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USE OF BIO-BASED WASTE MATERIALS IN CONCRETE: A GREEN APPROACH TO CONSTRUCTION

Muskan[1] and Nitu[2]

Civil Engineering Department, Matu Ram Institute of Engineering & Management, Model Town, Rohtak, Haryana 124001

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Abstract - *This study investigates the use of agro-industrial waste materials as partial replacements in M45 grade concrete. Wood ash (WA), rice husk ash (RHA), and corn cob granules (CCG) were tested as cement, fine aggregate, and coarse aggregate replacements, respectively, at varying levels. A total of 25 concrete mixes were prepared using an L25 orthogonal array, adhering to IS 10262:2019 guidelines with a constant water-cement ratio of 0.37. Mechanical and durability properties, including compressive strength, split tensile strength, flexural strength, water absorption, and density, were evaluated at 28, 56, and 90 days. Results showed that mixes with up to 10% WA, 20% RHA, and 20% CCG demonstrated comparable performance to the control mix. However, higher replacement levels, especially for RHA and CCG, led to decreased strength and increased water absorption, affecting durability. WA at 10-15% proved beneficial for long-term strength development and microstructure refinement.*

Key Words: Agro-industrial waste, concrete, wood ash, rice husk ash, corn cob granules, durability, mechanical properties, sustainability.

1.INTRODUCTION

Concrete, a widely used construction material, is composed primarily of cement, sand, water, and aggregates. Its unparalleled versatility, strength, and durability have made it a fundamental material in modern infrastructure. However, the environmental impact of concrete production is substantial, primarily due to the energy-intensive process of cement manufacturing. Cement production alone is responsible for a significant share of global carbon dioxide emissions, contributing to the ongoing challenges of climate change. As a result, there is increasing pressure to develop more sustainable alternatives to traditional concrete ingredients.

One promising approach to reducing the environmental footprint of concrete is the use of bio-based materials as partial replacements for conventional materials like cement, sand, and coarse aggregates. Bio-materials are derived from renewable, natural sources and offer several advantages, including waste reduction, lower energy consumption, and potentially enhanced material properties. By replacing a portion of conventional concrete ingredients with bio-based materials, it is possible to not only mitigate environmental harm but also improve the performance characteristics of the resulting concrete.

2 LITERATURE STUDY

Aduldejcharas (2024) investigates the use of mussel shell waste as a bio-responsive block material for concrete in Samut Songkhram Province's Bang Ja Kreng Community, addressing environmental issues from traditional disposal methods. Mussel shells, when burned at various temperatures, undergo a chemical transformation, enhancing their calcium oxide content and compressive strength. The study demonstrates the material's potential for concrete, showing strength up to 500 kg (4,000 N). By incorporating mussel shells into concrete, the research highlights an eco-friendly solution for waste management and sustainable construction, with community involvement being key for success.

Al-Sabaeei et al. (2022) examine the potential of crude palm oil (CPO) and its by-products, like palm oil fuel ash (POFA) and palm oil clinker, in green construction. POFA improves concrete strength and durability, while palm oil clinker enhances asphalt mixtures. These materials offer sustainable alternatives to petroleum-based products, reducing environmental impact. However, challenges such as sourcing enough palm oil for non-food applications and variability in performance based on oil type remain. The study highlights the feasibility of CPO-based products for sustainable construction. Amantino et al. (2022) assess bio-concretes made with rice husk (RH) bio-aggregates, focusing on mechanical, thermal, and physical performance over six months. Replacing cement with rice husk ash (RHA) and natural sand with rice husk decreased compressive strength by up to 36%. While mechanical properties were compromised, the bio-concretes maintained good thermal performance, making them suitable for lightweight, insulating applications. This substitution reduces the carbon footprint, enhancing the material's sustainability and durability. Despite lower strength, rice husk-based bio-concretes are a promising eco-friendly option for construction.

Ansari, Tabish, and Zaheer (2025) review hemp-infused concrete, emphasizing its environmental and structural benefits in reducing carbon emissions in construction. Hempcrete, made from hemp and lime, offers thermal insulation, moisture control, and enhanced energy efficiency. It is resistant to fire, pests, and mold, providing durability and low maintenance. However, its low compressive strength limits its use in load-bearing applications. Despite this, hempcrete's seismic resistance and ability to regulate humidity make it suitable for earthquake-resistant structures. The review identifies challenges such as lack of standardization and high costs, which hinder widespread adoption. Bardouh et al. (2024) review the mechanical behavior of bio-based concrete under various loadings, analyzing 120 studies. The paper discusses factors like aggregate content, binder type, and aging that influence bio-based concrete's mechanical properties. It highlights that increased aggregate content reduces strength, while finer aggregates improve mechanical properties. The study finds bio-based concrete exhibits elastoplastic behavior, aiding energy dissipation during seismic events. With sustainability and carbon-negative potential, bio-based concrete offers a promising alternative, though its mechanical properties need careful formulation to meet construction standards.

Caldas et al. (2021) assess greenhouse gas (GHG) emissions in wood bio-concrete production using Life Cycle Assessment (LCA). The study finds that increasing wood waste content reduces GHG emissions and promotes a circular economy. The research also highlights the role of transportation efficiency in affecting carbon footprints. Recycled wood shavings had a lower impact on emissions compared to virgin wood. This supports the use of recycled wood in construction to reduce environmental impact. The study advocates for waste wood over virgin sources to promote low-carbon, sustainable building materials. Cavalli et al. (2024) review bio-based rejuvenators in asphalt pavements, focusing on their eco-friendly and renewable properties. These rejuvenators restore the rheological properties of aged asphalt, improving elasticity, crack resistance, and fatigue performance. They offer environmental benefits by reducing greenhouse gas emissions and are biodegradable and non-toxic. While bio-based rejuvenators improve asphalt durability, their effectiveness varies based on type, dosage, and compatibility with existing materials. Long-term performance monitoring is necessary to ensure their efficiency, but they present a promising sustainable solution for enhancing asphalt pavements. Chen and Yu (2024) study the surface modification of miscanthus fiber using hydrophobic silica aerogel to enhance its compatibility with cement in lightweight concrete. The modification improves compressive and flexural strength, reduces water absorption, and enhances thermal insulation and sound absorption. Hydrophobic treatment also minimizes organic matter leaching, improving the durability and strength of the material. The study suggests that aerogel-modified miscanthus fibers are a promising eco-friendly solution for improving the performance of lightweight concrete, offering enhanced insulating and acoustic properties for construction materials.

Chen, Yu, Wang, and Yu (2024) explore bio-corrosion mechanisms in marine concrete, which degrade infrastructure in marine environments. The review identifies fouling, biophysical, and biochemical processes as key bio-corrosion mechanisms. These processes impact the mineral composition and microstructure of concrete, reducing its lifespan and compressive strength. The paper emphasizes the importance of understanding hydrodynamics in bio-corrosion and suggests that antifouling measures should be designed with these mechanisms in mind. Despite advances in bio-corrosion research, the study calls for more research to predict and mitigate its effects on concrete durability. De Andrade et al. (2024) evaluate the potential of macauba endocarp as a coarse aggregate in bio-concretes, assessing its chemical compatibility with cement. The study finds that treatment improves the chemical compatibility of macauba endocarp, with bio-concretes showing promising mechanical properties. A 25% endocarp substitution led to a 7% increase in compressive strength, while higher substitution levels reduced strength. The addition of endocarp improved ductility and fracture control, making it suitable for non-critical load-bearing applications. Despite decreased elastic modulus, macauba endocarp shows potential as a sustainable bio-aggregate for construction. De Pascale et al. (2024) investigate the use of waste bivalve shells as biofillers in porous asphalt concrete. The study finds that these biofillers, made from mussels, oysters, and clams, do not significantly alter physical properties like skid resistance or air void content. Mussel shell filler showed higher vertical permeability, while oyster shell filler demonstrated superior rutting resistance. However, clam shell filler negatively impacted mechanical properties. The study suggests combining different biofillers could optimize asphalt performance, offering an eco-friendly solution for waste management in construction.

Elgaali, Lopez-Arias, and Velay-Lizancos (2024) examine CO2 exposure treatment on recycled concrete fine aggregates (RCFA) to enhance bio-receptivity in mortars. The study finds that CO2 treatment improves the bio-receptivity of RCFA mortars, increasing porosity and reducing surface pH, which enhances biofouling organism growth. The treatment also boosted compressive strength by 83%. RCFA mortars showed better porosity and carbonation depth, making them suitable for bio-receptive applications. The study suggests that combining RCFA with CO2 exposure can create low-carbon, bio-receptive cementitious materials, promoting sustainable construction practices. There are several gaps in the literature regarding bio-based concrete, including the optimization of its performance for specific structural applications like energy absorption structures, and the long-term environmental benefits of using bio-based aggregates such as waste wood and bivalve shells. Additionally, there is limited research on the influence of bio-fillers like bivalve shells on asphalt properties, and the effects of various bio-based aggregates (e.g., hemp, rice straw, corn stalk) on concrete performance. Studies comparing the environmental impacts of bio-based and conventional aggregates, understanding the interaction of these aggregates with cement hydration, and exploring the scalability and commercial viability of bio-based aggregates in large-scale production are also lacking, along with knowledge on their behavior in critical load-bearing elements.

3 MATERIALS USED

This study used Ordinary Portland Cement (OPC) of 43 grade as the primary binder, complying with IS 8112:2013. The cement, grey in color, free from lumps, with a specific gravity of 3.14, exhibited good consistency. Natural river sand, clean and well-graded under Zone II (IS 383:2016), served as the fine aggregate with a specific gravity of 2.60. Wood ash (WA) was used as a partial cement replacement, contributing to sustainability with its pozzolanic properties, while rice husk ash (RHA) replaced fine aggregates, enhancing workability and strength. Corn cob granules (CCG), a lightweight coarse aggregate, were tested for their impact on performance, although their high porosity limited their structural behavior. Crushed angular coarse aggregates of 20 mm size conformed to IS 383:2016, and potable water was used for mixing and curing. A superplasticizer, added at 1.2% by weight of cement, reduced water demand by 19.2%, ensuring desired workability.

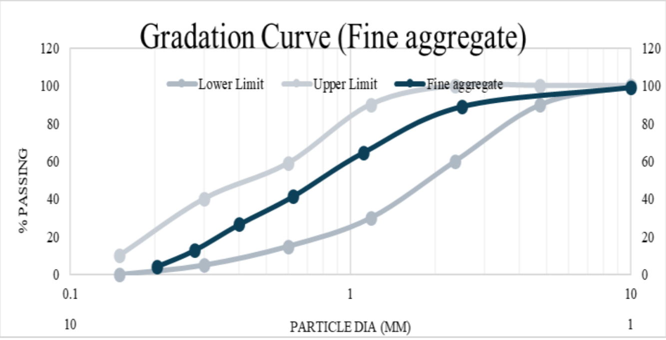

Figure 1: Gradation Curve (Fine aggregate)

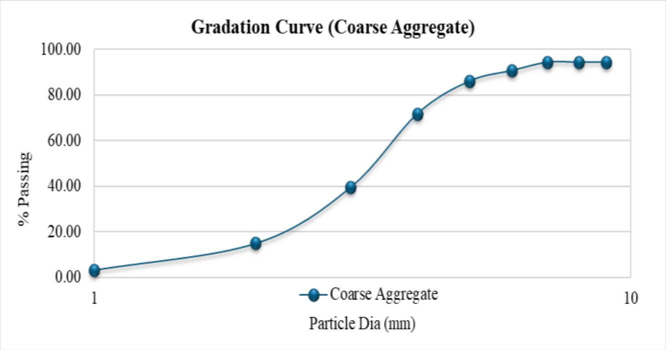

Figure 2: Gradation Curve (Coarse Aggregate)

The M45 concrete mix was designed using a blend of OPC 43 and GGBFS, with 20% of the cement replaced by GGBFS to enhance sustainability and durability. The mix comprises 355.50 kg/m^3 of OPC 43, 88.87 kg/m^3 of GGBFS, 663.93 kg/m^3 of fine aggregate (sand), and 1067.19 kg/m^3 of 20 mm coarse aggregate.

Table 1: Mix Table with Replacement Content (kg/m^3)

Abbreviation (WA_RHA_CCG)	OPC (kg)	WA (kg)	Sand (kg)	RHA (kg)	Coarse Agg. (kg)	CCG (kg)
W0_R0_C0	444.37	0	663.93	0	1067.19	0
W0_R10_C10	444.37	0	597.54	66.39	960.47	106.72
W0_R20_C20	444.37	0	531.14	132.79	853.75	213.44
W0_R40_C40	444.37	0	398.36	265.57	640.31	426.88
W0_R50_C50	444.37	0	331.97	331.97	533.59	533.59
W5_R0_C10	422.15	22.22	663.93	0	960.47	106.72
W5_R10_C0	422.15	22.22	597.54	66.39	1067.19	0
W5_R20_C40	422.15	22.22	531.14	132.79	640.31	426.88
W5_R40_C50	422.15	22.22	398.36	265.57	533.59	533.59
W5_R50_C20	422.15	22.22	331.97	331.97	853.75	213.44
W10_R0_C20	400	44.44	663.93	0	853.75	213.44
W10_R10_C50	400	44.44	597.54	66.39	533.59	533.59
W10_R20_C0	400	44.44	531.14	132.79	1067.19	0
W10_R40_C10	400	44.44	398.36	265.57	960.47	106.72
W10_R50_C40	400	44.44	331.97	331.97	640.31	426.88
W15_R0_C40	377.71	66.66	663.93	0	640.31	426.88
W15_R10_C20	377.71	66.66	597.54	66.39	853.75	213.44
W15_R20_C50	377.71	66.66	531.14	132.79	533.59	533.59
W15_R40_C0	377.71	66.66	398.36	265.57	1067.19	0
W15_R50_C10	377.71	66.66	331.97	331.97	960.47	106.72
W20_R0_C50	355.5	88.87	663.93	0	533.59	533.59
W20_R10_C40	355.5	88.87	597.54	66.39	640.31	426.88
W20_R20_C10	355.5	88.87	531.14	132.79	960.47	106.72
W20_R40_C20	355.5	88.87	398.36	265.57	853.75	213.44
W20_R50_C0	355.5	88.87	331.97	331.97	1067.19	0

A water content of 164.42 kg/m^3 was maintained, achieving a water-cement ratio of 0.37. To improve workability, 5.33 kg/m^3 of superplasticizer was added. Each mix variation in the study is coded based on the percentage replacements for easy identification and tracking during testing and analysis.

Wood Ash (WA), Rice Husk Ash (RHA), and Corn Cob Granules (CCG) to ensure easy identification and tracking. The mix code follows the format W<WA%>_R<RHA%>_C<CCG%>, representing the percentage of each replacement material used. For example, a mix with 10% wood ash, 40% rice husk ash, and 20% corn cob granules is labeled as W10_R40_C20, allowing for a concise and systematic way to refer to all 25 mix combinations in the experimental program.

The casting process began with accurate batching of materials as per the designed mix proportions, ensuring precise weighing of cement, fine aggregate, coarse aggregate, water, and superplasticizer. These materials were thoroughly mixed in a mechanical mixer to produce a uniform and workable concrete mix. Standard moulds for cubes (150×150×150 mm), cylinders (150×300 mm), and beams (100×100×500 mm) were cleaned, oiled, and prepared before casting. The concrete was placed in the moulds in layers, with each layer compacted using a table vibrator to remove air voids. After casting, the specimens were covered with a plastic sheet to prevent moisture loss and demoulded after 24 hours. The specimens were then transferred to a water curing tank, fully submerged at a controlled temperature for 28, 56, and 90 days, ensuring proper hydration and development of strength and durability properties.

3.1 Testing Procedure

The mechanical performance and durability of concrete were evaluated through a series of standardized tests conducted at 28, 56, and 90 days of curing, following relevant Indian Standard (IS) codes. Compressive strength was measured using cube specimens (150×150×150 mm) in a compression testing machine, and the split tensile strength was assessed with cylindrical specimens (150 mm diameter and 300 mm height) by applying compression along the vertical diameter. Flexural strength was determined using beam specimens (100×100×500 mm) subjected to two-point loading. Water absorption was tested by drying specimens, then immersing them in water to measure the percentage of water absorbed. All tests were performed under controlled laboratory conditions to ensure accuracy and consistency in the results.

4 RESULTS AND DISCUSSION

4.1 Compressive Strength Performance

The compressive strength results across 28, 56, and 90 days revealed that the use of wood ash (WA), rice husk ash (RHA), and corn cob granules (CCG) significantly influences the mechanical behavior of concrete. The control mix (W0_R0_C0) achieved a maximum strength of 52.89 MPa at 28 days and reached 61.82 MPa at 90 days, setting a benchmark for comparison. Low to moderate replacement levels—specifically up to 10% WA, 20% RHA, and 20% CCG—exhibited compressive strength values comparable to or slightly below the control mix. Mixes like W5_R10_C0, W10_R0_C20, and W5_R0_C10 maintained strengths close to the target value even at early ages and showed significant improvement with prolonged curing, benefiting from delayed pozzolanic reactions. However, higher replacement levels, especially those with 40–50% RHA or CCG, showed a considerable decline in strength due to increased porosity, weaker aggregate-matrix bonding, and dilution of the cementitious content. The results emphasize that while WA and RHA contribute positively through pozzolanic activity over time, CCG primarily acts as a filler and introduces mechanical weakness. Thus, optimal performance is achieved when SCMs are used within threshold limits and balanced carefully in the mix. Continued curing proved vital in strength gain, particularly for ash-based concrete, underlining the importance of hydration kinetics and binder reactivity. The compressive strength findings validate the potential of using agro-industrial waste in high-performance concrete applications with judicious mix design.

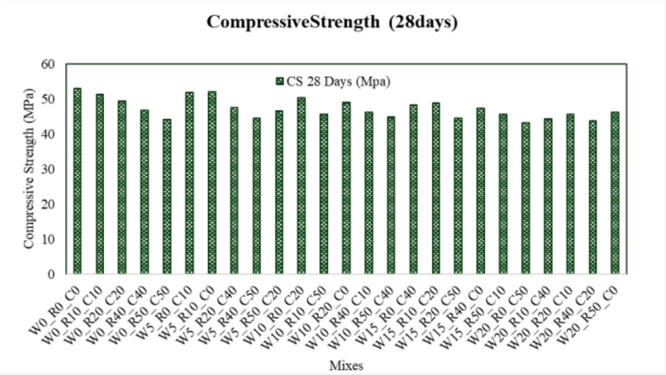

Figure 3: 28-Day Compressive Strength

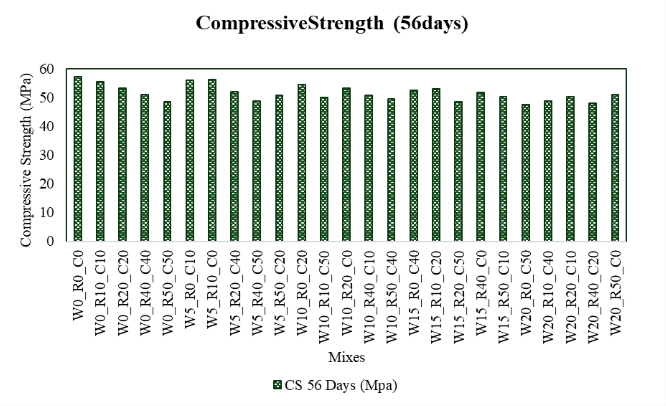

Figure 4: 56-Day Compressive Strength

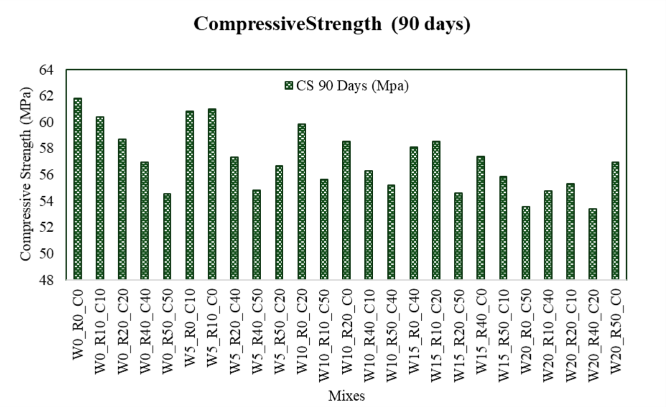

Figure 5: 90-Day Compressive Strength

4.2 Split Tensile Strength Performance

Split tensile strength (STS) is crucial in evaluating concrete's resistance to cracking and its behavior under tensile stress. The control mix demonstrated a 90-day STS of 6.18 MPa, showing a steady increase from 5.29 MPa at 28 days. Modified mixes with low WA and RHA content—such as W5_R10_C0 and W10_R0_C20—closely matched or even approached this benchmark, reaching up to 6.10 MPa at 90 days. The increase in STS over time is primarily due to the pozzolanic contributions of WA and RHA, which refine the pore structure and enhance matrix cohesion. However, high CCG content negatively influenced tensile strength at all ages. Mixes like W0_R50_C50 and W15_R20_C50 consistently displayed lower STS, peaking only at 5.30 MPa after 90 days. The porous and lightweight nature of CCG results in weak bonding within the matrix, especially under tensile loading where stress transfer across the aggregate interface is critical. RHA, when used up to 20%, had a mild impact on early STS but improved long-term performance through enhanced microstructure.

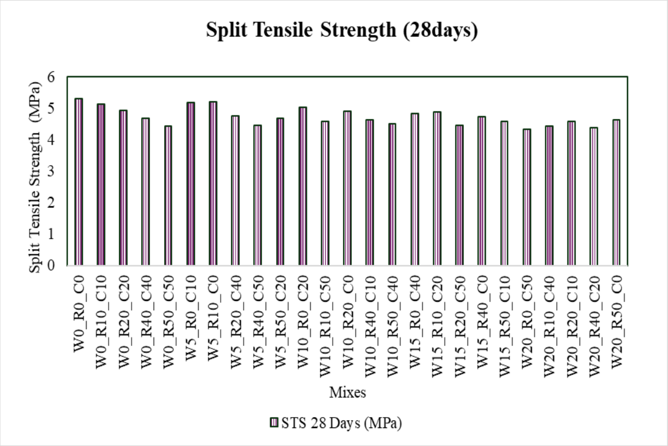

Figure 6: 28-Day STS

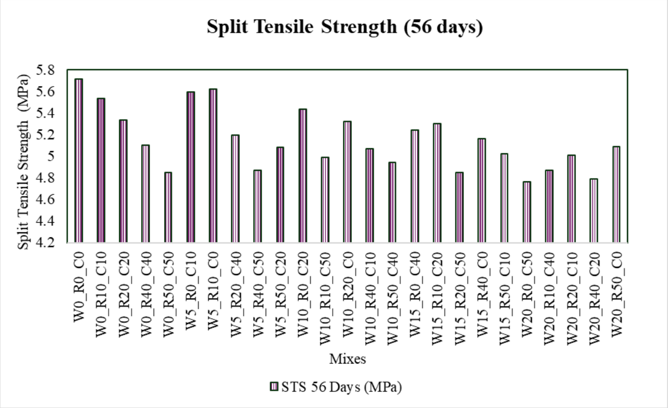

Figure 7: 56-Day STS

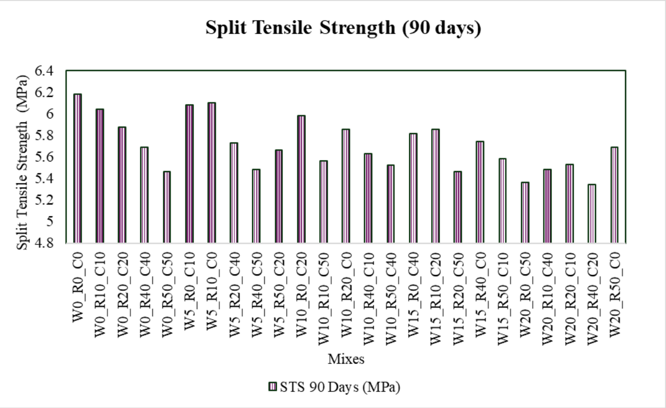

Figure 8: 90-Day STS

WA, especially at 5–10%, helped in retaining early-age strength and supported late strength gains through secondary gel formation. The findings demonstrate that while tensile strength can be maintained with careful substitution, mixes with excessive CCG compromise durability and ductility. The best tensile performance was observed in mixes that excluded or limited CCG while optimizing WA and RHA. Therefore, for applications requiring high tensile durability, maintaining aggregate integrity while leveraging the pozzolanic potential of WA and RHA is essential. The 90-day results confirm that split tensile strength benefits significantly from curing and that composite mixes can meet structural performance requirements when well-proportioned.

4.3 Flexural Strength Performance

Flexural strength results indicated similar trends to compressive and tensile strengths but revealed even more sensitivity to the quality and characteristics of the coarse aggregates. The control mix achieved a flexural strength of 8.35 MPa at 90 days, improving consistently from 7.14 MPa at 28 days. Flexural loading places maximum stress at the outer fibers of a concrete beam, making the aggregate-paste interface critical. Mixes like W5_R10_C0, W5_R0_C10, and W10_R0_C20 exhibited excellent performance, with flexural strength values ranging between 8.08–8.23 MPa at 90 days, almost equal to the control. These mixes had a balanced blend of WA and RHA with minimal or moderate CCG content, allowing strong paste-aggregate bonding and stress distribution. On the contrary, mixes containing 40–50% CCG, such as W10_R10_C50 and W15_R20_C50, showed significantly lower flexural strength, around 7.37–7.51 MPa. The reduced bond strength between the matrix and the porous CCG particles led to crack propagation under flexural stress. RHA had a mixed impact: while it added reactivity and densified the matrix, excessive replacement (40–50%) disrupted particle gradation and weakened the beam's tension zone. Wood ash consistently improved long-term performance due to its micro-filler effect and pozzolanic contribution. These observations confirm that flexural strength depends heavily on the mechanical quality of aggregates, and while SCMs enhance paste properties, they cannot compensate for poor aggregate-matrix interaction. Thus, a balanced proportion of SCMs with high-quality aggregates yields optimal flexural performance. The findings support the use of WA and RHA for strength retention, but caution against high-volume CCG use in structural concrete requiring bending resistance.

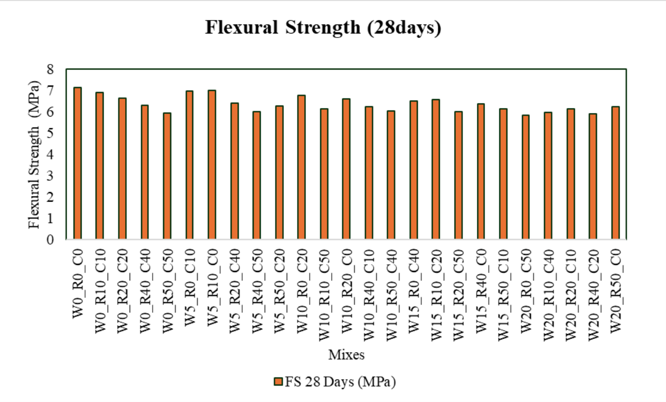

Figure 9: 28-Days FS

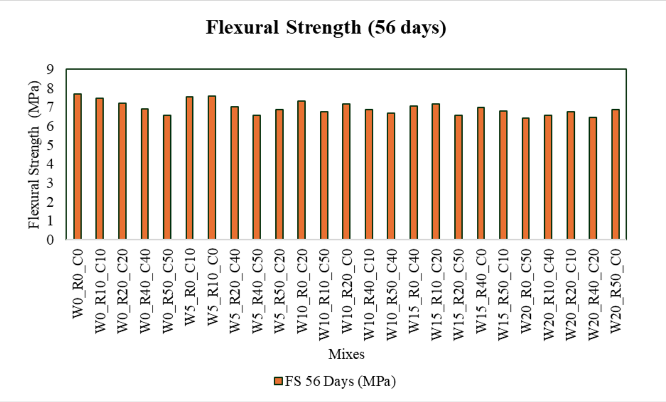

Figure 10: 56-Days FS

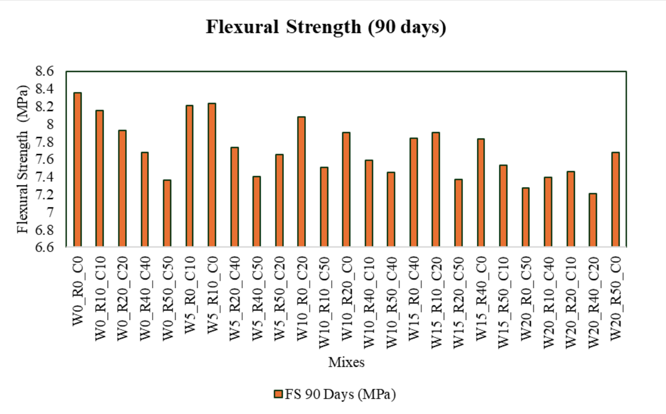

Figure 11: 90-Days FS

4.4 Water Absorption Behavior

Water absorption testing at 90 days provided valuable insights into the durability and permeability of the concrete mixes. The control mix (W0_R0_C0) showed the lowest water absorption at 4.10%, confirming its dense, low-porosity structure. As replacement levels of RHA and CCG increased, water absorption values rose sharply. Mixes with 40–50% RHA and CCG, such as W0_R50_C50 and W15_R20_C50, recorded the highest absorption values of 5.20% and 5.30%, respectively. The increased absorption is due to the porous and irregular nature of these materials, which allow higher moisture ingress. In contrast, mixes with limited or no CCG but higher WA content, like W15_R40_C0 and W20_R50_C0, maintained relatively low absorption values (~4.60–4.65%), indicating that WA does not significantly increase permeability. WA improves the matrix density over time by filling capillary voids and generating additional C–S–H gel, thereby reducing connectivity between pores. RHA, while reactive, is lighter and less dense than natural sand, disrupting gradation and increasing internal voids when used in excess. CCG is the most detrimental to water absorption due to its high porosity and organic composition. The results underline that to achieve durable concrete with low water absorption, CCG should be limited to ≤20%, and RHA should ideally not exceed 20–30%. WA, when used at 10–15%, offers durability benefits and improves long-term resistance to moisture penetration. This test affirms that while sustainability-driven material substitutions are viable, they require precise control and proportioning to avoid compromising the long-term integrity of concrete in aggressive environments.

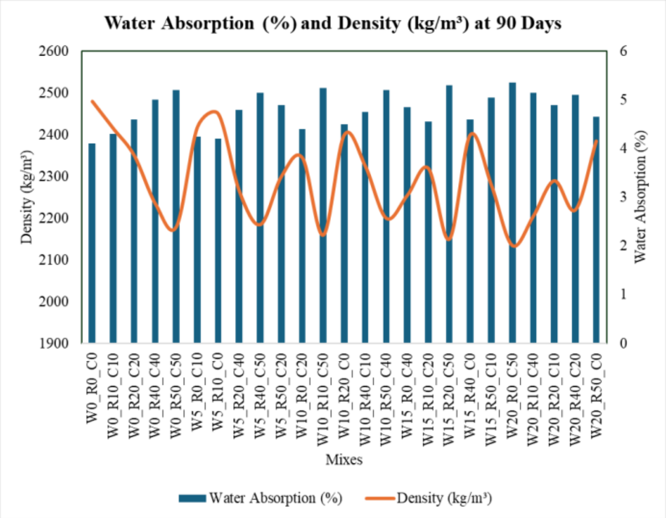

Figure 12: Water Absorption (%) and Density (kg/m^3)

4.5 Density Characteristics

Concrete density is an indicator of its strength, compactness, and durability. The control mix recorded the highest density of 2480 kg/m^3 at 90 days. As expected, mixes with higher volumes of RHA and especially CCG experienced significant reductions in density. Mixes like W0_R50_C50 and W15_R20_C50 had densities of 2180 kg/m^3 and 2150 kg/m^3, respectively, indicating the lightweight nature of these mixes. This reduction is directly linked to the low bulk densities and high porosity of the substitute materials. CCG, being highly porous and fibrous, contributes very little to the mass of the concrete while increasing the air void content. RHA, though pozzolanic, also has a lower specific gravity than natural sand and contributes to reduced compactness when used in large volumes. On the other hand, mixes like W20_R50_C0 and W15_R40_C0, which had high WA and RHA but retained natural coarse aggregates, showed significantly higher densities (~2385–2400 kg/m^3), proving that maintaining strong, dense aggregates helps preserve overall concrete mass. Wood ash had minimal negative impact on density and in some cases enhanced the matrix structure due to its fine particle size and reactivity. These results suggest that while density can be lowered for lightweight applications using agro-waste materials, structural applications should limit the use of CCG and high RHA content to preserve strength and load-carrying capacity. Proper selection of replacement levels allows customization of concrete density based on the application, balancing sustainability with performance.

4.6 Best-Performing Mixes

Based on comprehensive evaluation across all mechanical and durability properties, the best-performing mixes were:

- W5_R10_C0 – Excellent strength and low water absorption
- W5_R0_C10 – Balanced compressive, tensile, and flexural strength
- W10_R0_C20 – Good long-term strength and moderate absorption
- W15_R40_C0 – High durability and density without CCG

These mixes maintained structural performance while incorporating sustainable materials in balanced proportions.

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