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A Review on the Strength Performance of Sisal Reinforced Cement Mortar Incorporating Rice Husk Ash and Steel Slag Powder as Cement Replacement

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ABSTRACT

The environmental needs for cement production have been raising the demand for underground construction materials and researchers throughout the world continue to search for alternative materials that can help replace cement in part. A number of Supplementary Cementitious Materials (SCMs, including agricultural waste by-products such as Rice Husk Ash (RHA) and industrial by-products such as Steel Slag Powder (SSP) which contain a high level of silica in addition to calcium) are receiving considerable attention as an alternative to cement, primarily for their pozzolanic properties and availability. In this review, a systematic approach to review was decided due to the technical, quantitative, question-like nature which was focused on understanding the effects of the three additives on the structural performances of cement mortar. Literature search and data collection method were followed to obtain appropriate publications from online databases like Scopus, ScienceDirect and journals, etc. Sisal fibers which are derived from the plant Agave sisalana are used as natural biodegradable materials that, due to their high tensile strength, offer some of the strongest reinforcement. The combination of RHA, SSP and sisal fibers with other materials helps to reduce waste while preserving resources because both components have their own ability to improve mortar structural performance and durability. Previous studies show that pozzolanic mortar improves concrete structure lifespan by reducing permeability and enhancing chemical degradation resistance. This review investigates how various RHA and SSP ratios impact mortar compressive and flexural strength to support sustainable construction methods. The review also extensively demonstrates that RHA, SSP and sisal fibres provide environmentally sustainable solutions to replace cement and strengthen mortar production.

Keywords: Strength performance, Pozzolanic mortar, Sisal fiber, Rice Husk Ash, Steel Slag Powder.

1. INTRODUCTION

The built environment of our world has received its most considerable transformation through cement which remains the primary binding component for all concrete mixtures used in construction throughout history. The material functions as a vital binding element which unites all concrete mixtures starting from basic residential walls up to large-scale public works (Devi et al., 2017). The construction industry uses concrete in an exceptional way because it remains the most extensive building material while its mechanical advantages make it the preferred selection for engineers and contractors. The production of concrete in today's world reaches approximately 6 billion tons which demonstrates the essential role this material plays in contemporary society (Mohamad et al., 2021). The essential role of Ordinary Portland Cement as the primary building material for concrete construction has remained unchanged since more than 200 years ago and this fundamental role will not end in the near future (Mohamad et al., 2021).

The cement production process creates serious environmental damage which requires urgent attention. The production process transforms raw materials through multiple energy-demanding phases which lead

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to air pollution through various harmful substances during all production stages from limestone quarrying to kiln combustion and clinker grinding. Cement plants release nitrogen oxides (NOx) and sulfur dioxide (SO2) and particulate matter as their most important sources of harmful emissions (Devi et al., 2017). The industry emits around 8 % of all anthropogenic carbon dioxide (CO2) emissions every year which makes it the second largest producer of climate change emissions among industrial sectors (IEA, 2018). The issues which scientists need to understand emerge as central elements in authentic dialogues about how we should develop our future cities. The kilns and precalciners involved in cement production result in noise pollution, waste heat, and leftover combustion gases (including CO2, NOx, SO2, and CO) a range of challenges that urgently need to be addressed (Nisa, 2023).

One of the most time-worn answers to that specific problem is pozzolanic mortar, a composite solution comprised of cement. In fact, a certain amount of evidence of its first use can be followed back to ancient Rome when engineers found that the Romans used volcanic powder, known as the 'pozzolana,' with lime to create an exceptionally protective binder (Mehta & Monteiro, 2014). Today, our modern investigation of those original hunches is the chemistry, the pozzolanic materials (whether siliceous or aluminosilicate) end up reacting with the calcium hydroxide (CH) produced during cement hydration to form calcium silicate hydrate (CSH), which is that gel that comprise the binding in 'plain' Ordinary Portland Cement (OPC) paste (Neville, 2011). The worldwide construction market has shown increasing interest in pozzolanic mortar because it successfully decreases environmental damage from cement production while improving concrete structure resilience and sustainability, and its cement-based materials function at higher efficiency (Kumar et al., 2020). Fly ash along with cassava peel ash and rice husk ash, operate as a secondary- cementitious material that enables chemical reactions that produce CSH through their pozzolanic capabilities which allow them to interact with CH (Li et al., 2021). The use of these materials as partial substitutes for cement will improve the mortar properties of compressive strength, durability and workability (Zhang et al., 2019). The use of pozzolanic mortar will lead to a significant decrease in the required cement volume which will result in substantial reductions of greenhouse gas emissions together with energy use connected to cement production (Mehta & Monteiro, 2014).

The building industry has increasingly adopted sustainable construction practices because they rely on environmentally friendly materials which provide cost-efficient solutions. Concrete exists as the most extensively used human-made material which the world employs in constructing buildings along with roads and pipelines and dams and drainage systems. The expansion of multi-storey and skyscraper building projects together with its superior early strength properties drive the rising need for concrete (Andrew, 2020). Each year, over 10 billion tons of concrete are consumed all around the globe, thus this requires a very large amount of raw material (Lazik & Garrecht, 2021). Beyond its high energy and water demands in cement manufacturing, the waste created during production and demolition, and the challenges of recycling construction debris, concrete overall falls short as a sustainable choice for the future (Andrew, 2020) (Tamanna, 2020). Limestone, the primary ingredient in cement manufacturing, accounts for roughly 55% of the sector's carbon output (Siddika, et al., 2019).

Rice husk is made up of the tough, protective outer layer of rice grains, separated during rice processing (Della et al., 2002). The waste material from rice-producing countries serves as a common pozzolanic reactant which contains 30-50% organic carbon (Hwang & Chandra, 1996). The process of removing husks from raw grains permitted the production of whole brown rice which then underwent milling to produce white rice by removing its bran. The current global rice production estimate stands at 541.4 million metric tons according to Vidalina et al. (2026). Rice husks account for 20% of the total weight of rice. Concrete achieves a 20% strength improvement through the addition of 15% rice husk ash. Research by Yuan in 2013 shows that 20% replacement, which produces the strongest results leads to strength loss of 4.5% when used beyond that threshold. The material's high permeability requires operators to control the water-cement ratio with great precision (Hwang & Chandra, 1996). Thus, according to scientific research, injecting RHA into concrete or cement mortar can enhance its mechanical attributes across all age categories. Consequently, RHA can be incorporated with OPC to form a binary cementitious material that promotes early strength development in mortar. Plate I, II, III and IV below shows the SSP and natural sound (NS) in their granular forms and their microstructural images under Scanning Electron Microscope (SEM). Plate V shows RHA (before and after combustion) and Plate VI shows Sisal fibers (the Agave sisalana plant and the processed sisal fibers).

Plate I: Picture of Steel Slag Powder -SSP

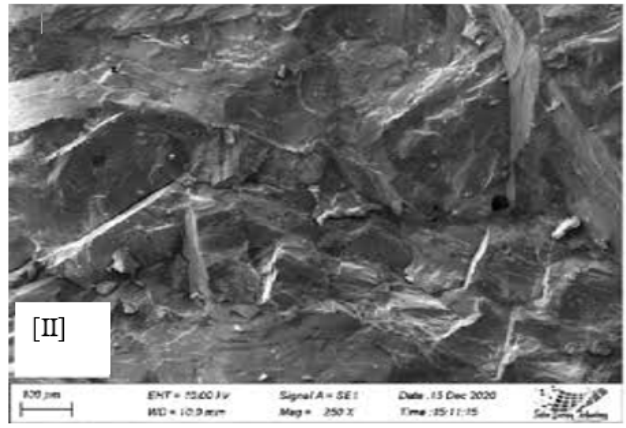

Plate II: SEM image of SSP

Plate III: Picture of Natural Sand -NS

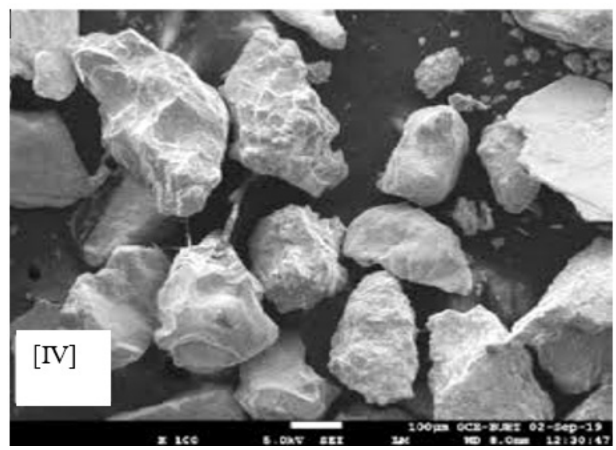

Plate IV: SEM image of NS

Plate V: Rice Husk Ash (Hemali, 2025)

Plate VI: Sisal Fiber (Textile_Coach, 2021)

SSP is another industrial by-product, which also has great potential as a cement substitute, with a high calcium content, contributing to its pozzolanic characteristics (Zhang et al., 2019). The application of SSP in various cementitious systems, including conventional concrete, recycled aggregate concrete, self-compacting, and foamed concrete, has demonstrated improvements in compressive strength, frost resistance, sulfate attack resistance, workability, and volumetric stability (Rongzhen et al., 2025). SSP actively participates in the hydration process, generating additional hydration products that densify the cementitious matrix and refine its overall physical attributes (Rongzhen et al., 2025). Moreover, SSP extends the setting time, reduces the heat of hydration, and improves the workability of fresh mixtures. While SSP delayed early hydration, its long-term influence on compressive strength was found to be negligible. (Rongzhen et al., 2025)

Sisal fiber completes the trio of materials under examination here. The use of sisal fibers in cement-based composites has been discovered to improve the flexural and tensile strengths, while reducing the brittleness of the material (Li et al., 2021). However, the performance of sisal fiber in reinforced cement mortar incorporating RHA and SSP as cement replacement materials are yet to be studied extensively. Natural fibers have been explored as reinforcement materials in cement-based composites, offering improved durability and sustainability (Li et al., 2021). Extracted from Agave sisalana leaves through decortication, this natural fiber is biodegradable, renewable, and available abundantly in tropical agricultural zones including Nigeria (Adeyemi et al., 2018). However, there was only a minor difference in compressive strength. (Sawant et al., 2023). Sisal fiber's mechanical characteristics (such as reasonable tensile strength, adequate thermal resistance, and moderate moisture tolerance) make it a plausible reinforcing agent for cement-based matrices (Li et al., 2021; Silva et al., 2010). Prior work has established that sisal additions improve the flexural and tensile responses of cement composites, while also reducing brittleness (Li et al., 2021).

However, one major drawback is not fully tackled, which is the structural behaviour of sisal fiber reinforced cement mortar (SSP & RHA) as partial cement replacement material. Hence, this review work seeks to systematically analyze the previous works, providing beneficial insights into the strength of the Sisal fibre reinforced cement mortar with RHA and SSP as replacement materials for Cement. The study will examine the impact of varying the proportions of RHA and SSP upon compressive and flexural strength, to highlight improved sustainable or building techniques.

2. MATERIALS AND METHODS

This review basically followed a systematic review way with appropriate and suitable manner based on the technical quantitative nature of central research question concerning the combined effect of RHA, SSP, and sisal fiber on the strength performance of pozzolanic mortar. Literature searches were done systematically across three major academic databases (Scopus, ScienceDirect, and peer-reviewed engineering journals, for example) using targeted search strings such as "rice husk ash mortar," "steel slag powder cement replacement," "sisal fiber reinforced concrete", and "pozzolanic mortar compressive strength." Literature searches were conducted systematically across three major academic databases (such as Scopus, ScienceDirect, and peer-reviewed engineering journals) using targeted search strings including "rice husk ash mortar," "steel slag powder cement replacement," "sisal fiber reinforced concrete," and "pozzolanic mortar compressive strength." Articles were selected against four explicit inclusion criteria: Published between 2002 and 2026, Reported at least one mechanical test result for cement-based composites incorporating the materials of interest, written in English and Sourced from peer-reviewed journals or recognised institutional publications. Following screening, 42 primary studies satisfied all criteria and formed the evidence base for this review.

The Pozzolanic mortar materials include cement, RHA, SSP, sisal fiber, fine aggregate (sand), water, and admixtures. The choice of percentage age replacement of the supplementary cementitious materials (i.e., RHA and SSP) and Sisal fiber will base on the experimental design mixture designed to ascertain the effects of such varying RHA and SSP proportions on the structural properties (such as compressive, flexural strengths) of the mortar. The proportions in which these materials are combined with cement distinctively affects the general structural properties of the pozzolanic mortar. Though previous studies show the potential of the individual pozzolans and addictive reinforced fibers incorporated in concrete, there were barely any studies conducted with the combination of these materials in pozzolanic mortar (as stated in this research review) that extensively examine the structural performance of mortar with the pozzolans and fiber combination.

2.1 Cement

Cement functions as a construction binder, a chemical compound designed to solidify, stiffen, and bond various materials. It is rarely used in isolation, primarily serving to bind aggregates like sand and gravel. Concrete tops the list of the most pervasive construction material globally, second only to water in terms of consumption (Rodgers, 2018). Construction cements are generally inorganic, frequently derived from lime or calcium silicate, and can be categorized as either hydraulic (curing in water) or, less commonly, non-hydraulic, based on their capacity to set immediately they are being exposed to water (Salman, 2026).

For pozzolanic mortar, grade 32.5 cement may be used, especially when producing spare component using pozzolanic material like RHA or Fly Ash. The interaction between the cement and pozzolanic material can bolster the mortar's strength and longevity. In Nigeria, cement grade 32.5 typically refers to OPC or PLC with a 28-day compressive strength of 32.5 MPa (or 325 kg/cm²). An experimental study was being performed on the effects of four different Nigerian cement brands on the concrete and mortar properties. These Nigerian brands of Portland cement include: Dangote Falcon (grade 32.5), Dangote 3 (grade 42.5), Elephant Lafarge (grade 32.5), and Elephant Superset (grade 42.5) (Gana et al, 2020). Based on the experimental study results, the conclusions drawn are as follows: Dangote Falcon cement had the highest compressive strength, followed by Elephant Supaset, Elephant LaFarge, and Dangote 3 in that order after a 21-day curing period with values 16.39N/mm2, 13.97N/mm2, 13.54N/mm2 and 13.11N/mm2 respectively (Gana et al, 2020). All specimens met the minimum strength of 6N/mm2 after 28 days of curing as recommended by BS 5224 (1976). Elephant Supaset cement had the highest density with 2000kg/m3, followed 1970.37kg/m3, 1955.56kg/m3, 1948.14Kg/m3, respectively for Dangote Falcon, Dangote 3, and Elephant Lafarge.

2.1.1. Physical and Chemical Characterization of Cement

Cement characterization is crucial because the physical and chemical traits they have really affect hydration and later on strength development. To find out what is really happening we rely on common standard test procedures such as specific gravity (BS EN 196-6:2010; ASTM C188), fineness (ASTM C204; ASTM C430), normal consistency (ASTM C187), setting times (ASTM C191), soundness (BS EN 196-3:2016; ASTM C151), and then XRF chemical analysis as well. These checks give us an approximate evaluation of the key properties such as density, fineness, water-requirement, setting movement in time and dimensional stability as the significance of slight variations is not negligible. With XRF analysis, we can more or less spot the main oxides such as SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, SO_3, plus loss on ignition LOI, and each component adds a piece to the story about cement hydration as well as the pozzolanic type reactions that come after.

2.2 Supplementary Cementitous Materials/ Pozzolans

Materials listed as having pozzolanic properties are referred to as Supplementary Cementitious Materials (SCMs), although individuals may interpret the word pozzolanic in a different way. In general, pozzolanic materials are materials that include siliceous or aluminosilicate component materials that when mixed with calcium hydroxide CH, and then react with it, form calcium silicate hydrate CSH, which is the most important binding phase of cement. The behavior of the pozzolanic additives is not permanent, but depend on the chemistry, the grain size and the reactivity of the additives in the actual systems. There are many reasons for using supplementary cementitious materials (SCMs) in concrete or mortar; they improve durability, lower permeability, ease pumping and finishing, prevent alkali-aggregate reactions, or enhance the properties of the hardened concrete or mortar through a combination of pozzolanic, hydraulic, or both properties. They can be blended with or partially replace Portland cement in these SCMs, and should be considered an integral component of the complete cementitious matrix. (NAHD, 2018).

2.2.1 Rice Husk Ash

RHA, also called rice husk ash, is essentially a by-product obtained from the burning of rice husk, it is a fibrous residue from the outermost layer of the rice grain and the ash yield can be as high as 20% of the total paddy harvested mass. However, it is normally reported that RHA produced in a controlled combustion (TC = $< \sim$ 900°C) contains approximately 90-96% amorphous silica (SiO_2). That the pozzolanic reaction is actually in that amorphous silica (Mosaberpanah & Umar, 2020). RHA contains a lot of silica, and any reaction with calcium hydroxide, a component of hydration of cement, can occur. During that interaction, more calcium silicate hydrate (CSH) gel will be formed. Because of an increased amount of CSH formed, the improved microstructure typically leads to better mortar and concrete performance. Research work has shown that RHA can enhance the compressive strength, flexural strength, tensile strength and can also contribute towards longer term durability. RHA is best used as 10-15% replacement of cement, which explains the relative interest in RHA as an effective and environmentally-friendly supplementary cementitious material (SCM) of cement-based composites. (Kumar et al., 2020).

Kumar et al. (2020) demonstrated that replacing the cement partially in the mortar with RHA leads to an increase in the compressive strength and flexural resistance as well as tensile strength. They also found that RHA increased chloride accession resistance, which would help to retard the corrosion of the reinforcement, and decreased water absorption and the resistance to freeze-thaw service. The literature suggests that RHA as a partial replacement of cement strengthens cement-based composites and results in better mechanical properties and durability.

2.2.1.1 Chemical Composition Analysis of RHA

The pozzolanic activity of RHA is predominantly related to its silica content, and the solid phases present in the ash. So, for that, we'll examine X-ray fluorescence (XRF) which shows important oxides like SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, and loss on ignition (LOI). Depending on the setup you follow this is done according to the ASTM C114 approach or BS EN 196-2 (2013). If, according to the ASTM C618, the summed mass fraction of $SiO_2 + Al_2O_3 + Fe_2O_3$ is to exceed 70%, then the water absorption value must be sufficiently low. The water absorption value should be sufficiently low when the summed mass fraction of $SiO_2 + Al_2O_3 + Fe_2O_3$ is to exceed 70% according to ASTM C618. At the same time, X-ray diffraction (XRD) is conducted to determine if the silica is in an amorphous state or not. On the other hand, if the material is amorphous, you will typically see a diffraction peak that is widely spread, something that looks like a hump, in the 2θ range from 15-35 degrees, which is indicative of increased reactivity. If the silica is crystalline, however, then you will have peaks that relate to quartz, cristobalite and such types of minerals and these peaks typically are considered less reactive. We also use scanning electron microscopy and energy dispersive X-ray spectroscopy (SEMEDS). This will help in confirming porous character of the ash, and will provide elemental data for components of the ash. These Chemical and Mineralogical Characteristics are important as they affect the reaction between RHA and Ca(OH)2 which is responsible for the formation of the extra CSH gel. It is thanks to that that cement systems modified with RHA have better strength and will have better durability over time.

2.2.1.2 Fineness and Particle Size Distribution of RHA

Fineness is the determining factor of RHA's participation in pozzolanic reaction. One kind of overall number and one number specific surface area in m^2/kg is provided by the Blaine air-permeability test (ASTM C204; BS EN 196-6, 2010) and this surface is often used for the purpose of lining up pozzolanic materials. Then, from a dispersed suspension in a suitable medium, perform a laser diffraction particle size analysis, you obtain the complete particle size distribution curve for the RHA. The D10, D50, D90 and the uniformity coefficient can be withdrawn from the curve. Fine RHA means that it has a larger surface area exposed to the cement paste which enables the pozzolanic reaction to develop more completely and rapidly. This yields additional amount of C-S-H gel, that typically appears as increased strength. There is a other aspect: The smaller the particle size, the more water will be absorbed by the particles, and the slump will decrease. Hence, the "balancing act" is a challenge for the mix designer, and in some cases, it can be achieved by altering the ratio of water to binder, or adjusting the amount of superplasticizer supplied (Mosaberpanah & Umar, 2020).

2.2.2 Steel Slag Powder

The metallurgical industry offers various secondary materials and it is worthwhile to look for ways to use these materials for building rather than extracting raw materials, and to implement principles of circular economy. (Nancy et al., 2025). One of the major examples is the steel slag (SS) produced in the iron-making process and throughout the different stages of the steel refining process. The physical and chemical characteristics of the furnace slag vary depending on the kind of furnace (EAF, BOF or LF) and the combination of pig iron, scrap and alloy additions to the furnace. (Nadine et al., 2015). Superfast air-quenching of the liquid slag, high-pressure air blasting, extends the amorphous phases in the slag and is effective in stabilizing the slag structure, improving usability of the liquid slag in cement blends. (Nancy et al., 2025). The replacement levels of around 10-15% will result in a vastly different outcome enhancing the cement mortar. The mix of slag and other supplementary materials provides an even higher level of benefit; slag + SSP and slag + RHA be able to achieve greater control on the pore size distribution, hydration kinetics and ion mobility within the paste than either can achieve individually (Nancy et al., 2025).

2.2.2.1 Chemical Composition and Oxide Analysis of SSP

The chemical composition of SSP needs to be completely known prior to beginning mix design. XRF analysis, after ASTM C114 or BS EN 196-2 (2013) does the job of quantifying the main oxides like CaO, SiO_2, Al_2O_3, Fe_2O_3, MgO, MnO and SO_3. These relative contents more or less govern the mineral phase set-up and the reactivity, not an easy process. Finally, XRD helps identify the crystallinity of the phases present, such as dicalcium silicate (C_2S), tricalcium silicate (C_3S), tetracalcium aluminoferrite (C_4AF) as well as free CaO, periclase (MgO) and the RO phases, solid solutions of FeO, MnO and MgO. Each of these specifically reacts slightly differently when wetted, and their reaction when wetted affects expansion, strength and durability. (Nancy et al., 2025).

2.2.2.2. Fineness and Particle Size Distribution of SSP

The fineness of SSP is important for determining its reactivity in cementitious systems. Typically, the most common single point measure is the Blaine specific surface area (ASTM C204; BS EN 196-6, 2010), which is typically increased measurably where the surface area exceeds 400 m2/g (Hossein et al., 2023). The distribution is measured by laser diffraction particle size analysis, so instead of only one number, D90 and D50 describes the coarser tail and median, respectively. The mechanical activation of SSP, caused by fine grinding, increases its specific surface area, increases the interaction between the surface of SSP and pore solution and accelerates the development of secondary hydration products (Zhixin et al., 2024).

2.3. Sisal Fiber

The leaves of Agave sisalana by mechanical decortication have been used to collect sisal fiber which has been gaining great attention as a tensile reinforcement agent in pozzolanic mortar systems (Li et al., 2021). In terms of its mechanical profile, like a reasonable tensile strength, some thermal resistance, and a tolerable level of moisture uptake, it fits well with scenarios where you want a fibrous crack-bridging network inside the mortar matrix (Li et al., 2021; Silva et al., 2010). Additionally, experiments indicate that the addition of sisal to pozzolanic mixes improves the compressive, flexural and tensile performance and reduces the permeability of the pozzolanic mixes and increases the resistance to chemical attack of the pozzolanic mixes. (Kumar et al., 2020; Li et al., 2021). It has also been noted that placement of the appropriate fiber dosage can give toughness, energy absorption, and abrasion resistance benefits as well as to control the development of plastic-shrinkage cracking for fiber-reinforced cement composites, in general. It also can reduce crack widths under service load; increase resistance to freezing and thawing; and increase overall ductility, at least until about 1% by volume when (if) fiber bond failure and loss in workability slowly take over and begin to offset the benefits of increased reinforcement (Shibata et al., 2005).

2.3.1 Water Absorption of Sisal Fiber

Incorporating plant fiber of course makes it hygroscopic, and with sisal no different. The water uptakeability of its cellulose microfibrils and the lignin matrix is very attractive. This ends up forming a locally higher watercement ratio area right next to each fiber. The non-treated fibers of sisal generally are reported to have water absorption in the range of approximately 70% to 120% by mass. (Li et al., 2021). That range is a great example of the high water-demand penalty that they impose. Otherwise, by alkaline treatment with NaOH, a bit of hemicelluloses and wax on the fibre surface become eliminated, making the fibre surface more open. This also alters the interstitial matrix of the cell wall. Yimer and Gebre (2023) reported that using proper treatment reduces water absorption and thus ensures a more controlled water-cement ratio in the vicinity of each fiber, promoting a better bond between the fiber and the cement.

2.3.2 Surface Morphology Characterization of Sisal Fiber

The most common method of studying these features is to visualize them using scanning electron microscopy (SEM) and magnifications of around 100× to 5000× (Yimer & Gebre, 2023). Untreated sisal usually shows a fairly flat surface in the SEM with a low-density layer of wax and unbroken cuticle layers. Micrographs taken following NaOH treatment reveal surface etching and the uncovering of the underlying cellulose microfibrils that provide mechanical bonding with the hardening paste, as well as an increase in surface roughness. Elemental composition approach using EDS analysis of the SEM shows presence at the fibre surface and whether the fibre has been embedded with calcium rich hydration products after immersion in alkaline solution, thereby signifying the beginning of mineralization, which is an additional fibre-matrix connection. SEM analysis of fiber surface morphology is necessary and critical to this research for the ability to provide a mechanistic understanding of the difference in composite mechanical behavior observed between fiber samples that were left untreated and treated samples, linking the fiber surface chemistry (at the nano and micro scales) to the fiber composite mechanical behavior (at the macro scale) outcomes (Sawant et al., 2023; Yimer & Gebre, 2023).

2.4 Sand (Fine Aggregate)

The fine aggregate of concrete and mortar systems is the naturally occurring granular material that is the result of physical and chemical weathering of parent rock over a long period of time to produce finely divided mineral particles (Neville, 2011). It is not a silent partner when it comes to governing the properties of mechanical behavior and durability in cement-based composites, as its properties including particle size distribution, grain shape, surface texture, and mineralogical composition, all interact with the cement paste for fresh state workability and hardened state properties such as strength, permeability, and chemical resistance (Mehta & Monteiro, 2014). In the past, it's been demonstrated, and somewhat proven, that sand is a popular fine aggregate in pozzolanic mortar due to its availability, low cost, and satisfactory physical and chemical properties for supplementary binders, like RHA and SSP (Kumar et al., 2020; Neville, 2011). The addition of sand to the pozzolanic mortar has also been reported to increase its compressive strength, flexural strength and tensile strength (Kumar et al., 2020).

2.4.1 Grain Size Distribution of Sand

The fineness of the fine aggregate is one of the most significant characteristics that influences the workability, packing density of the aggregates in the mortar, the demand of the paste required in mortar and ultimately the strength of the mortar in compression and flexure. The grading is accomplished by dry sieve analysis per ASTM C136 or BS 812-103.1 (1985) which involves shaking a representative portion of the oven-dried sample of a specific quantity through a series of known sieve apertures. Typically, the size range starts at 4.75 mm and decreases to 150 µm, and is then shaken for a consistent length of time with a mechanical sieve shaker. After that, the mass that stays on each sieve is weighed, then turned into a cumulative percentage passing, based on the results. The resulting grading curve is looked at against the zone limits noted in BS EN 12620 (2013) or ASTM C33, for fine aggregate that is meant for mortar and also concrete. A well-graded sand is one that has the widest possible range of sieve sizes that there isn't excessive accumulation in any individual sieve size that would adversely affect the packing density of the sand in the mortar. That reduces the amount of paste required to proceed through and to fill in between the particles, and thus allows an increase in the compressive strength at the same water-binder ratio (Neville, 2011). Conversely, a poorly graded sand, or a gap graded sand will leave larger voids that need to be filled by paste, thus increasing the amount of paste required, shrinkage potential, and potentially reducing the strength depending on the circumstances.

2.4.2 Specific Gravity and Water Absorption of Sand

Specific gravity of the fine aggregate is measured according to ASTM C128 or BS 812-2 (1995) on the Saturated Surface Dry (SSD) pycnometer method and water absorption is measured as the percentage increase in a fine aggregate's mass from its oven dry to the SSD condition. Two of these parameters are absolutely required in mix proportioning specific gravity of the sand is the first; it is used to compute absolute volumes of each constituent in the mix design to ensure maintenance of aggregate-to-paste volume ratios across the series of mixes tested at different RHA, SSP and fibre content levels. Concretes or mortars produced by an excess of mixing water in conjunction with more absorptive version of cement/aggregate may actually have less effective water binder ratio and consequently you will see misleadingly high numbers for strengths; this sort of calls into question whether or not you can compare at all with mixes that end up using less absorptive cement/aggregate (Neville, 2011).

2.5 Water

Water is the catalyst in any system that uses cement, in essence, the key to the success of hydration without which it couldn't occur. In the absence of water, the calcium silicate hydrate binding gel cannot form, and the mortar essentially remains a collection of unreacted powders, comprising the aggregate particles (Mehta & Monteiro, 2014). However, its application does not end with the chemical aspects. In fresh condition, the quantity of the water controls workability (such as ease of placing, compaction and finishing). However, the water-binder ratio dominates, increasing the capillary porosity which in turn dominates the strength and overall durability (Neville, 2011). Mortar samples bound with potable tap water actually showed a significant increase in compressive, flexural and tensile strengths compared to similar mixes using seawater, per Kumar et al. (2020), which essentially confirms the previous guidance that only potable tap water, or the best available equivalent quality water, should be used for the structural mortar construction.

2.5.1 Water-Binder Ratio Determination and Control

The ratio of water to binder (w/b), being the ratio of the mass of free water in the mixture to the total mass of cement, RHA and SSP, becomes the most crucial factor of the mix design process that influences properties of the hardened mortar such as porosity, strength, and durability. When considering each of the setups herein (each cement grade, each RHA replacement level, each SSP replacement level), each setup will have a fixed target w/b determination indicated by a normal consistency (NC) test (ASTM C187; BS EN 196-3, 2016). That test is used to narrow down the specifications on water demand of the blended binder, and then the w/b is adjusted to place the mortar flow (deemed as mortar flow diameter per ASTM C1437) within a narrow "okay" band, typically 110 ± 5 mm. This ensures that all mixes from the test series are placed and compacted under relatively similar conditions and variations in hardened strength can therefore be attributed to both the compaction quality (which could be influenced by variations in working ability) and the compositional side conditions (RHA fraction, SSP fraction, fibre quantity).

2.6 Structural Testing Methods

2.6.1 Compressive Strength Test

The testing routine is governed by ASTM C109 or BS EN 196-1 (2016). Mortar gets poured into 50 mm cube moulds, in two layers, with each layer compacted by tamping following the specified standard method; after that the filled moulds are wrapped with damp cloth and kept in an environment where the temperature is controlled at 20 ± 2°C for 24 hours, then demoulding occurs. Once the specimens have been demoulded, the specimens are transferred to a tank of water where they are cured for pre-determined curing times, typically 7days, 28days, 56days and 90days, to ensure that both early age cement hydration products as well as late age pozzolanic reaction products are considered. During each curing time, three cubes are removed, dried on the surface, placed under loading at the specified, controlled loading rate of 2400N/s ± 200N/s (as per BS EN 196-1, 2016) until failure occurs on a compression testing machine calibrated according to the specifications. The average of the three cubes values found from each cube is computed as the failure load by the nominal cross-sectional area of the cube and the standard deviation is recorded. It is generally recommended to use statistical interpretation based on one way ANOVA and Tukey post hoc test to determine whether differences are actually statistically significant at a 95% confidence interval, as per the mix batches.

2.6.2 Flexural Strength Test

The test procedure follows ASTM C348 or BS EN 196-1 (2016). Standard sized mortar prisms of dimensions of 40 mm x 40 mm x 160 mm are poured in two layers, each layer is tapped to remove air. Covered & stored in controlled temp for 24 hours after which they are demoulded. The specimens are water-cured within 7, 14 and 28 days (test age) at 20 ± 1°C. A controlled loading rate of 50 N/s ± 10 N/s is chosen and three replicate prisms are loaded centrally over a 100 mm support span until fracture occurs at each age. The modulus of rupture is calculated from the standard formula for beam bending, which is: $f = 1.5FL / b^3$ where: F is the failure load in pounds; L is the span over which it is bending; and "b" is the side length of the square cross-section. The mean plus standard deviation of the three repeats is reported and tests the statistical significance via the same ANOVA setup as that done for the compressive strength results. It has been demonstrated previously that around 1% (by volume) of sisal addition can increase flexural strength by as much as 37% over plain mortar (Kumar et al., 2020), which is often associated with the crack-bridging ability described above. The combined effect can be better described based on flexural strength data plotted on various age points for all the combinations of RHA, SSP, and various amounts of fiber (Adeyemi et al., 2018; Kumar et al., 2020).

2.6.3 Workability Test (Flow Table Test)

The standard approach to the measurement of mortar workability is to examine it through flow table test, according to ASTM C1437 or BS EN 1015-3 (1999). In practice you place a fresh mould of the Frustum cone, fill with fresh mortar in two layers, then lift the cone to let the mortar slump and spread on its own and the flow table is given 15 drops. Then the spread diameter is measured in two directions orthogonal to one another, an average is taken and it is this average that is used to calculate the flow value. The "target" flow diameters of mortar mixes for structures are approximately 110 (+ 0r – 10) mm, so in the experimental series all mixes were adjusted to obtain a "target" diameter that was close to this value. This is done either by adjusting the water content, or by the addition of a super plasticizer, before any of the specimens are cast. (Neville, 2011; ASTM, 2019b).

3. STRUCTURAL PERFORMANCE RESULTS AND DISCUSSION

Compressive strength is defined as the resistance of the material to crushing under axial load and is measured after applying the axial load on cube samples according to ASTM C109. This strength is very important for any load-bearing application. The flexural strength or modulus of rupture, as per ASTM C348 using prismatic specimens, provides a measure of resistance to bending moments in relation to beams, slabs and elements of panels. By comparing both parameters to past work patterns are clearly visible that are created by both individual and combined rounds of effects. Multiple properties are affected by multiple mix variables, dose and type of pozzolan, water/binder ratio, cement type and proportion, and curing procedure applied.

3.1 Compressive Strength Performance

RHA is claimed to enhance the properties of compressive strength of cement-based system. There are numerous studies that illustrate this trend, which generally sees compressive strength increasing with higher RHA levels until a maximum is reached of about 10–20 percent RHA replacement. For instance, Kumar et al. (2020) reported that there is a 19.5% increase in 28-day strength when 20% of the cement was replaced. After this, the strength drops off, likely due to the combined effect of cementitious and pozzolanic phases being weaker with the former taking over the latter's contribution as the cementitious phase increases in mass by dilution in the same unit of mix volume. Steel slag powder (SSP) differs in its effect in that it forms putty and locks into place to provide strength. However, under certain reactive conditions, the SSP can still chemically react with, for example, dicalcium silicate (C_2S) and tetracalcium aluminoferrite (C_4AF) to create additional binding products which accrue over time. Generally, the replacement of moderate SSP (around 10-20%) results in good compressive strength and durability. However, the risk of having too many of these free limes and periclase becoming apparent in the mix may lead to a reduction in early age strength if continued to be increased. A synergy can be obtained with regard to compressive strength when RHA and SSP are used in combination. With the combination of RHA and SSP (which maintains the hydration) you will create a matrix that will be harder and more durable. Another study done by Adeyemi et al. (2018) revealed that the mix made from the combination of 10% RHA and 10% SSP achieved better performance than the mixes containing RHA or SSP alone. Yet, in the case of sisal fiber, it is not exactly the compressive strength player as it primarily works for crack bridging and post cracking reinforcement rather than chemical strengthening. When low (0.5-1.0%), the compressive strength is generally quite consistent; however, higher percentages of fiber can cause clumping and then a slight reduction in compressive strength. The overall result, therefore, is that sisal fiber may be used in conjunction with RHA and SSP to increase toughness and crack resistance, without sacrificing the compressive strength contributions provided by RHA and SSP.

3.2 Flexural Strength Performance

These are properties which are generally improved significantly when reinforced with sisal, as the case of pure mortar which bends until a point without any yielding. With sisal fibers, they actually bridge the cracks when those are beginning to develop, then they their shuffle around the tensile stresses and then in a more controlled way boost the energy absorbing capacity. Several studies show that flexural strength rises with increasing fiber content until it reaches a certain peak – about 1% by volume. For example, Kumar et al. (2020) reported a 37% increase compared to the control mix. Once just add more fibres, however, a fibre agglomeration occurs, creating weak regions and overall effect reduces, too. Another, too, alkali treatment of the fibers in sodium hydroxide increases stress transfer due to rougher sur faces, yields more conductive post cracking responses are much more stable (Yimer & Gebre, 2023).

There are also additives for cement that are called supplementary cementitious materials, which are also used to increase flexural strength: These include rice husk ash (RHA) and steel slag powder (SSP). They help to increase the pore system and they enhance the interfacial transition zone, primarily through pozzolanic reactions and hydraulic reactions. Most published literature indicate that the best range for RHA replacement is 10-15%, whereas it is around 10% for SSP replacement for a significant increase in flexural performance. If you exceed those levels, however, you may decrease in strength as the microstructure may be unstable, (Kumar et al., 2020; Li et al., 2021). When RHA, SSP and fibers made from sisal are used simultaneously, it is quite a synergistic arrangement. The minerals create increased density of the matrix and the fibres act as crack bridging reinforcement. So overall, there is more flexural strength, greater toughness and enhanced post-cracking energy absorption than for most individual components when they are used alone (Adeyemi et al., 2018).

4. CONCLUSION

Overall, it can be concluded that the rice husk ash, steel slag powder and sisal fiber can be used to enhance the performance of mortar, provided that the dosages are optimized. The increase of strength at RHA appears to be primarily due to its conversion to the pozzolanic action to create additional calcium silicate hydrate (CSH gel thing) with the microstructure becoming denser. Meanwhile, SSP introduces latent hydraulic activity so that you obtain better long duration strength and matrix continues to become even closer. The real answer to that question isn't increasing compressive strength but more properly helping the flexural behaviour of material by bridge the cracks and this does add to the energy absorbed. Just combine them, and you obtain a synergy which leads to better compressive and flexural results, improvement of toughness and a more sustainable cementitious composite than ordinary mortar.

RHA replacement: The optimum replacement values for RHA are about 10-20% as this will optimize high compressive and flexural strength through additional secondary CSH development. In a few instances, an increase in strength by up to 19.5% has been reported (Kumar et al., 2020).

SSP replacement: 10-15% SSP provides good balance between strength and durability; increasing SSP will exhibit a decrease in strength, due primarily to dilution effects, and additionally to free-lime type expansion (Nancy et al., 2025; Imam et al., 2020).

Sisal fibre content: A content of about 1% is optimal, and it can be increased to a maximum of 37% if crack bridging occurs. Apart from that, fibers can agglomerate, which is not an option (Kumar et al., 2020).
The combined application: In most cases, ternary blends containing RHA, SSP and sisal fiber work better than single additive systems due to the complementary effect of reinforcement with fibers and densification of the matrix (Adeyemi et al., 2018).

Mix design consideration: RHA uses are well known for having high water requirements so the water to binder ratio should be carefully controlled. The use of superplasticizers is preferable and it can ensure good performance of pozzolanic properties of the mixture (Mosaberpanah & Umar, 2020).

5. RECOMMENDATIONS

Proportioning: In future experimental programs, combined RHA and SSP replacement should (be placed around) 515% RHA, 0.510% SF for Sisal, and for the initial yardstick for optimization of the mix, RHA at 515% should be replaced by Sisal fiber with 0.510% in volume.

Long-term field validation: It is necessary to perform reliable service-life predictions on structures produced with these hybrid mortars by real climate fluctuations, long-term loading and chemical exposure conditions throughout the field validation, in order to actually predict the actual strength. Characterisation of SSP to be used: The amount of free-CaO present should be determined for all.

In terms of durability: compressive plus flexural tests should be extended to include paired testing of the important durability properties of the concrete wrack: permeability, chloride penetration and sulfate resistance to ensure that any strength gains are reflected in a real increase in the life of the structure under harsh conditions (Zhang et al., 2019).

6. CONFLICT OF INTEREST

No conflict of interest is associated with this work.

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