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Assessing the Mechanical Properties and Durability of Concrete with Partial Cement Replacement by Rice Husk Ash (RHA) under Hydrochloric Acid Exposure

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Abstract: *This study evaluated the chemical, mineralogical, mechanical and durability performance of concrete containing a locally sourced rice husk ash (RHA) used to replace Limestone Portland Cement (OPC) at 0, 5, 10, 15 and 20% by mass. The aim was to determine whether practical (field-sourced) RHA can provide pozzolanic benefit and whether partial replacement affects resistance to aggressive hydrochloric-acid (HCl) exposure. RHA was characterised by X-ray fluorescence (XRF), and X-ray diffraction (XRD). Concrete mixes were cast, cured 28 days (control) and tested for compressive and splitting-tensile strength. A second set of specimens was water-cured for 28 days then immersed in 1.0 M HCl for 56 days and retested. Means (n=3) and percentage strength loss were computed and microstructural analyses performed on selected samples. XRF showed SiO_2 = 81.06 wt% while XRD quantified crystalline SiO_2 ≈ 41.7 wt% and a large calcite fraction ≈ 33.5 wt% plus ≈4.1 wt% graphite, indicating limited reactive (amorphous) silica. 28-day compressive strengths fell with increasing RHA: M0 = 25.16 MPa, M5 = 22.87 MPa, M10 = 21.96 MPa, M15 = 20.99 MPa, M20 = 16.74 MPa. After 56 days HCl immersion compressive strengths were M0 = 20.87 MPa, M5 = 19.06 MPa, M10 = 15.78 MPa, M15 = 18.36 MPa, M20 = 11.27 MPa. Compressive strength loss relative to 28-day baseline was lowest for M15 (~12.5%) and highest for M20 (~32.7%).The tested, unprocessed RHA contains substantial inert/carbonate phases that limit pozzolanic contribution and increase vulnerability to acid attack at high replacement levels. Modest replacement (≤10%) is advisable for this material; higher substitutions require RHA upgrading (controlled calcination, de-carbonation, milling) and re-qualification before structural use.*

Keywords: *Rice husk ash (RHA); Supplementary cementitious material (SCM); Pozzolanic activity; Mineralogical characterization; Compressive strength; Hydrochloric acid resistance; Durability*

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1. INTRODUCTION

The global construction industry relies heavily on Ordinary Portland Cement (OPC) as its primary binder. However, the production of OPC is a significant source of anthropogenic carbon dioxide, accounting for approximately 7-8% of total global CO_2 emissions (Andrew, 2018). This substantial environmental footprint has driven extensive research into sustainable alternatives, primarily Supplementary Cementitious Materials (SCMs). SCMs, which include industrial by-products like fly ash and silica fume, as well as agricultural wastes, are used to partially replace cement, thereby reducing the carbon footprint and, in many cases, enhancing the long-term durability of concrete (Mehta & Monteiro, 2013).

Among agricultural wastes, Rice Husk Ash (RHA) has garnered significant attention. As a by-product of rice milling, RHA is abundant globally and its disposal presents an environmental challenge. When rice husks

are burned under controlled temperatures, the resulting ash is rich in amorphous silicon dioxide (SiO_2), which exhibits high pozzolanic reactivity (Givi et al., 2010). This pozzolanic reaction consumes the undesirable calcium hydroxide (CH) produced during cement hydration and forms additional calcium-silicate-hydrate (C-S-H) gel, the primary compound responsible for concrete's strength and durability.

However, the pozzolanic efficacy of RHA is not uniform; it is critically dependent on its chemical and mineralogical composition, which is dictated by the incineration process (Habeeb & Fayyadh, 2009). An RHA with a high concentration of crystalline silica or other impurities, such as calcite ($CaCO_3$), may exhibit reduced pozzolanic activity and act merely as a filler, potentially compromising the concrete's mechanical performance (Siddique & Khan, 2011). Furthermore, while the mechanical properties of RHA concrete are widely studied, its performance in aggressive chemical environments remains a critical area of investigation. Acid attack, in particular, is a severe durability concern for concrete structures in industrial zones, sewage systems, and coastal areas, where exposure to substances like hydrochloric acid (HCl) can lead to rapid degradation (Bâ et al., 2018).

Therefore, this study aims to provide a comprehensive evaluation of concrete mixes incorporating a specific, locally sourced RHA.

1.1 Supplementary Cementitious Materials (SCMs) for Sustainable Concrete

The imperative to reduce the environmental footprint of Ordinary Portland Cement (OPC) production has positioned supplementary cementitious materials (SCMs) at the heart of sustainable concrete technology. SCMs defined as materials which, when blended with OPC, contribute to the hardened concrete properties through hydraulic and/or pozzolanic activity are increasingly employed worldwide (Siddique & Khan, 2011). Recent life cycle assessment research highlights that the cement industry accounts for roughly 7–8 % of global carbon dioxide (CO_2) emissions, underscoring the urgency for SCM deployment (Klemm et al., 2019; see also “Low-Carbon Cement Production Issue Paper”, 2022). SCMs such as fly ash, ground granulated blast-furnace slag, calcined clays and agricultural-waste derived pozzolans substitute a portion of OPC, thereby reducing clinker content and associated emissions (Klemm et al., 2019; Alliance for Low-Carbon Cement & Concrete, 2023). For example, substituting 10 % of OPC with fly ash has been reported to reduce the global warming potential of concrete by up to ~9 % (Knight et al., 2023). Beyond environmental benefits, SCMs often improve technical properties of concrete such as reduced permeability, slower heat of hydration, and enhanced durability thereby aligning sustainability with performance (Federal Highway Administration, 2019; Holcim, n.d.). These dual advantages environmental and technical make SCMs a cornerstone of modern, greener concrete technology (Penta Consulting Group, 2022).

1.2 The Pozzolanic Nature of Rice Husk Ash (RHA)

Among agricultural-waste-derived materials, Rice Husk Ash (RHA) stands out due to the high silica (SiO_2) content in rice husks and the resulting ash when carefully processed (Ganesan, Rajagopal, & Thangavel, 2008). The efficacy of RHA as an SCM relies primarily on its pozzolanic activity the chemical reaction between amorphous silica in the RHA and calcium hydroxide ($Ca(OH)_2$) liberated during cement hydration, yielding additional calcium-silicate-hydrate (C–S–H) gel, which is the principal binding phase in concrete (Mehta & Monteiro, 2013). This reaction both consumes less desirable $Ca(OH)_2$ (which is prone to leaching or weakening) and increases the volume of C–S–H, thereby densifying the microstructure and improving strength and durability (Chindaprasirt & Rukzon, 2008; Saad et al., 2019). However, the pozzolanic performance of RHA is highly dependent on its physical and chemical state; key factors include the degree of silica amorphousness, fineness, specific surface area, and calcination/grinding regime (Nair et al., 2008; frontiers study, 2019). For example, combustion of rice husks at moderate temperatures (ca. 500–700 °C) tends to produce RHA rich in amorphous silica and hence high reactivity; whereas uncontrolled or higher-temperature burning (800–900 °C or more) often yields crystalline silica phases (quartz, cristobalite) that are largely inert and thus merely filler rather than reactive SCM (Li et al., 2025; The Influence of RHA on Mechanical Properties, 2023). Consequently, thorough mineralogical and chemical characterisation (e.g., via X-ray diffraction for amorphous vs crystalline silica, and LOI for carbon content) is a prerequisite to evaluate RHA’s suitability as a true pozzolan rather than a simple filler (Saad et al., 2019).

1.3 Influence of RHA on Mechanical Properties

The incorporation of rice husk ash (RHA) as a supplementary cementitious material has been shown to significantly affect the mechanical performance of cement-based composites. Due to its high silica content and pozzolanic activity, RHA interacts with hydration products to refine the microstructure and improve strength development. These effects are particularly evident in properties such as compressive strength, , and tensile strength capacity, which are governed by the degree of matrix densification and the formation of

additional calcium silicate hydrate (C–S–H). The extent of improvement is influenced by factors such as RHA fineness, burning temperature, replacement level, and curing conditions. As a result, RHA offers a sustainable pathway to enhance mechanical characteristics while reducing cement consumption.

1.4.1 Compressive Strength

A substantial body of experimental work affirms that high-quality, amorphous RHA may significantly enhance the compressive strength of concrete. The mechanism is dual: the pozzolanic reaction generates additional C–S–H, and fine RHA particles act as micro-fillers, improving particle packing and reducing porosity, thus yielding a denser matrix (Le et al., 2014; Islam & Fapohunda, 2023). Numerous studies identify an optimal replacement level, typically in the range of 10–20 % by weight of cement, beyond which the "dilution effect" (i.e., reducing OPC too far without commensurate reactive replacement) leads to strength reduction (Kartini et al., 2017; Islam & Fapohunda, 2023). Conversely, incorporation of RHA with low pozzolanic activity due to high crystalline silica or high residual carbon (LOI) often results in lowered strength and increased water demand, because inert particles or residual charcoal disrupt the hydration system and degrade microstructure (Ahsan & Hossain, 2018).

1.4.2 Splitting Tensile Strength

Splitting (or indirect) tensile strength is a key indicator of crack resistance and load-transfer capacity in concrete. The influence of RHA on tensile strength typically echoes its impact on compressive strength: by refining the pore structure and improving the interfacial transition zone (ITZ) between aggregates and cement paste, reactive RHA can improve tensile performance (Ahsan & Hossain, 2018). A denser matrix restricts micro-crack initiation and propagation, thereby increasing the load required to split the specimen. Some studies show that tensile strength gains are somewhat less pronounced than compressive strength gains, but the trend remains positive when RHA is optimally dosed and of high quality (Islam & Fapohunda, 2023).

1.5 Durability of RHA Concrete in Acidic Environments

Durability is as critical as strength for concrete in aggressive chemical environments. Acid attack especially by hydrochloric acid (HCl) is among the most severe degradation modes, where acid reacts first with $Ca(OH)_2$, then attacks the primary C–S–H binder, causing dissolution, increased porosity, and loss of mechanical integrity (Bertron, et al., 2004). High-quality RHA has been widely reported to enhance concrete's resistance to acid attack through two principal mechanisms:

i. by reducing the content of free $Ca(OH)_2$ via pozzolanic reaction (thus removing the most acid-vulnerable phase), and
ii. by producing a denser microstructure that slows the ingress of aggressive H^+ and Cl^- ions (Mehta, 1992; Li et al., 2025).

Recent studies further show that RHA-modified concrete exhibits lower permeability and reduced chloride penetration depth, thereby improving not only acidic resistance but also overall durability performance under aggressive chemical exposure (Li et al., 2025).

Although the scholarly literature is rich with trials demonstrating the benefits of high-reactivity, lab-produced amorphous RHA in concrete applications (Kartini et al., 2017; Nair et al., 2008), there remains a notable gap concerning the performance of RHA derived from practical, industrial or field-level burning operations. Such RHA is often of variable and inferior quality characterised by significant crystalline silica content, high unburnt carbon content, and other impurities and may not deliver the expected pozzolanic benefits. Little is known about whether such "low-quality" RHA can meaningfully enhance durability or whether its inert/filler nature or contaminant content (e.g., calcite which is vulnerable to acid) might instead accelerate degradation under aggressive conditions. This study therefore pivots from the idealised conditions towards a more practical scenario: it investigates the performance of concrete using as-sourced RHA, comprehensively characterised for its chemical and mineralogical composition, and assesses its mechanical and durability performance (particularly under HCl exposure). Such work addresses the pragmatic applicability of RHA in real-world circumstances, rather than controlled laboratory settings alone.

II. MATERIALS AND METHOD

2.1 Materials

The concrete mixtures in this study were prepared using standard Ordinary Portland Cement as the primary binder, which was supplemented with a processed Rice Husk Ash (RHA). Before being incorporated, the RHA was extensively characterized using XRF and XRD techniques to identify its precise oxide composition and quantify its crystalline and amorphous phases. For the aggregate framework, natural fine aggregate (sand) and crushed coarse aggregate were utilized. It's important to note that the proportions of these aggregates were kept constant

across all concrete batches to isolate the effects of the RHA.

Potable (tap) water was used for all stages of the experiment. This wasn't just for mixing the concrete components but was also used for curing the samples and for preparing the various aggressive solutions (like acids or sulfates) for the durability immersion tests. Finally, the mixtures were prepared without any chemical admixtures, such as superplasticizers or air-entraining agents, unless a specific mix variation is explicitly noted to include one.

2.2 Mix Proportions

To investigate the RHA's influence, we developed five distinct concrete mixes. The first, labeled M0, served as our control batch, containing 0% RHA. We then created four additional mixes by replacing a portion of the cement's mass with Rice Husk Ash at increasing levels: 5% (M5), 10% (M10), 15% (M15), and 20% (M20).

The precise "recipe" for each of these mixes, detailing the exact quantities of all materials per cubic meter, is fully summarized in Table 1. This table provides a complete breakdown of the proportions and includes the key values that guided the preparation of all our test specimens.

Table 1: Detailed Mix Design Table

S/N	Mix ID	QTY of Cement (kg/m³)	QTY of RHA (kg/m³)	QTY of Fine Agg (kg/m³)	QTY of Coarse Agg (kg/m³)	QTY of Water (kg/m³)	Water-Cement Ratio
1	M0 (0% RHA)	13.28	0.00	21.58	39.85	5.98	0.45
2	M5 (5% RHA)	12.62	0.66	21.58	39.85	6.31	0.50
3	M10 (10% RHA)	11.95	1.33	21.58	39.85	6.57	0.55
4	M15 (15% RHA)	10.63	2.66	21.58	39.85	6.38	0.60
5	M20 (20% RHA)	9.30	3.98	21.58	39.85	5.58	0.60

Water contents and w/c ratios were adjusted to maintain workable mixes across increasing RHA content.

2.3 Curing and Chemical Exposure Regimes

After demoulding, all specimens began curing in potable water, which we kept at a consistent laboratory temperature of 20 ± 2 °C. We established our baseline properties by testing these control specimens for both compressive and tensile strength right at the 28-day mark.

For the acid exposure phase of the study, specimens first underwent the same initial 28 days of water curing. Following this, we moved them into a far more aggressive environment, submerging them in a 5% hydrochloric acid (HCl) solution. To ensure the acidic attack remained consistently potent, we'd periodically refresh this solution to maintain its target pH and concentration. These samples were left to soak in the acid for an additional 28 days.

This gave us our two clear testing schedules: the control series was tested at 28 days, while the acid-exposed series was tested at a total age of 56 days (following its 28 days in water and 28 days in acid) to evaluate its deterioration.

2.4 Chemical and Mineralogical Characterisation

The representative samples of Rice Husk Ash (RHA) powder were subjected to X-ray fluorescence (XRF) analysis to evaluate their oxide composition. The obtained results, expressed in weight percentages, provided valuable information on the concentration of major oxides such as silicon dioxide (SiO_2), calcium oxide (CaO), and aluminum oxide (Al_2O_3). These oxides are essential indicators of the material's pozzolanic reactivity and its potential contribution to cementitious performance.In addition, X-ray diffraction (XRD) analysis was conducted on the RHA samples to examine the relative proportions of crystalline and amorphous phases present in the material. This technique enabled the identification and quantification of distinct mineral phases, offering insights into the structural characteristics of the ash. The interpretation of the phase composition data was particularly useful in assessing the pozzolanic potential of the RHA and determining the extent to which inert or deleterious components were present.

2.5 Mechanical Testing

Compressive strength testing was conducted on cylindrical concrete specimens measuring 150 × 300 mm in accordance with the relevant standard procedures. A calibrated compression testing machine

was used, applying load at a uniform rate suitable for the specimen dimensions to ensure consistency in measurement. The control specimens were tested after 28 days of standard curing, while the acid-conditioned samples were evaluated after 56 days. For each mix and testing age, the compressive strength results were calculated as the mean value obtained from three identical specimens, ensuring the reliability of the reported data.

Similarly, the splitting tensile strength of the concrete was determined using cylindrical samples tested under standardized conditions. The specimens were subjected to a consistent loading rate, and the test procedure followed established guidelines for accuracy and repeatability. Each set of results represents the average tensile strength derived from three specimens prepared under identical mix proportions and exposure conditions.

During testing, key data such as the maximum load at failure, the observed failure pattern, and the corresponding strength values were systematically recorded for every specimen. The reported results reflect the mean of the replicate values, providing a representative assessment of the material's mechanical performance.

2.6 Data Analysis and Reporting

For each concrete mix and testing age, the mean strength and corresponding standard deviation were determined based on the results obtained from replicate specimens. These statistical parameters provided an indication of the variability and reliability of the experimental data. Trends in compressive and tensile strength with respect to the varying percentages of Rice Husk Ash (RHA) replacement were analyzed and represented graphically to facilitate clear visual comparison and interpretation.

To assess the influence of RHA incorporation, the percentage change in both compressive and splitting tensile strengths was calculated relative to the control mix (M0) at each curing or conditioning period. This comparative approach allowed for the quantification of the performance improvement or reduction attributable to RHA inclusion. The mechanical test results were further interpreted in relation to the chemical and mineralogical properties obtained from the XRF and XRD analyses. This integration helped establish the connection between observed strength variations and the pozzolanic reactivity of the RHA, as well as the influence of phases such as crystalline silica, calcite, and other minor constituents.

2.7 Quality Control and Repeatability

All testing equipment and measuring instruments were carefully calibrated prior to the commencement of the experimental program to ensure accuracy and consistency of results. To maintain uniformity in material properties, single batches of RHA and aggregates were utilized throughout the study whenever possible, and any change in material source was thoroughly documented. Each test condition involved at least three specimens to ensure sufficient data reliability, and any anomalous results clearly attributed to casting defects or handling errors were excluded with appropriate justification. Comprehensive records, including details of mixing operations, ambient laboratory conditions, curing environments, and acid solution maintenance, were systematically maintained to guarantee full traceability and reproducibility of the experimental procedures.

2.8 Safety and Waste Handling

All activities involving chemical substances, particularly hydrochloric acid, were performed in accordance with established laboratory safety protocols. Personnel were required to wear appropriate personal protective equipment (PPE), and all operations were conducted under controlled conditions with adequate fume extraction and spill response measures in place. Waste solutions, including spent acids and rinse water, were neutralized prior to disposal to ensure compliance with institutional and environmental safety regulations. These measures were implemented to minimize health risks and environmental impact throughout the experimental process.

III. RESULTS AND DISCUSSION

3.1 Chemical composition (XRF)

Table 2: Oxide composition of RHA (wt%, XRF)

S/N	Oxide	Concentration (wt%)
1	SiO_2 (Silicon dioxide)	**81.06**
2	CaO (Calcium oxide)	**6.92**
3	Al_2O_3 (Aluminium oxide)	**2.31**
4	Fe_2O_3 (Iron oxide)	**1.17**
5	K_2O (Potassium oxide)	**2.46**
6	SO_3 (Sulphur trioxide)	**1.44**
7	P_2O_5 (Phosphorous pentoxide)	**0.63**
8	Cl (Chlorine)	**1.4**
9	MgO (Magnesium oxide)	**~1.70**
10	Others (TiO_2, Na_2O, minor oxides)	**<0.5 each**

XRF analysis shows that the RHA sample is dominated by silica (SiO_2 = 81.06 wt%), with smaller amounts of CaO, K_2 O and alumina. Trace levels of iron, magnesium and sulfur are present.

The very high total silica content indicates the potential for pozzolanic reactivity, provided a large fraction of that silica is amorphous. The presence of CaO (6.92 wt%) and SO_3 (1.44 wt%) suggests there may be minor free lime or carbonate-derived phases and sulphate-bearing impurities. Potassium and chlorine contents are consistent with residual biomass-derived alkalis and halides; these can influence setting and durability if present in elevated amounts. The XRF data provide a bulk oxide picture but do not discriminate between crystalline and amorphous silica a distinction important for predicting pozzolanic activity.

3.2 Phase quantification (XRD)

Table 3: Phase quantification from XRD (wt% phases)

S/N	Phase	Quantity (wt%)
1	Silicon oxide (crystalline/quantified phase)	**41.71**
2	Calcite ($CaCO_3$)	**33.46**
3	Orthoclase (K-feldspar)	**15.8**
4	Graphite (carbon)	**4.06**
5	Goethite (FeOOH)	**4.95**
6	Forsterite (minor)	**0.01**

XRD phase analysis shows a substantial crystalline silicon oxide fraction (41.7 wt%) and a surprisingly large calcite content (33.5 wt%). Orthoclase and iron oxyhydroxide phases are also present; a small graphite (carbon) fraction (~4 wt%) was detected.

The disparity between XRF (SiO_2 ~81 wt%) and XRD crystalline silica (41.7 wt%) is expected: XRF reports total elemental oxide while XRD quantifies crystalline phases. The difference implies a large proportion of silica is either amorphous (XRD-amorphous halo) or poorly crystalline this amorphous fraction underpins pozzolanic reactivity. However, the high calcite fraction (33.5 wt%) indicates significant carbonation or incomplete combustion residues (limestone contamination or CO_2 uptake during/after burning). High calcite reduces available reactive silica per mass and can decrease the reactivity of the RHA as a pozzolan. The presence of graphitic carbon (~4 wt%) suggests incomplete combustion or char; residual carbon can entrain air, reduce workability, and impair strength development if present in high amounts.

3.3 Mechanical properties — 28-day (Control Curing)

Table 4: Average 28-day Compressive and Tensile Strengths (Control Curing).

S/N	RHA replacement (%)	Avg. compressive strength (28 days) — MPa	Avg. splitting tensile strength (28 days) — MPa
1	M0 (0% RHA)	25.16	2.74
2	M5 (5% RHA)	22.87	2.77
3	M10 (10% RHA)	21.96	2.68
4	M15 (15% RHA)	20.99	2.56
5	M20 (20% RHA)	16.74	2.66

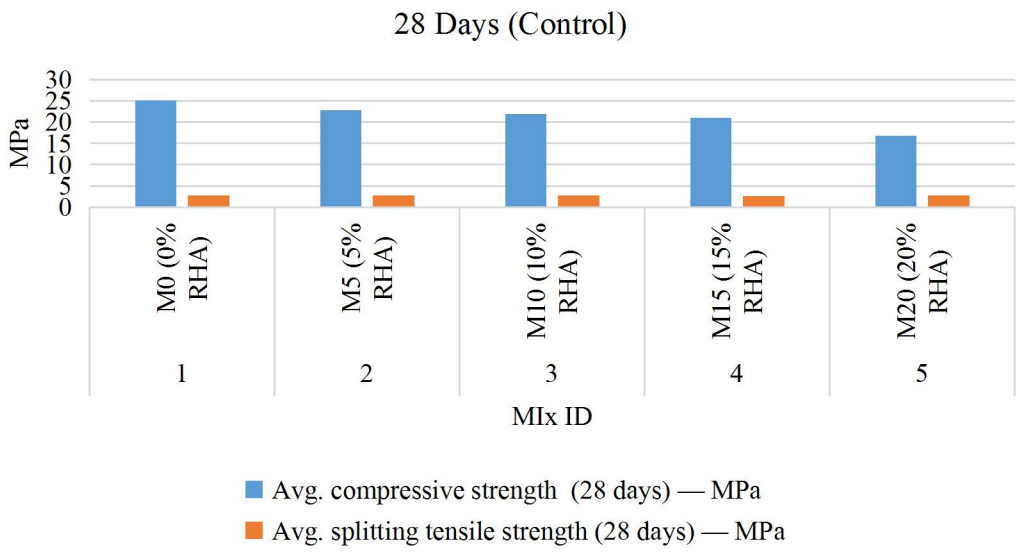

Fig 1: Average 28-day Compressive and Tensile Strengths (Control Curing).

Under standard curing, compressive strength decreases monotonically with increasing RHA content: from 25.16 MPa (control) to 16.74 MPa (20% replacement). The observed percentage changes relative to the control are: M5 −9.10%, M10 −12.72%, M15 −16.57% and M20 −33.47%. Splitting tensile strength is relatively stable across mixes, with small fluctuations: M5 +1.09%, M10 −2.19%, M15 −6.57% and M20 −2.92% relative to control.

The compressive strength reduction with increasing RHA replacement can be explained by a combination of the dilution effect (cement mass replaced by a partially reactive material), the limited early-age pozzolanic contribution of RHA (pozzolanic reaction is typically slower than Portland cement hydration), and the material characteristics observed in the compositional analyses (notably the high calcite and residual carbon content which reduce the effective reactive silica fraction). The relatively small change in tensile strength compared with compressive strength suggests that microcracking and matrix–aggregate

bond behaviour were less sensitive to the RHA levels used, or that internal stress redistribution preserved tensile capacity at the tested ages.

The slight improvement or parity in tensile strength at low replacement (M5) may indicate that limited RHA addition contributed to matrix refinement and improved interfacial transition zone (ITZ) packing, while still retaining sufficient cementitious binder for strength. At higher replacements (≥10%) the dilution effect outweighs any pozzolanic gain at 28 days. From an application perspective, these results indicate that—

given the present RHA material—replacement levels above ~10% produce notable compressive strength losses under the curing and mix conditions tested.

3.4 Mechanical properties — 56-day in HCl exposure (acid attack)

Table 5: Average 56-day compressive and tensile strengths under HCl.

S/N	RHA replacement (%)	Avg. compressive strength (56 d, HCl) MPa	Avg. splitting tensile strength (56 d, HCl) MPa
1	M0 (0% RHA)	20.87	2.44
2	M5 (5% RHA)	19.06	2.14
3	M10 (10% RHA)	15.78	1.94
4	M15 (15% RHA)	18.36	2.51
5	M20 (20% RHA)	11.27	2.41

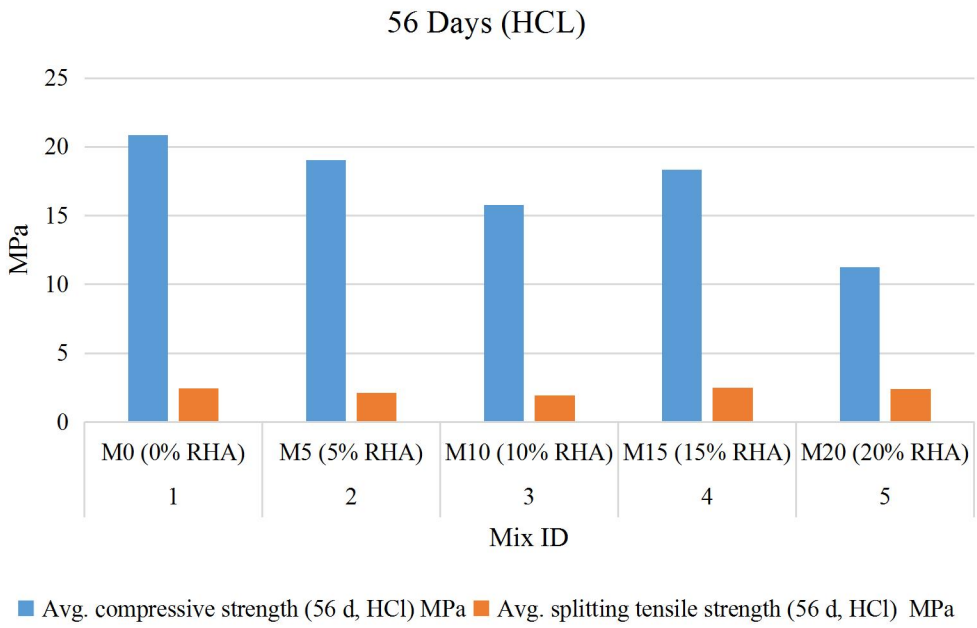

Fig. 2: Average 56-day compressive and tensile strengths under HCl.

After 56 days in HCl, compressive strengths are reduced for all blends relative to the 28-day control values; compared to the 56-day control (M0 = 20.87 MPa), percentage changes are: M5 −8.67%, M10 −24.39%, M15 −12.03% and M20 −46.00%. Splitting tensile strengths under HCl show variable behaviour: M5 −12.30%, M10 −20.49%, M15 +2.87% and M20 −1.23% relative to the M0 (2.44 MPa) baseline.

Acid exposure (HCl) causes deterioration through leaching of portlandite and decomposition of C–S–H, increasing porosity and reducing load-carrying capacity. The larger compressive strength losses at higher RHA replacements (notably M20) can be linked to the increased porosity and reduced cementitious matrix continuity from the dilution effect, amplified by the RHA sample's limited reactive silica (as inferred from the high calcite and carbon contents). M15 shows a less severe loss than M10 and M20 a non-monotonic trend that could arise from experimental variability, local densification effects at that replacement level, or test-to-test differences in sample condition. The tensile strength retention in M15 (a small increase) suggests that the microstructure under HCl for that mix may have developed a different crack pattern or that the residual matrix/ITZ was less adversely affected in the tested specimens.

The particularly large loss for M20 (−46% compressive strength) under HCl indicates poor acid resistance for high RHA replacement with this material and under the current processing conditions. This behaviour emphasises that simply substituting cement with RHA does not guarantee improved durability; the chemical and mineralogical quality of the RHA, and its interaction with aggressive agents, are decisive.

IV. CONCLUSION AND RECOMMENDATION

4.1 Conclusions

The tested rice husk ash (RHA) is chemically silica-rich (SiO_2 ≈ 81.1 wt%) but mineralogically compromised: XRD shows a large crystalline silica fraction (~41.7 wt%), very high calcite (~33.5 wt%) and ~4 wt% graphitic carbon. This composition implies a low effective fraction of reactive (amorphous) silica and measurable residual carbon characteristics that limit early pozzolanic contribution and tend to increase porosity when used unprocessed. Under control curing, compressive strength fell steadily with increasing RHA content (M0 = 25.16 MPa → M20 = 16.74 MPa), while splitting tensile strength remained comparatively stable. After 56 days of continuous 1.0 M HCl exposure all mixes lost strength; mixes with modest RHA (M5–M15) showed smaller relative losses than the highest replacement (M20). In particular, M15 exhibited the best retention of mechanical performance under the aggressive regime (lowest compressive and tensile losses), whereas M20 suffered the greatest compressive deterioration. Taken together, the results show that unprocessed, field-sourced RHA of the examined chemistry cannot reliably replace large fractions of cement without compromising strength and acid resistance; modest substitution (≤10%) is the safer option unless the RHA is upgraded and re-qualified.

4.2 Practical recommendations (for engineers, specifiers and laboratories)

i. Pre-qualification of RHA require routine RHA characterisation prior to use: XRF, XRD (to estimate amorphous fraction), LOI, BET/PSD, and a Strength Activity Index (SAI) or Frattini/Chapelle test. Do not accept RHA for structural use unless it meets predetermined reactive-silica and LOI thresholds.

ii. Recommended maximum replacement based on the present results, limit unprocessed, field-sourced RHA to ≤10% cement replacement for general concrete unless RHA quality is improved. For load-bearing or aggressive environments, prefer minimal or no replacement until RHA is processed and re-qualified.

iii. RHA processing if higher replacement is required for environmental or economic reasons, apply processing (controlled calcination at ~500–700 °C, acid washing to remove carbonates, sieving/grinding to target fineness, and removal/abatement of residual carbon) to increase the amorphous-SiO_2 fraction and reduce calcite/graphitic content. Re-test after processing.

iv. Design and mix adjustments include workability and admixture optimization (superplasticizers) and consider blended SCM strategies (e.g., combining RHA with fly ash, slag or metakaolin) to offset dilution and improve matrix continuity.

v. Regulatory and safety compliance handle and dispose of acidic test solutions, spent wash liquors and RHA wastes in accordance with institutional hazardous-waste rules and local environmental regulations (neutralisation of acid wastes, PPE, fume-hood usage, MSDS availability). Seek institutional safety approval before large-scale trials.

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