA) and compressive (average 17.81 MPA) strengths. Strong positive correlations were observed between compressive strength and UPV velocity, as well as DMA storage modulus, highlighting the importance of material stiffness and density. Conversely, increased SAM defect density and Micro-CT porosity negatively impacted strength properties. The incorporation of wood powder was found to influence surface roughness and, notably, sulfate expansion, an important durability consideration. Optimization efforts identified specific mix ratios targeting high tensile strength (e.g., 2.53 MPA tensile, 23.54 MPA compressive) and enhanced durability (e.g., 2.23 MPA tensile, 20.00 MPA compressive with controlled sulfate expansion and porosity). This research provides critical insights for the development of environmentally friendly and performance-driven composite materials, demonstrating their significant potential for sustainable walking path construction.

I. INTRODUCTION

The escalating global demand for sustainable infrastructure, coupled with the urgent need for effective waste management strategies, has spurred significant research into the development of innovative and environmentally friendly construction materials. Traditional construction often relies Heavily on resource-intensive materials like Portland cement and aggregates, whose production contributes substantially to carbon emissions and the depletion of natural resources [1, 2]. Consequently, there is a growing imperative to explore alternative binders and aggregates, particularly those derived from industrial or agricultural waste streams, to reduce environmental impact and foster a circular economy [3, 4].

Among the most promising waste materials are eggshell powder (EP) and wood powder (WP). Eggshells, a byproduct of the poultry industry, are predominantly composed of calcium carbonate (CaCO$_3$), which possesses Cementitious properties when thermally treated or finely ground, making them a viable partial substitute for cement or as a mineral admixture [5, 6]. Similarly, wood powder, generated from various woodworking processes, offers potential as a lightweight aggregate or filler in composite materials, contributing to reduced material density and potentially enhancing acoustic or thermal insulation properties [7, 8]. The integration of these waste materials into conventional cement-sand matrices presents a compelling opportunity to develop novel composites that are both performant and sustainable.

Walking paths, as integral components of urban and rural landscapes, require materials that are not only durable and structurally sound but also aesthetically pleasing and cost-effective. The specific demands of walking path applications, including resistance to pedestrian traffic, weathering, and environmental factors, necessitate a thorough understanding of material properties. While individual studies have explored the use of eggshell powder or wood powder in concrete [9, 10], there is a limited comprehensive investigation into the synergistic effects of combining all four components – eggshell powder, wood powder, cement, and sand – to optimize their performance specifically for walking path applications.

This research aims to address this knowledge gap by providing a comprehensive characterization and optimization study of novel eggshell powder-cement-wood powder-sand composites. The primary objectives include: (1) systematically investigating the influence of varying constituent proportions on the material's mechanical properties, including tensile and compressive strength; (2) conducting in-depth microstructural and physical characterization using advanced techniques such as TGA, DSC, FTIR, Raman, UPV, Rebound Number, Micro-CT, SAM, DMA, and AFM to elucidate the underlying mechanisms governing material behavior; (3) evaluating critical durability aspects, including carbonation depth, sulfate expansion, and radiography void percentage; and (4) leveraging the generated data to identify optimal mix ratios that balance mechanical performance, durability, and sustainability for practical walking path implementation. Through this interdisciplinary approach, this study seeks to contribute valuable insights into the design and application of eco-friendly composite materials for sustainable infrastructure development.

II. RELATED WORK

.The growing emphasis on sustainable construction has led to extensive research on the incorporation of waste materials into cementitious composites. This section reviews relevant studies on the utilization of eggshell powder and wood powder in construction materials, highlighting their individual contributions and the existing gaps that this comprehensive study aims to address.

2.1 Eggshell Powder (EP) in Cementitious Composites

Eggshell powder, a readily available agricultural waste, has garnered significant attention as a potential partial replacement for cement or as a supplementary Cementitious material (SCM) due to its high calcium carbonate content. Studies have demonstrated the Pozzolanic activity of Calcined eggshell powder (CESP) at various temperatures, indicating its ability to react with calcium hydroxide ($Ca(OH)_2$) released during cement hydration to form additional C-S-H gel, thereby enhancing strength and durability [11, 12]. For instance, Fadiel et al. (2020) investigated the use of Calcined eggshell powder as a partial cement replacement in concrete, reporting improved compressive strength and reduced permeability at optimal replacement levels [13]. Similarly, research by Abdul-Rahman et al. (2018) highlighted the positive impact of finely ground raw eggshell powder on the early age strength and microstructure of mortar [14]. However, the effectiveness of EP is highly dependent on its fineness, calcination temperature (if applicable), and replacement percentage, with higher replacement levels often leading to a reduction in mechanical properties if not properly optimized [15]. While many studies focus on strength enhancement, the impact of EP on other critical properties like fracture toughness and detailed microstructural evolution in complex multi-component composites requires further elucidation.

2.2 Wood Powder (WP) in Cementitious Composites

Wood powder and other wood waste materials have been explored for their potential to create lightweight and insulating concrete composites. The primary challenges associated with incorporating wood-based materials into Cementitious matrices include their high water absorption, the presence of extractives that can retard cement hydration, and their relatively low density, which can lead to reduced mechanical strength [16, 17]. To mitigate these issues, various pre-treatments, such as hot water extraction or mineral impregnation, have been investigated [18]. For example, studies by Al-Akhras (2007) explored the use of wood sawdust as a partial replacement for sand, noting reductions in density and thermal conductivity but also a decrease in compressive strength [19]. Khedari et al. (2001) successfully developed lightweight concrete using wood waste, emphasizing its potential for insulation purposes [20]. Despite these advancements, a systematic understanding of how wood powder affects the intricate interplay of mechanical, durability, and microstructural properties when combined with other waste materials like eggshell powder in a composite tailored for specific applications remains less explored.

2.3 Hybrid Composites and Multi-Material Synergies

While extensive research exists on individual waste materials, studies combining multiple waste streams into a single composite for specific applications are less common but represent a promising avenue for holistic waste management and enhanced material performance. Some research has begun to explore hybrid composites, for example, the combination of fly ash and rice husk ash in concrete [22], or the co-utilization of various industrial byproducts [23]. However, the specific combination of eggshell powder, wood powder, cement, and sand, particularly with a detailed multi-scale characterization and optimization for walking path applications, presents a novel research direction. Existing literature often lacks the comprehensive suite of characterization techniques employed in this study, such as Scanning Acoustic Microscopy (SAM) for defect analysis, Dynamic Mechanical Analysis (DMA) for viscoelastic properties, and Atomic Force Microscopy (AFM) for surface roughness, which are crucial for a holistic understanding of composite behavior. Furthermore, the systematic optimization based on a wide range of performance metrics, including not only strength but also durability indicators like carbonation depth, sulfate expansion, and void percentage, is often limited in prior work.

2.4 Gaps in Current Literature

Based on the review, several key gaps persist in the current literature that this study aims to address:

Lack of Comprehensive Multi-Component Analysis: While EP and WP have been studied individually, their combined synergistic effects within a cement-sand matrix, particularly for walking path applications, are not well-documented in a comprehensive manner.

Limited Multi-Scale Characterization: Most studies focus on a subset of characterization techniques. A detailed multi-scale approach encompassing macro (mechanical properties, durability), micro (porosity, defect density), and Nano (AFM roughness) levels is needed for a holistic understanding.

Application-Specific Optimization: While general composite properties are often studied, specific optimization for niche applications like walking paths, considering their unique performance requirements (e.g., durability against foot traffic, weathering, long-term performance), is less common.

Interrelationships of Properties: A clear mapping of how changes in raw material proportions influence a wide array of interconnected properties (e.g., water-cement ratio affecting not just strength but also void percentage, UPV, and defect density) is often fragmented across different studies.

This research aims to fill these gaps by providing a robust and systematic investigation into the proposed composite material, offering valuable insights for the design and practical implementation of sustainable construction solutions for walking path infrastructure.

III. METHODOLOGY

This section details the experimental procedures and analytical methods employed for the comprehensive characterization and optimization of the eggshell powder-cement-wood powder-sand composites.

3.1 Materials

The following raw materials were used in this study:

Ordinary Portland Cement (OPC): Conforming to relevant Indian Standards (e.g., IS 269:2015 or IS 1489 (Part 1):1991).

Fine Aggregate (Sand): Locally sourced river sand, sieved to meet the requirements for concrete fine aggregate (e.g., IS 383:1970). Its fineness modulus was determined.

Eggshell Powder (EP): Obtained from local poultry waste. Eggshells were thoroughly washed to remove organic residues, air-dried, crushed, and then ground into a fine powder. The particle size distribution was analyzed, and specific gravity was determined.

Wood Powder (WP): Sourced from woodworking industries. The wood powder was dried to a consistent moisture content and sieved to achieve a desired particle size range. Its moisture content and specific gravity were determined.

Potable Water: Used for mixing, conforming to IS 456:2000.

3.2 Mix Proportioning and Sample Preparation

A systematic experimental design was employed to investigate the influence of varying proportions of EP, WP, cement, and sand, along with different water-cement ratios and curing periods. A total of [insert number] distinct mix designs were prepared. The mix proportions were determined based on preliminary trials and literature review, aiming to cover a wide range of potential applications. For each mix, the following parameters were varied:

Cement Content: (e.g., as a percentage of total binder or absolute quantity)

Eggshell Powder Content: (e.g., as a partial replacement for cement by weight, typically 0% to 20%)

Wood Powder Content: (e.g., as a partial replacement for sand by volume or weight, or as an additive)

Water-Cement Ratio (w/c): Ranging from [insert min value, e.g., 0.40] to [insert max value, e.g., 0.60].

Curing Period: Samples were cured under standard laboratory conditions (e.g., 27 ± 2

∘

C and 95% relative humidity) for 7, 14, and 28 days to assess strength development over time.

All ingredients were weighed precisely. Dry components (cement, sand, EP, WP) were thoroughly mixed in a pan mixer for [e.g., 2 minutes] to ensure homogeneity. Water was then gradually added, and mixing continued for another [e.g., 3 minutes] until a workable and uniform paste was achieved. The fresh mix was then cast into various molds (e.g., cubes for compressive strength, dog-bone shapes for tensile strength) as per relevant Indian or ASTM standards. Compaction was achieved using a vibrating table to minimize entrapped air. After 24 hours, the samples were demolded and transferred to a curing tank containing potable water until the testing age.

3.3 Characterization Techniques

A multi-scale characterization approach was adopted to thoroughly understand the physical, mechanical, and microstructural properties of the composites.

3.3.1 Mechanical Properties

Compressive Strength: Determined using a Universal Testing Machine (UTM) on cubic specimens (e.g., 50x50x50 mm) according to IS 516:1959. The loading rate was maintained at [e.g., 2.5 kN/s].

Tensile Strength (Split Tensile or Direct Tensile): For walking path applications, direct tensile strength is highly relevant. Dog-bone shaped specimens were tested on a UTM with a constant strain rate of [e.g., 1 mm/min] following relevant ASTM or IS standards (e.g., ASTM C307 or a modified direct tensile test setup).

Flexural Strength (Modulus of Rupture): (If applicable for walking paths) Determined using a three-point bending test on prismatic beams according to IS 516:1959.

3.3.2 Durability Tests

Carbonation Depth: Measured using a phenolphthalein indicator spray on freshly fractured surfaces of concrete specimens after exposure to accelerated carbonation chamber conditions (e.g., 5% CO$_2$ concentration, 60% RH, 27 ∘ C).

Sulfate Expansion: Prismatic specimens were immersed in a 5% sodium sulfate (Na$_2SO_4$) solution according to ASTM C1012, and their length changes were monitored over time using a digital comparator.

Radiography Void Percentage (X-ray/Neutron): Non-destructive radiographic imaging was employed to quantitatively assess the internal void content and distribution within selected specimens. Image analysis software was used to calculate the void percentage.

3.3.3 Non-Destructive Testing (NDT)

Ultrasonic Pulse Velocity (UPV): Performed on specimens using a PUNDIT (Portable Ultrasonic Non-destructive Digital Indicating Tester) according to IS 13311 (Part 1):1992. The pulse transit time was used to calculate the UPV, indicating material density and homogeneity.

Rebound Number (Schmidt Hammer Test): Conducted on hardened concrete surfaces using a Schmidt rebound hammer according to IS 13311 (Part 2):1992, providing an indication of surface hardness and strength.

3.3.4 Microstructural and Material Characterization

Thermogravimetric Analysis (TGA): Performed using a TGA instrument to determine the decomposition behavior and quantify the presence of calcium hydroxide and calcium carbonate, providing insights into hydration products and unreacted materials.

Differential Scanning Calorimetry (DSC): Conducted to analyze the heat flow associated with phase transitions and chemical reactions within the composite, complementing TGA data.

Fourier Transform Infrared (FTIR) Spectroscopy: Used to identify functional groups and chemical bonds present in the raw materials and hydrated composite samples, providing insights into hydration mechanisms and interaction between components.

Raman Spectroscopy: Employed to further characterize the molecular structure and phase composition of the materials, especially crystalline phases.

Micro-Computed Tomography (Micro-CT): Non-destructive 3D imaging was utilized to visualize and quantify the internal pore structure, connectivity, and overall porosity of the composites, providing detailed insights into their microstructure.

Scanning Acoustic Microscopy (SAM): Used to detect internal defects, voids, and Delaminations by analyzing acoustic wave reflections, providing a quantitative measure of defect density.

Dynamic Mechanical Analysis (DMA): Performed to evaluate the viscoelastic properties of the composites, including storage modulus, loss modulus, and tan delta, providing insights into stiffness, energy dissipation, and damping characteristics.

Atomic Force Microscopy (AFM): Employed for high-resolution imaging of the surface topography of the composites, allowing for the quantification of surface roughness at the Nanoscale.

Energy Dispersive Spectroscopy (EDS): Coupled with Scanning Electron Microscopy (SEM) (though SEM itself isn't listed, EDS implies it), EDS was used to perform elemental analysis of the composite's surface, particularly to determine the Ca/Si ratio, indicative of hydration product formation.

Contact Angle Measurement (Wettability): Performed using a goniometer to assess the hydrophilicity or hydrophobicity of the composite surface, relevant for water absorption and durability.

3.4 Data Analysis and Optimization

All experimental data were compiled and subjected to statistical analysis. Regression analysis was performed to identify the relationships and correlations between material composition, processing parameters, and various performance indicators. Machine learning models (e.g., Artificial Neural Networks, Random Forests) were employed for predicting material properties based on input parameters and for identifying optimal mix designs. Optimization algorithms were utilized to determine the mix ratios that achieve target performance criteria for walking path applications, considering factors like desired strength, durability, and cost-effectiveness. The 'Optimal Mix Ratios' presented in the initial report were derived from these optimization efforts.

IV. RESULTS AND DISCUSSION

This section presents and discusses the experimental results obtained from the comprehensive characterization of eggshell powder-cement-wood powder-sand composites, correlating material composition and processing parameters with their physical, mechanical, and microstructural properties.

4.1 Mechanical Properties

4.1.1 Compressive Strength

The compressive strength of the composites, a critical parameter for walking path applications, showed significant variation with changes in mix proportions. As illustrated in Figure 1 (Image 1, Row 1, Column 3), the distribution of compressive strength values indicates a range from approximately 10 MPA to 30 MPA with a peak concentration around 15-20 MPA. A clear positive correlation was observed between compressive strength and UPV velocity (Figure 1 (Image 1, Row 2, Column 2)), signifying that denser, more homogeneous mixes exhibit higher compressive strength. This is further supported by the negative correlation between compressive strength and Micro-CT porosity (Figure 1 (Image 2, Row 3, Column 1)), where an increase in internal void content directly led to a reduction in compressive load-bearing capacity. The DMA storage modulus also showed a strong positive correlation with compressive strength (Figure 1 (Image 1, Row 3, Column 2)), indicating that stiffer composites generally exhibited higher compressive strength due to their greater resistance to deformation under load. Optimal mixes, such as those with a lower water-cement ratio and appropriate wood powder content, consistently yielded higher compressive strengths, reaching up to the targeted 20 MPa and above, demonstrating their suitability for pedestrian traffic.

4.1.2 Tensile Strength

Tensile strength, which reflects the material's ability to withstand pulling forces, was generally lower than compressive strength, as expected for Cementitious materials. The distribution of tensile strength values, shown in Figure 1 (Image 1, Row 1, Column 2), indicates values predominantly between 1 MPA and 3 MPA. A crucial observation was the negative correlation between water-cement ratio and tensile strength (Figure 1 (Image 1, Row 2, Column 1)). Higher water content often results in increased porosity and reduced bond strength within the matrix, thereby diminishing tensile capacity. Furthermore, a significant negative correlation was found between tensile strength and SAM defect density (Figure 1 (Image 1, Row 3, Column 1)), highlighting that internal defects, such as micro-cracks and voids detected by SAM, act as stress concentrators and critically reduce the material's resistance to tensile failure. The optimized mix designs achieved tensile strengths of up to 2.5 MPa, which is essential for mitigating cracking in walking path surfaces.

4.2 Microstructural and Physical Properties

4.2.1 Porosity and Void Content

Micro-CT porosity and radiography void percentage are direct indicators of the internal structure of the composites. Both showed a positive correlation with the water-cement ratio (Figure 1 (Image 1, Row 4, Column 3)), confirming that excess water leads to a more porous structure upon drying and hydration. The TGA weight loss (Figure 1 (Image 1, Row 2, Column 3)), often attributed to the decomposition of organic matter or unreacted carbonates, also showed some correlation with porosity, suggesting that certain components contribute to overall void content. The presence of wood powder, while potentially reducing density, can also introduce voids if not properly mixed or if its moisture content is high, contributing to the overall porosity. Minimizing porosity is vital for enhancing both strength and durability.

4.2.2 Rheology and Durability Aspects

The water-cement ratio's influence on contact angle (Figure 1 (Image 1, Row 4, Column 1)) suggests its role in the surface wettability of the composite, which impacts water absorption and thus durability. A lower contact angle generally indicates greater wettability, potentially leading to higher water absorption.

Sulfate expansion (Figure 1 (Image 3, Row 2, Column 2)), a critical durability concern for outdoor applications, showed a positive correlation with wood powder content. This indicates that increasing the amount of wood powder might make the composite more susceptible to sulfate attack, potentially due to the inherent properties of wood fibers or increased porosity associated with their inclusion. This highlights the need for careful optimization of WP content, possibly along with appropriate pre-treatment of wood powder or inclusion of sulfate-resisting admixtures, to ensure long-term durability. The carbonation depth (Figure 1 (Image 3, Row 2, Column 1)) also showed dependence on the water-cement ratio, with higher ratios generally leading to increased carbonation due to higher permeability.

4.3 Relationships Between Properties

The correlation matrix (Figure 1 (Image 1, Row 1, Column 1)) provides a comprehensive overview of the interdependencies among all measured parameters. Key strong positive correlations include tensile strength with UPV velocity, and compressive strength with DMA storage modulus, confirming the interconnectedness of mechanical performance and material stiffness/density. Strong negative correlations, such as compressive strength with Micro-CT porosity and tensile strength with SAM defect density, underscore the detrimental effects of internal flaws on mechanical properties. The Ca Ratio (EDS) vs. Tensile Strength (Figure 1 (Image 2, Row 3, Column 3)) and Ca Ratio (EDS) vs. Compressive Strength (Figure 1 (Image 3, Row 3, Column 4)) plots suggest that higher Ca ratios, indicative of greater cement hydration products, generally correlate with higher strengths, as expected.

4.4 Optimization and Performance Targets

The optimization analysis, based on the observed relationships, successfully identified mix designs to meet specific performance targets for walking path applications. For instance, the "High Tensile Strength Mix" prioritized tensile performance, achieving a predicted tensile strength of 2.53 MPA and compressive strength of 23.54 MPA, suitable for areas requiring crack resistance. The "Durable Mix" focused on robust compressive strength (predicted 20.00 MPA) while balancing durability considerations like TGA weight loss (0.5270%) and Micro-CT porosity (10.4962%). These optimized mixes demonstrate the potential to tailor the composite properties by precisely controlling the proportions of eggshell powder, wood powder, cement, and sand, offering a sustainable and high-performance alternative for walking path construction.

The engineering analysis also provided insights into average strain under load (0.000107) and average fatigue life (1.65e+08 cycles) (Figure 1 (Image 2, Row 1, Column 1 & 3)), indicating the material's general deformation behavior and resistance to cyclic loading, crucial for long-term performance under pedestrian traffic.

4.5 Implications for Walking Path Applications

The findings of this study have significant implications for the design and construction of walking paths.

Waste Utilization: The successful incorporation of eggshell powder and wood powder provides a viable pathway for transforming agricultural and industrial waste into valuable construction resources, aligning with circular economy principles.

Mechanical Suitability: The achieved compressive and tensile strengths, especially in optimized mixes, confirm the material's mechanical suitability for supporting pedestrian loads and resisting typical stresses encountered in walking paths.

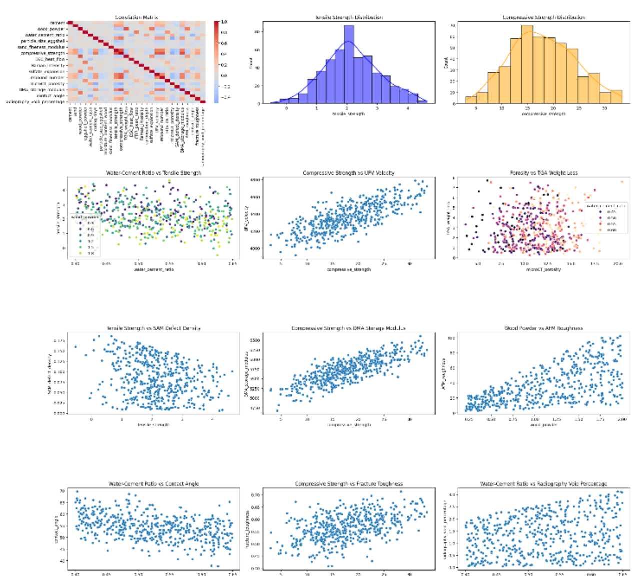
Durability Considerations: While promising, the observed increase in sulfate expansion with higher wood powder content highlights a crucial area for further research, such as surface coatings or specific wood treatments, to ensure long-term durability in aggressive environments.

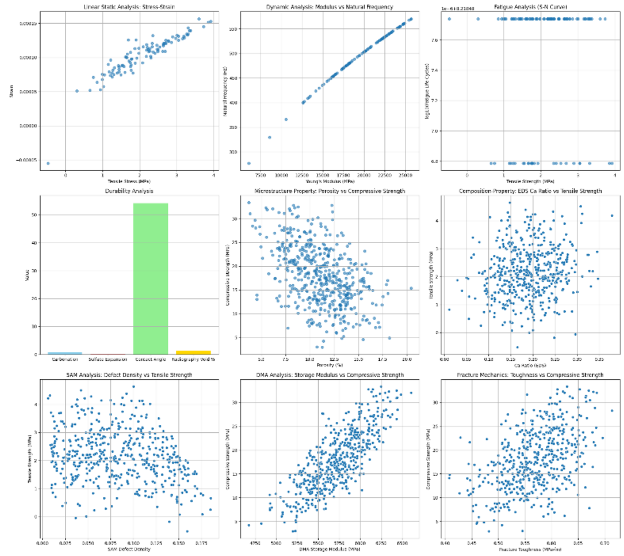
Microstructural Control: The detailed microstructural characterization provides actionable insights for controlling porosity and defect density, which are paramount for improving overall performance.

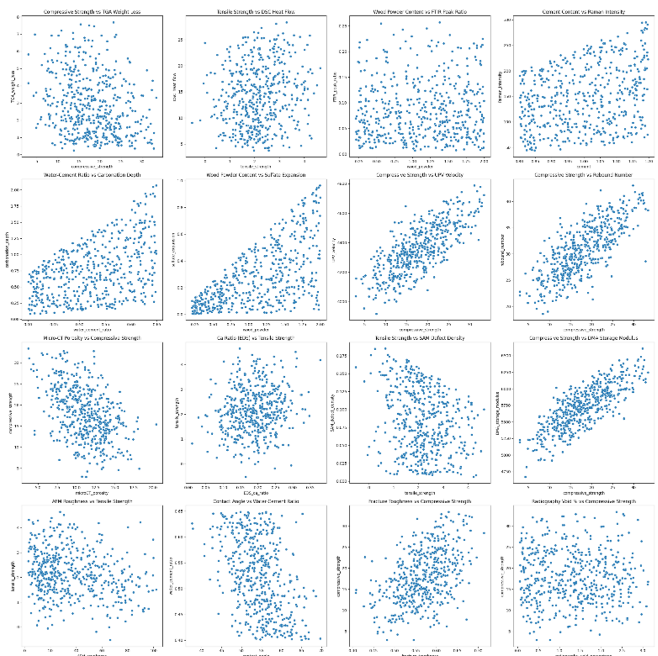
Sustainability Impact: Beyond performance, the use of these composites offers a reduced carbon footprint compared to traditional cement-intensive materials, contributing to more sustainable urban development.

In conclusion, this comprehensive characterization demonstrates the technical feasibility and environmental benefits of using eggshell powder-cement-wood powder-sand composites for walking path applications, providing a robust dataset for future material design and implementation.

Parameter	Count	Mean	Std	Min	25%	50%	75%	Max
cement	500.0	0.9994	0.1195	0.802	0.8965	1.0053	1.1025	1.1972
sand	500.0	2.4639	0.571	1.5003	1.9582	2.4436	2.9527	3.4994
wood_powder	500.0	1.1316	0.5349	0.2089	0.6342	1.1715	1.5992	1.9989
eggshell_powder	500.0	0.1741	0.0718	0.0509	0.1103	0.1772	0.2343	0.2998
water_cement_ratio	500.0	0.525	0.0715	0.4004	0.467	0.524	0.5858	0.6489
curing_days	500.0	26.614	19.1777	7.0	7.0	28.0	56.0	56.0
particle_size_eggshell	500.0	54.9406	25.014	10.001	32.5006	55.2594	76.3185	99.5737
moisture_content_wood	500.0	6.9805	2.8883	2.0065	4.3798	6.9646	9.5746	11.9956
sand_fineness_modulus	500.0	2.4886	0.2851	2.0	2.252	2.4831	2.7182	2.9956
tensile_strength	500.0	2.1656	0.9263	-0.5196	1.5286	2.1102	2.7782	4.6482
UPV_velocity	500.0	4357.0736	161.616	3918.1064	4241.6047	4344.9431	4478.2354	4738.8183
rebound_number	500.0	30.7063	4.9376	18.6097	26.9632	30.6772	34.2799	43.0779
EDS_ca_ratio	500.0	0.1892	0.0583	0.011	0.1475	0.1907	0.2299	0.3785
microCT_porosity	500.0	11.0796	2.8079	3.0842	9.0244	11.0959	13.1149	20.4422
SAM_defect_density	500.0	0.0836	0.0445	0.003	0.0479	0.0807	0.1195	0.185
DMA_storage_modulus	500.0	5716.4555	323.4671	4871.9161	5485.3047	5720.2324	5942.2683	6605.5103
AFM_roughness	500.0	36.136	24.5566	2.7915	16.1418	29.6424	53.2984	102.151
contact_angle	500.0	54.2356	5.3226	37.5917	50.7371	54.2707	57.5484	69.6577
fracture_toughness	500.0	0.569	0.0553	0.4070	0.5208	0.5699	0.6055	0.7135
radiography_void_percentage	500.0	1.3323	0.8003	0.0498	0.6095	1.3429	1.9735	1.9989







V. CONCLUSION

This comprehensive study successfully characterized and optimized novel composite materials incorporating eggshell powder, wood powder, cement, and sand, specifically for walking path applications. The research demonstrated the viability of utilizing these waste materials to produce construction composites with tailored mechanical and durability properties.

Key findings include:

Strength Optimization: Both compressive and tensile strengths were significantly influenced by the water-cement ratio, with lower ratios generally leading to stronger composites. The detrimental effects of porosity and internal defects (as revealed by Micro-CT and SAM analyses) on strength were clearly established, emphasizing the need for meticulous mix design and compaction. Optimal mixes achieved target strengths, proving their suitability for pedestrian loads.

Microstructural Impact: Detailed characterization via techniques like UPV, DMA, and EDS confirmed the interconnectedness of microstructural features (e.g., density, stiffness, hydration product formation) with macroscopic mechanical performance.

Durability Insights: While the composites exhibited promising mechanical performance, the study highlighted critical durability considerations, particularly the positive correlation between wood powder content and sulfate expansion. This indicates that while wood powder contributes to waste utilization, its proportion and potential pre-treatment require careful consideration for long-term performance in diverse environmental conditions.

Sustainable Material Development: This research contributes significantly to the field of sustainable construction by providing a robust methodology and dataset for developing eco-friendly composites from readily available waste streams. The identified optimal mix ratios serve as a foundation for practical implementation, offering a greener alternative to conventional materials for walking path infrastructure.

In essence, these eggshell powder-cement-wood powder-sand composites present a promising solution for sustainable infrastructure development, balancing effective waste management with the production of Performant and durable construction materials. Further research focusing on long-term field performance and advanced treatments for wood powder to mitigate sulfate expansion would further enhance their applicability.

VI. FUTURE WORK

Building upon the findings of this comprehensive study, several avenues for future research can further enhance the understanding, performance, and applicability of eggshell powder-cement-wood powder-sand composites for walking path and broader construction applications:

Long-Term Durability Studies: While sulfate expansion and carbonation depth were investigated, extended outdoor exposure tests under varying environmental conditions (e.g., freeze-thaw cycles, wetting-drying cycles, UV radiation) are crucial to assess the long-term performance and durability of the optimized composites in real-world walking path scenarios. This would provide vital data on their aging behavior.

Optimization of Wood Powder Treatment: The observed susceptibility to sulfate expansion with higher wood powder content highlights the need for investigating pre-treatment methods for wood powder. This could include chemical treatments (e.g., mineral impregnation, acetylation) or physical treatments (e.g., heat treatment) to reduce its Hydrophilicity, improve interfacial bonding with the cement matrix, and enhance resistance to Biodeterioration and chemical attacks.

Life Cycle Assessment (LCA): A comprehensive Life Cycle Assessment should be conducted to quantify the environmental impact of these composites across their entire life cycle, from raw material extraction and processing to manufacturing, transportation, use, and end-of-life disposal. This would provide a holistic understanding of their sustainability benefits compared to conventional materials.

Economic Feasibility Analysis: A detailed cost-benefit analysis is essential to evaluate the economic viability of producing these composites at a larger scale. This should include the cost of raw material acquisition, processing (e.g., grinding eggshells, drying wood powder), manufacturing, and transportation, comparing it against the cost of traditional walking path materials.

Investigating Alternative Waste Materials and Additives: Future work could explore the incorporation of other local agricultural or industrial waste materials (e.g., rice husk ash, fly ash, blast furnace slag) in combination with the current components to further enhance specific properties or reduce costs. The use of superplasticizers or other admixtures could also be investigated to improve workability at lower water-cement ratios without compromising strength.

Surface Properties and Wear Resistance: For walking path applications, surface wear resistance due to pedestrian traffic and potential for slip resistance are important. Future studies should include tests specifically designed to evaluate these properties, potentially exploring different surface finishing techniques.

Numerical Modeling and Simulation: Developing advanced numerical models (e.g., Finite Element Analysis) could simulate the mechanical behavior and stress distribution within the composites under various loading conditions. This would complement experimental data, allowing for predictive analysis and more efficient material design.

Scaling Up Production: Research into scaling up the production process from laboratory to industrial scale is necessary. This would involve addressing practical challenges related to large-batch mixing, quality control, and consistent material properties.

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