Optimizing Concrete Durability in Aggressive Environments Using Silica-Rich Tropical Hardwood Ash as a Supplementary Cementitious Material (SCM)

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ABSTRACT

The advancements in concrete technology have focused on finding alternative binders to reduce the environmental impact and economic costs of Portland cement (PC) production. These efforts aim to lower the CO_2 emissions, conserve the finite natural resources, and cut the overall construction costs. However, most existing research mainly emphasizes the compressive strength, often overlooking durability—a critical property for concrete exposed to aggressive conditions. In response, the present study assesses the performance of silica-rich tropical hardwood ash as a Supplementary Cementitious Material (SCM), with a focus on improving durability. A total of 252 concrete cubes (100 mm × 100 mm × 100 mm) were prepared using a nominal mix ratio of 1:2:4 and a water–cement ratio of 0.55, with cement replaced at levels of 5%, 10%, 15%, 20%, and 25% by weight. Of these, 180 specimens were tested for compressive strength, while 72 were examined for abrasion resistance and water absorption at 28 and 56 days under both standard curing and sulfate-rich conditions. The results showed only a slight reduction in compressive strength at 20% replacement—0.84% under normal curing at 28 days and 1.63% for unblended mixes exposed to sulfate solution—while significant improvements were noted in abrasion resistance and water sorptivity at 56 days. Additionally, the tropical hardwood ash met the pozzolanic criteria specified in [14], demonstrating its potential as a sustainable binder suitable for durability-focused concrete applications.

Keywords-silica-rich tropical hardwood ash; supplementary cementitious material; concrete durability; aggressive environments; pozzolanic binder

I. INTRODUCTION

The human development demands have placed stress on environmental systems, primarily driven by the unsustainable resource consumption patterns. Among the most resource-intensive sectors is the construction industry, where the production and use of concrete, a dominant material, consumes vast quantities of cement, aggregates, and water. Although infrastructure development delivers essential societal and economic benefits by enabling the construction of homes, roads, hospitals, and educational facilities, it involves environmental challenges. The extraction and processing of raw materials for concrete, coupled with the operational activities on construction sites, contribute to significant air and water pollution, land degradation, and high energy usage [1, 2]. Moreover, concrete alone is responsible for twice the environmental footprint of all other building materials combined, making it a critical focus in sustainability-oriented innovation.

The ecological burden of concrete largely stems from the substantial carbon footprint of cement manufacturing. For every ton of PC produced, almost an equivalent mass of carbon dioxide (CO_2) is released, underscoring the incompatibility of conventional cement with global climate mitigation goals [3]. This has prompted a shift toward more sustainable construction practices, emphasizing the need to reduce embodied carbon in building materials [4]. Furthermore, the long-term availability of PC is threatened by the diminishing reserves of limestone, its primary raw material. As such, the industry is compelled to explore innovative pathways to reduce the cement usage, not only to lower emissions, but also to ensure material availability in the future. One potential strategy involves partially replacing PC with SCMs, especially those sourced from industrial by-products or agricultural residues. Blended cements incorporating pozzolanic materials have shown substantial improvements in environmental, economic, and technical performance [5, 6]. Through their reaction with calcium hydroxide released during cement hydration, pozzolans generate supplementary Calcium Silicate Hydrates (CSH), thereby improving both the strength and long-term durability of concrete. Research has validated the feasibility of using ash from various waste streams, including landfill incineration residues and fly ash, to produce low-carbon eco-cement alternatives [7]. Among these options, wood ash is a viable SCM due to its pozzolanic behaviour, rich silica content, and local availability in timber-producing regions. It has been demonstrated that integrating wood waste ash into concrete not only enhances its durability, but also addresses solid waste management challenges [8-10]. Despite this progress, certain high-potential biomass resources remain underexplored. One such material is the ash derived from tropical hardwood species commonly found in African savanna regions.

This research investigates the use of ash derived from a native tropical hardwood, a species traditionally utilized in roofing and carpentry but not previously explored as a cement replacement material. Despite being regarded as a timber of only moderate quality [11, 12], its ash is expected to exhibit adequate pozzolanic activity to function as a sustainable SCM. Aligned with efforts to advance high-performance and eco-friendly concrete technologies [13], the study evaluates both the mechanical and durability properties of concrete incorporating different proportions of silica-rich tropical hardwood ash under chemically aggressive exposure conditions. Despite the growing interest in sustainable alternatives to PC, the use of silica-rich tropical hardwood ash remains underexplored, particularly in regions where such biomass resources are abundant. Although the pozzolanic properties of widely studied agricultural and industrial ashes, including rice husk ash, fly ash, and incinerator residues, have been addressed, there is a scarcity of experimental data concerning the behavior of tropical hardwood ash in concretes subjected to chemically aggressive conditions. This gap is particularly evident in sub-Saharan African contexts, where large quantities of tropical hardwood waste are generated but not valorized. Given the high silica content of certain hardwood ashes, they may offer significant benefits in enhancing durability, reducing permeability, and mitigating the environmental impacts associated with cement production. Therefore, this research is significant as it investigates the untapped potential of a regionally available, renewable biomass waste in addressing both the sustainability challenges and performance deficiencies in concrete. By doing so, it contributes to the advancement of green construction materials and supports the global agenda for low-carbon, durable infrastructure solutions.

II. MATERIALS AND METHODS

A. Experimental Program

The experimental materials comprised Dangote OPC, crushed stone serving as the coarse aggregate, and sharp river sand as the fine aggregate. To obtain the ash, the chosen tropical hardwood species, widely available in Makassar, Indonesia, was incinerated in a drum-type furnace owing to equipment constraints. This ash was initially screened using a 300 µm sieve to eliminate oversized particles. For uniform fineness, the ash was further processed by grinding in a ball mill in small batches, followed by re-sieving to ensure a consistent particle size of 75 µm. The resulting material, identified as silica-rich tropical hardwood ash, is illustrated in Figure 1 after passing through the 75 µm mesh. This investigation explores the potential of silica-rich tropical hardwood ash as a partial cement substitute in concrete, specifically under chemically aggressive conditions. Despite its widespread availability in sub-Saharan Africa and long-standing use in construction applications, such as roofing, this wood species has received little attention for its potential as an SCM. Its chemical characterization confirmed that the ash complies with the pozzolanic requirements of [14], as its combined oxide content ($SiO_2 + Al_2O_3 + Fe_2O_3$) surpasses the 70% benchmark, distinguishing it from many other biomass-derived ashes.

Fig. 1. Silica-rich tropical hardwood ash.

To evaluate its effect on concrete performance, six different mix proportions were prepared, consisting of 100% OPC and replacements of 5%, 10%, 15%, 20%, and 25% tropical hardwood ash by weight of cement. These substitution levels were chosen in line with methodologies reported in previous investigations on wood ash-based concrete [15]. A uniform water-to-binder (w/b) ratio of 0.55 was applied to all mixtures to maintain consistent workability. The prepared concretes were then assessed through comprehensive material characterization, compressive strength testing, abrasion resistance, water absorption, and visual inspections under varied curing conditions.

B. Materials Characterization Test

The physical properties of the constituent materials, namely crushed granite (coarse aggregate), river sand (fine aggregate), OPC, and silica-rich tropical hardwood ash, were evaluated through bulk density and specific gravity measurements carried out in compliance with [16]. Bulk density was determined by measuring the mass of each material within a known volume, while specific gravity was evaluated using the pycnometer method with a calibrated density bottle and analytical balance. These measurements are essential in concrete mix design because they influence the water demand, compactness, and ultimately the workability, strength, and stability of hardened concrete. Following standardized procedures ensures accuracy and repeatability, which is particularly important when incorporating alternative binders into sustainable concrete production [16]. The setting behavior and soundness of cement pastes containing different proportions of silica-rich tropical hardwood ash were evaluated. The initial and final setting times were measured using the Vicat apparatus, while soundness was assessed with the Le Chatelier method, following [17]. Six blend ratios (0%–25% ash replacement) were tested to examine the hydration characteristics and consistency. These tests provide insight into the changes in water demand caused by ash incorporation and are essential for determining the feasibility of using tropical hardwood ash in concrete, particularly its effect on early-age performance and its potential to enhance sustainable mix design [17].

C. Fresh-State Performance of Concrete Blended with Tropical Hardwood Ash

The consistency of fresh concrete incorporating silica-rich tropical hardwood ash was evaluated through the slump test, following the standard procedure of [18], which is widely recognized for assessing concrete workability. The test setup included essential tools, such as a slump cone mold, tamping rod, sampling tray, and measurement scale. Prior to testing, the mold's interior was moistened and placed securely on a flat surface to prevent displacement. The concrete was placed into the mold in three successive layers, with each layer compacted by 25 uniform strokes to remove any entrapped air. Once filled, the mold was lifted vertically, allowing the concrete to settle freely under its own weight. The slump value was determined by measuring the vertical displacement between the mold's original height and the subsided concrete profile, recorded with an accuracy of 5 mm. This procedure provides valuable insights into the ease of placement and handling of concrete modified with tropical hardwood ash, ensuring consistency and reliability in evaluating its fresh-state behavior within standardized parameters [18].

D. Evaluation of Hardened Concrete Properties

In this study, 342 concrete specimens were prepared and cured in two environments: clean water, used as the control, and a 2.2% magnesium sulfate ($MgSO_4$) solution, representing an aggressive chemical environment. The 2.2% concentration was chosen in line with established standards to ensure consistency and comparability in durability testing [19]. Concrete mixes containing 0%, 5%, 10%, 15%, 20%, and 25% silica-rich tropical hardwood ash as partial cement replacement were cast into both cube and cylindrical molds. Of these, 252 cube specimens were tested for compressive strength at 7, 14, 21, 28, and 56 days under both curing conditions. In addition, a subset of samples was evaluated for abrasion resistance and water absorption at 28 and 56 days to provide a comprehensive assessment of durability performance.

III. RESULTS AND DISCUSSION

A. Physical Density Properties

Table I presents the density-related properties of the main materials used in this study, including their specific gravity and bulk density. The silica-rich tropical hardwood ash showed a specific gravity of 2.38, which falls within the typical range for pozzolanic materials (2–2.5). This suggests good reactivity in cementitious systems, particularly its ability to bind with calcium hydroxide during hydration. Its bulk density, however, was comparatively low at 780 kg/m³, reflecting the lightweight nature typical of biomass-derived ashes. This characteristic may affect the behavior of fresh concrete, especially workability and volumetric mix proportions, highlighting the need for careful consideration when designing durable, ash-blended concrete mixtures.

TABLE I. PHYSICAL DENSITY CHARACTERISTICS OF CONSTITUENT MATERIALS

No	Material	Specific gravity	Bulk density (kg/m³)
1	Coarse aggregate	2.59	1,519
2	Fine aggregate	2.64	1,584
3	OPC	3.12	1,450
4	Silica-rich tropical hardwood ash	2.38	780

B. Oxide Composition of the Silica-Rich Tropical Hardwood Ash

Table II presents the oxide composition of the silica-rich tropical hardwood ash as determined by X-ray Fluorescence (XRF) analysis. The findings reveal that silicon dioxide (SiO_2) is the dominant oxide, likely resulting from mineral absorption from the soil throughout the tree's growth cycle, a characteristic commonly observed in lignocellulosic biomass [21]. The total proportion of silica, alumina, and ferric oxide surpasses 70%, thereby satisfying the chemical requirements for Class N pozzolans as defined by [14]. This suggests that the ash has significant pozzolanic potential, capable of contributing to the development of secondary cementitious compounds in blended concrete systems [14]. Additionally, the Loss on Ignition (LOI) is measured at 3.18%, well below the 10% threshold permitted by ASTM standards, indicating a minimal presence of unburnt organic matter. The low LOI value is significant, since high carbon residues may hinder the pozzolanic activity by functioning as inert fillers, which in turn could adversely affect the mechanical strength and durability of the concrete. The oxide profile supports the suitability of this tropical ash as an environmentally friendly SCM. These results verify the chemical adequacy of the ash for application as a pozzolanic material in the development of sustainable concrete.

TABLE II. OXIDE COMPOSITION OF SILICA-RICH TROPICAL HARDWOOD ASH (XRF RESULTS)

No	Oxide compound	Composition (% by weight)	Requirement of [14]
1	Silicon Dioxide (SiO_2)	74.6	
2	Aluminium Oxide (Al_2O_3)	5.8	
3	Iron Oxide (Fe_2O_3)	1.2	
Total ($SiO_2 + Al_2O_3 + Fe_2O_3$)		**81.6**	**≥ 70%**
4	Calcium Oxide (CaO)	3.1	—
5	Potassium Oxide (K_2O)	6.9	—
6	Titanium Oxide (TiO_2)	0.1	—
7	Manganese Oxide (MnO)	0.28	—
8	Zinc Oxide (ZnO)	0.05	—
9	Copper Oxide (CuO)	0.03	—
10	Barium Oxide (BaO)	0.09	—
11	Sulphur Trioxide (SO_3)	2.5	≤ 4%
12	LOI	3.18	≤ 10%

C. Mixtures Design

The concrete formulations in this research were designed to investigate the impact of substituting OPC with silica-enriched tropical hardwood ash at incremental replacement rates of 0%, 5%, 10%, 15%, 20%, and 25%. The total binder content remained constant, with the ash incrementally substituting for cement by mass. A consistent nominal mix of 1:2:4 (cement: sand: coarse aggregate) with a water-to-binder ratio of 0.55 was applied across all concrete formulations. Adjusted mix proportions for the cube and cylinder specimens are presented in Tables III and IV, respectively. As the percentage of ash increased, the cement content decreased proportionally, while other components, such as fine and coarse aggregates and water, remained constant. This uniformity ensured that any variations in performance could be directly attributed to the ash replacement level, thereby allowing for an assessment of the ash's influence on concrete properties. The mass adjustments remained within practical and engineering limits, enabling reliable mixing, workability, and casting processes. Maintaining a constant water content across all mixtures was critical in minimizing the external variables that could affect the workability and strength development. This approach ensured that the role of the tropical hardwood ash could be accurately isolated and evaluated in both fresh and hardened states.

TABLE III. MIX PROPORTIONS FOR CUBE SAMPLES (PER UNIT MIX)

% Replacement	Tropical hardwood ash (kg)	Cement (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	Water (kg)
0%	0	14.6	29.2	58.4	8
5%	0.73	13.87			
10%	1.46	13.14			
15%	2.19	12.41			
20%	2.92	11.68			
25%	3.65	10.95			

TABLE IV. MIX PROPORTIONS FOR CYLINDER SAMPLES (PER UNIT MIX)

% Replacement	Tropical hardwood ash (kg)	Cement (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	Water (kg)
0%	0	8.2	16.4	32.8	4.5
5%	0.41	7.79			
10%	0.82	7.38			
15%	1.23	6.97			
20%	1.64	6.56			
25%	2.05	6.15			

D. Hydration and Stability Properties of Binder Pastes

Assessment of cement paste soundness using the Le Chatelier apparatus indicated a progressive rise in expansion as the proportion of silica-rich tropical hardwood ash increased, ranging from 0.5 mm at 0% replacement to 1.4 mm at 25%. This modest growth could be attributed to residual unreacted ash particles or minor formation of expansive by-products; however, all measurements fell well within the specifications in [22], demonstrating that the incorporation of ash does not adversely affect the dimensional stability. Regarding the setting characteristics, the initial setting time increased from 150 min for the control mix to 198 min at a 25% replacement level, whereas the final setting time extended from 340 to 435 min. The retardation reflects the lower reactivity of the ash, which slows hydration kinetics. While extended setting times can enhance workability in hot climates, they may also require adjustments in the construction schedules. Consistency tests indicated a rise from 33% in the control paste to 40.8% at a 25% replacement level, which is attributed to the ash's porous and lightweight characteristics that elevate the water demand. This trend was reflected in the slump test, where flowability improved steadily with higher ash content. The slump values increased from 40 mm in the control to 75 mm at 25% replacement, and even a 5% substitution produced a 72% rise, from 36 mm to 62 mm. The improved workability can be explained by finer ash particles reducing the inter-particle friction, leading to easier handling and better surface finishing. These results suggest that while tropical hardwood ash enhances the fresh concrete properties, the optimal replacement level must balance the workability, setting characteristics, and strength development, as summarized in Table V.

TABLE V. EFFECTS OF SILICA-RICH TROPICAL HARDWOOD ASH ON SETTING PROPERTIES AND WORKABILITY OF CONCRETE

Replacement	**Soundness (mm)**	**Initial setting time (min)**	**Final setting time (min)**	**Consistency (%)**	**Slump (cm)**
0%	0.5	150	340	33	40
5%	0.6	158	355	34.5	58
10%	0.8	165	370	36	63
15%	1	175	388	37.8	66
20%	1.2	185	410	39	71
25%	1.4	198	435	40.8	75

E. Compressive Strength

Figure 2 illustrates the compressive strength progression of concrete containing different proportions of silica-rich tropical hardwood ash. The control mix (100% PC) consistently exhibited the highest strength, whereas the 20% replacement level provided the optimal balance between the pozzolanic activity and cement hydration. At this substitution, secondary CSH formation enhanced the matrix density and durability, while higher replacement levels caused strength reductions due to the excessive dilution of the OPC. As evidenced in Figure 3, the 80/20 PC/ash blend exhibited comparable strength gain trends to the control across curing stages, with the statistical analysis ($p = 0.9643$) confirming no significant difference between the mixes. Under aggressive exposure, as shown in Figure 4, the 20% blend slightly outperformed the control at 28 days in $MgSO_4$ solution (20.56 vs. 20.23 N/mm²), suggesting that the enhanced pozzolanic activity, pore refinement, and reaction product formation improved both the chemical resistance and mechanical strength. Figure 5 underscores the superior sulfate resistance of the 80/20 PC/ash concrete compared to the control mix. The improved performance under $MgSO_4$ exposure can be linked to multiple interrelated mechanisms. First, the pozzolanic reaction facilitated by the ash forms additional CSH gel, reducing free calcium hydroxide and enhancing the matrix's binding capacity. Second, the presence of potassium and sodium oxides in the ash may react with sulfate ions to form insoluble precipitates that seal the micro-pores, thereby limiting the ion penetration. Ultimately, the micro-filler action of the ash likely promotes a denser and less permeable microstructure, hence improving the concrete's resistance to sulfate attack. In contrast, the control mix does not benefit from these interactions, making it more vulnerable to deterioration. Although a 20% replacement seems optimal, higher levels, such as 25%, may excessively dilute the reactive cement content, compromising both the structural integrity and long-term performance of the concrete. Visual inspections further reinforced the mechanical findings, as the control concrete (100% PC) exhibited distinct signs of surface deterioration, notably the formation of a whitish deposit commonly associated with magnesium sulfate ($MgSO_4$) attack. In contrast, the concrete incorporating 20% silica-rich tropical hardwood ash showed no visible signs of surface degradation, implying superior resistance to sulfate intrusion.

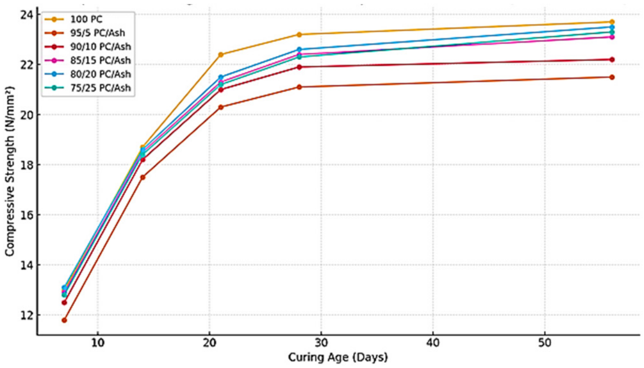

Fig. 2. Progression of compressive strength in water-cured concrete.

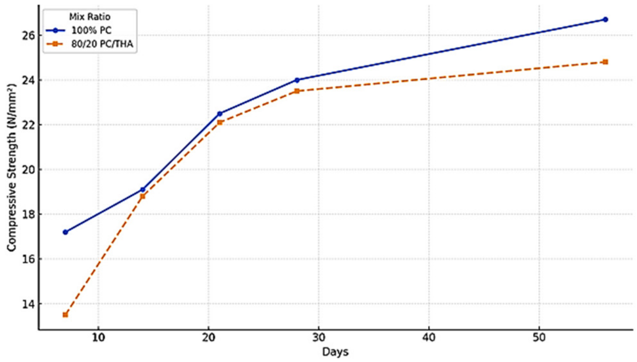

Fig. 3. Evaluation of compressive strength for 100% PC and 80/20 PC/THA concrete mixes cured in water.

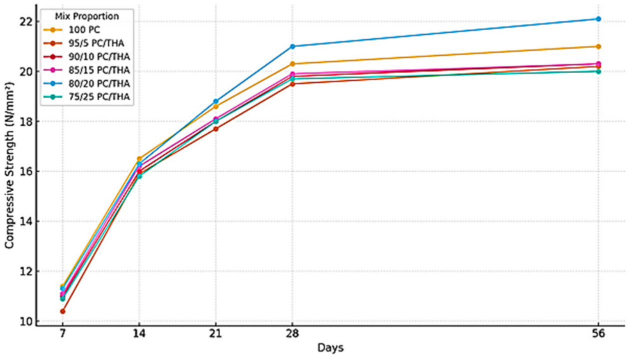

Fig. 4. Strength performance of concrete exposed to magnesium sulfate environment.

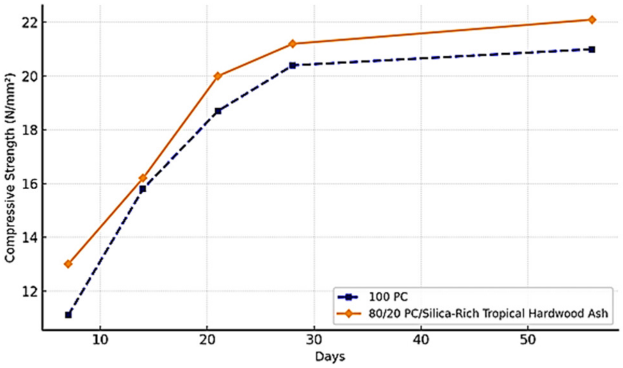

Fig. 5. Compressive strength behavior of OPC and 20% silica-rich ash concrete under magnesium sulfate exposure.

This improved durability is likely due to the ash's capacity to refine the pore structure and lower calcium hydroxide levels, thus restricting the development of harmful reaction products. An observable inverse relationship emerged between the replacement level of the ash and the extent of surface scaling; higher proportions of the ash correlated with a reduced manifestation of the whitish scum. The whitish deposit, primarily consisting of magnesium hydroxide along with other magnesium compounds, forms when $MgSO_4$ reacts with calcium hydroxide ($Ca(OH)_2$) in the cement matrix, yielding both $Mg(OH)_2$ and calcium sulfate. This reaction ($MgSO_4 + Ca(OH)_2 \rightarrow Mg(OH)_2 + CaSO_4$) is a key indicator of sulfate-induced degradation, which compromises the integrity of concrete. The mitigation of such visual and chemical damage in ash-blended specimens highlights the potential of silica-rich tropical hardwood ash as an effective SCM for sulfate-rich environments. The improved durability noted in concretes incorporating tropical hardwood ash is mainly attributed to the pozzolanic reaction between the ash's silica and calcium hydroxide, which promotes the formation of additional CSH. This secondary CSH phase refines the pore structure, reduces permeability, and creates a denser microstructure that is less susceptible to the ingress of sulfates and chlorides. Similar mechanisms have been reported for fly ash and rice husk ash, where pore refinement significantly improves sulfate resistance and chloride penetration resistance. The consistency of the results obtained in the present work with these studies suggests that tropical hardwood ash, despite its different origin, follows comparable reaction pathways. Furthermore, the reduced visible surface deterioration observed in ash-containing mixes supports the hypothesis of enhanced matrix densification. Future microstructural studies (e.g., SEM, MIP) would be valuable to confirm these mechanistic insights.

F. Abrasion Resistance

The incorporation of silica-rich tropical hardwood ash as a partial replacement for PC markedly improves the abrasion resistance of concrete under both standard and aggressive curing conditions. With a 20% replacement of PC by the ash, the concrete mix showed substantially reduced weight loss from abrasion after 56 days of curing, registering just 0.04% in water and 0.05% in magnesium sulphate ($MgSO_4$) solution. In contrast, the control mix (100% PC) experienced higher surface degradation, with weight losses of 0.08% and 0.16%, respectively. This enhancement in performance is ascribed to the pozzolanic properties of the ash, which interact with the calcium hydroxide released during cement hydration to form supplementary CSH. The development of CSH results in a denser and more compact microstructure, thereby restricting both the depth and severity of surface abrasion. These findings underscore the potential of silica-rich tropical hardwood ash to enhance the durability and mechanical integrity in concrete, particularly in environments where surface abrasion is a critical concern.

G. Water Absorption

The water absorption test results for concrete specimens cured under different conditions reveal a clear pattern: the partial replacement of PC with silica-rich tropical hardwood ash significantly improves the concrete's resistance to moisture penetration. Throughout the 56-day curing period, water absorption values declined progressively, with specimens containing 0% ash exhibiting a sorptivity of 0.35%, while those with 25% replacement showed a significantly lower value of 0.09%. These findings align with [22], according to which concrete absorption should not surpass 5%. The reduction in sorptivity observed with a higher ash content is attributed to the pozzolanic reaction of the silica-rich ash, which interacts with the released calcium hydroxide to produce additional CSH gel. This gel improves the microstructural density of the concrete matrix, thereby reducing the porosity and permeability. Even in aggressive environments, such as magnesium sulphate ($MgSO_4$) exposure, ash-blended concrete maintained lower absorption rates compared to the control, demonstrating enhanced resistance to chemical intrusion. Overall, the inclusion of silica-rich tropical hardwood ash contributes significantly to the development of durable, low-permeability concrete suitable for use in moisture-laden and chemically aggressive conditions. Previous studies have shown that conventional SCMs, such as fly ash and ground granulated blast furnace slag enhance durability by refining the pore structure and reducing permeability, especially under aggressive environmental conditions. Rice husk ash, another silica-rich agro-waste, has also been reported to improve sulfate and chloride resistance owing to its high amorphous silica content. Tropical hardwood ash demonstrates comparable silica content and pozzolanic activity, indicating similar potential for enhancing durability. Unlike industrial by-products, such as fly ash and slag, hardwood ash originates from biomass waste, aligning more closely with the circular economy principles. This makes tropical hardwood ash a promising alternative SCM, particularly in regions where industrial by-products are limited but biomass residues are plentiful.

IV. CONCLUSIONS

This study examined the mechanical and durability performance of Portland cement (PC) concrete incorporating silica-rich tropical hardwood ash under aggressive environmental conditions. A total of 252 concrete cubes were cast and tested over a 56-day curing period, with compressive strength, abrasion resistance, and water absorption evaluated in both water and magnesium sulphate ($MgSO_4$) solutions. Visual inspections were also conducted on specimens exposed to $MgSO_4$. The results showed that incorporating 20% tropical hardwood ash significantly enhanced the sulphate resistance, with improved the compressive strength and reduced the surface degradation compared to the control mix. These improvements can be attributed to an optimized pozzolanic reaction that generated additional Calcium Silicate Hydrates (CSH) and refined the microstructure, thus lowering permeability and limiting the ingress of aggressive ions. The visual observations supported these findings: concrete with 20% ash showed no visible deterioration, while the control samples displayed surface damage and whitish scum deposits. Beyond chemical resistance, tropical hardwood ash also improved resistance to mechanical wear. At 20% replacement, the abrasion losses were substantially lower than in the control mixes across both curing environments. Similarly, water absorption decreased with increasing the ash content, confirming reduced sorptivity and better protection against moisture and chemical intrusion. Overall, these findings demonstrate that silica-rich tropical hardwood ash enhances both the mechanical properties and durability of concrete. Its ability to improve sulfate resistance, abrasion resistance, and impermeability highlights its promise as a sustainable Supplementary Cementitious Material (SCM) for durable construction applications.

V. LIMITATIONS AND FUTURE WORK

Although this research offers valuable insights into the short- to medium-term behavior of concrete incorporating silica-rich tropical hardwood ash, certain limitations persist. The durability assessment was restricted to 66 days, without extending to longer periods (90, 180, or 365 days) that could capture long-term pozzolanic activity and microstructural evolution. Furthermore, no formal statistical analysis was performed to validate the significance of the differences between the control and ash-blended mixes, which limits the robustness of the findings. The visual inspections suggested improved durability, but the absence of microstructural techniques, such as SEM, XRD, or MIP, restricted the ability to directly confirm the pore refinement, matrix densification, and phase transformations associated with pozzolanic reactions. Moreover, while the study emphasizes the promise of tropical hardwood ash as an SCM, it does not provide a quantification of its environmental advantages. No Life-Cycle Assessment (LCA) or carbon footprint estimation was conducted, leaving the ecological trade-offs of waste valorisation unexplored. Future studies should, therefore, include extended durability testing, comprehensive statistical validation, microstructural investigations, and detailed sustainability assessments. These steps will provide stronger evidence for the technical and environmental viability of tropical hardwood ash as a durable, eco-friendly alternative in concrete production.

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