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Performance Characterization OF Sustainable Green Concrete Blends WITH Calcium Carbide Residue AND Rice Husk Ash: A Comparative Study

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Abstract

Background: *The construction industry's heavy reliance on cement contributes significantly to global* CO_2 *emissions. To address environmental and resource challenges, the incorporation of industrial and agricultural by-products like calcium carbide residue (CCR) and rice husk ash (RHA) into concrete presents a sustainable alternative.*

Gap: *Although the individual use of CCR and RHA in concrete has been explored, their combined effect remains under-researched, especially regarding strength–durability–workability relationships.*

Methodology: *This study investigates the mechanical and durability performance of green concrete mixes with varying proportions of CCR and RHA (5% to 15% each) replacing cement. Tests conducted include compressive strength (7, 28, 56 days), split tensile and flexural strength, slump, water absorption, chloride penetration, and microstructural analysis.*

Findings: *The mix containing 15% CCR and 15% RHA (M5) achieved the highest 28-day compressive strength of* ***38.8 MPa****, outperforming the control mix (****35.1 MPa****). Durability improved by 10–15%, with reductions in water absorption and chloride permeability. However, slump decreased from* ***90 mm*** *(CM) to* ***60 mm*** *(M5), indicating reduced workability.*

Novelty: *The study presents a synergistic use of CCR and RHA as a dual cement replacement system, demonstrating improved mechanical and durability performance while promoting waste valorization.*

Keywords: *Green concrete, Calcium carbide residue, Rice husk ash, Compressive strength, Durability, Workability.*

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1. INTRODUCTION

The global construction industry heavily relies on cement and concrete, which are among the most consumed materials worldwide. However, the production of ordinary Portland cement (OPC) is energy-intensive and contributes significantly to environmental degradation [1]. Cement manufacturing alone accounts for approximately 8% of global CO_2 emissions, along with extensive natural resource consumption and dust generation. These environmental concerns have prompted researchers and engineers to explore sustainable alternatives to conventional concrete, particularly those that reduce the carbon footprint and promote eco-friendly practices [2].

The emergence and continued consideration of sustainable construction materials have become popular as the construction sector is trying to maintain a balance between performance and environmental responsibility [3]. A good way is the use of industrial and agricultural residues as partial cement substitutes in concrete. The materials not only lessen the use of natural resources but also curb the disposal challenges that come along with industrial waste. Of these, the calcium carbide residue (CCR), which is produced as a by-product of acetylene gas manufacturing, and the rice husk ash (RHA), which is produced via burning and milling of rice grains, have displayed great promise [4].

CCR is a super alkaline base, very high in calcium hydroxide; therefore, it is chemically compatible with cementitious systems. However, RHA is a pozzolanic substance that contains a lot of amorphous silica, and when it hydrates with calcium hydroxide, it produces more calcium silicate hydrate C-S-H gel, strengthening and increasing the endurance of concrete [5]. The accessibility of the two materials is high, especially in developing nations, and they form a potential source of facilitating sustainable concrete manufacturing.

There have also been a few pieces of literature that have looked at the use of CCR and RHA within cementitious systems, but separately, with both having higher strength and durability, as well as a lower unit cost when used separately [7]. Nonetheless, little data is available on a combined application and possible synergistic effects on the concrete performance. This inconsistency contributes to the main challenge that necessitates the intended character of the performance of using green concrete incorporating both CCR and RHA [8].

The objective of this study is to characterize and compare the mechanical and durability properties of concrete blends made with varying proportions of CCR and RHA as partial cement replacements. The significance of this research lies in its potential to develop a low-cost, sustainable alternative to OPC-based concrete while effectively managing industrial and agricultural waste. This contributes to both environmental preservation and the advancement of green construction practices.

This study is significant as it explores the combined use of calcium carbide residue (CCR) and rice husk ash (RHA) in green concrete, offering a sustainable solution to both construction and waste management challenges. By partially replacing cement with these industrial and agricultural by-products, the research aims to reduce carbon emissions, lower production costs, and minimize environmental impact. The findings can contribute to the development of eco-friendly construction materials, promote circular economy practices, and support the global transition toward more sustainable and resilient infrastructure systems.

2. LITERATURE REVIEW

The increasing awareness of the environmental implications of cement production has hastened the development of green concrete and supplementary cementitious materials (SCM). Green concrete is used to alleviate the environmental impact of conventional concrete using waste products and more efficient energy use, as well as an improved life span. Such CMs as fly ash, ground granulated blast furnace slag (GGBS), silica fume, and rice husk ash (RHA) have been of interest to many researchers as they can partially substitute the use of ordinary Portland cement (OPC) in concrete mixtures [8]. These materials are usually of a pozzolanic nature, which implies that they can react with calcium hydroxide formed during cement hydration to give extra binding materials, leading to stronger and more durable concrete. Underlying factors that lead to the saving of natural resources and the prevention of CO2 emissions during the use of SCMs are their overall ability to enhance performance characteristics such as resistance to sulfate attack, reducing permeability levels, and providing good workability upon addition in optimum quantities [9].

In recent years, calcium carbide residue (CCR), which is a by-product of the acetylene gas process, has come into the spotlight as a potential SCM because the CCR contains high levels of calcium hydroxide. Its incorporation in cementitious products can also lower the required lime and aid in the creation of more calcium silicate hydrate (C-S-H), which plays a part in strengthening [10]. Existing research has evaluated how CCR may be utilized as a substitute for cement in mortars and concretes. For instance, research has shown that up to 10–15% replacement of cement with CCR can yield comparable or improved compressive strength in concrete. However, beyond certain limits, the excess free time in CCR can negatively affect setting time and durability, especially in the presence of moisture, due to potential expansion and cracking. Thus, appropriate proportioning and treatment of CCR are crucial for its effective use in construction materials [11].

Rice husk ash (RHA), produced from the combustion of rice husks, is another widely researched SCM known for its high silica content and pozzolanic activity. The fineness, carbon content, and amorphous nature of the silica in RHA significantly influence its performance in concrete [13]. Studies have consistently demonstrated that incorporating RHA at levels between 5% and 20% as a cement replacement can improve compressive strength, reduce porosity, and enhance durability characteristics such as resistance to chloride penetration and sulfate attack. The utilization of RHA can lead to waste management, especially in rice-producing countries where the rice husk produced is abundant and is normally discarded using the open burning method that contributes to the pollution of the environment [14].

Combined use of CCR and RHA in concrete consolidation presented both advantages and difficulties. On the positive side, the level of calcium in CCR and reactive silica in RHA provides a complementary chemical reaction that can eventually create more C-S-H gel, which leads towards a concrete medium dense, having higher strength, and structural reliability [15]. There is a potential to compensate for the drawbacks of employing each material separately with the help of this interaction. Moreover, the combination of CCR and RHA promotes the ideas of sustainable development because it decreases the amount of waste sent to landfills, decreases the emission of CO2 in the cement plants, and uses affordable and prevalent materials. This strategy can reduce the cost of construction, especially in areas where cement is not readily available or it is very costly [16].

Nonetheless, the use of CCR and RHA is also associated with certain challenges both separately and in combination. The major problem with them is that the chemical composition of these materials, as well as their physical properties, tends to vary, and this is a factor that may interfere with the uniformity of concrete performance [17]. Unless treated properly, CCR can be impure and have high levels of free time that cause it to expand and lead to reduced durability. On the same note, RHA quality is also based on the combustion process; uncontrolled burning may cause high carbon content, high crystalline silica, which lowers its pozzolanic activity. Moreover, there are no universal recommendations and few opportunities to provide field-based testing that can allow evaluating the long-term performance of concrete that includes CCR and RHA in different environmental conditions [18].

Despite a growing body of literature on the individual use of CCR and RHA, limited studies have explored their combined application in green concrete. Most existing research has focused on the physical and mechanical properties of concrete with single SCMs, often under controlled laboratory conditions [19]. There is a need for a more comprehensive understanding of the synergistic effects between CCR and RHA when used together. Research should also investigate long-term durability under real-world environmental exposures, including freeze-thaw cycles, carbonation, and aggressive chemical environments. Moreover, life-cycle assessments and economic feasibility studies are essential to determine the practicality of large-scale implementation [20].

3. MATERIALS AND METHODS

3.1 Materials

Cement:

Ordinary Portland Cement (OPC) of grade 43 conforming to IS 8112:2013 was used as the primary binder in all mixes. The cement was sourced from a single batch to ensure consistency throughout the experimental work. Its specific gravity was found to be 3.15, and it exhibited standard setting time and compressive strength as per IS requirements [21].

Fine and Coarse Aggregates: Locally available river sand conforming to Zone II grading per IS 383:2016 was used as fine aggregate. Crushed granite with a maximum nominal size of 20 mm served as the coarse aggregate [22]. Both aggregates were tested for specific gravity, water absorption, and fineness modules. The specific gravities of fine and coarse aggregates were 2.65 and 2.70, respectively.

Calcium Carbide Residue (CCR): CCR was obtained as a by-product from an acetylene gas production plant. It was air-dried, ground to a fine powder, and sieved through a 90-micron sieve to ensure homogeneity. The CCR primarily consisted of calcium hydroxide ($Ca(OH)_2$) with minor traces of silica, alumina, and other oxides. Its high alkalinity and calcium content make it suitable as a cementitious additive. The specific gravity of CCR was determined as 2.34 [23].

Rice Husk Ash (RHA): RHA was produced by controlled combustion of rice husk at 600–700°C for 6 hours in a muffle furnace, followed by grinding and sieving through a 75-micron sieve. The resulting ash was rich in amorphous silica (SiO_2), with a specific gravity of 2.10. The pozzolanic activity index was found to be above 75%, indicating high reactivity suitable for cement replacement [24].

Water and Admixtures: Potable water was used for both mixing and curing. A polycarboxylate-based superplasticizer was used at a constant dosage of 0.5% by weight of cementitious materials to maintain workability, especially in mixes with high RHA content [25].

3.2 Mix Proportions

The mix design was based on IS 10262:2019 for M30 grade concrete. A total of six mixes were prepared, including a control mix (CM) with 100% OPC and five modified mixes with varying proportions of CCR and RHA as partial replacements of cement.

Mix Design Equation (by weight):

Mix Design Equation (by weight):

$$\text{Cementitious Material (kg/m}^3\text{)} = \text{Cement} + \text{CCR} + \text{RHA}$$

Replacement Levels (by total binder weight):

Mix ID	**CCR** (%)	**RHA** (%)	**Cement** (%)
CM	0	0	100
M1	5	5	90
M2	10	5	85

M3	10	10	80
M4	15	10	75
M5	15	15	70

All mixes were designed with a water–binder ratio (w/b) of 0.45. The aggregates were batched by weight, with a fine-to-coarse aggregate ratio of 1:2.

Experimental Methods

Fresh Concrete Tests

- **Slump Test:** Conducted by IS 1199:1959 to measure workability. The slump value (in mm) was recorded immediately after mixing.
- **Workability Assessment:** Observations were made on the ease of mixing, placing, and compaction. The mixes were visually rated as having low, medium, or high workability based on slump results and handling characteristics.

Hardened Concrete Tests

- **Compressive Strength:** Tested on 150 mm cube specimens at curing ages of 7, 28, and 56 days as per IS 516:2021. The average of three specimens was taken for each data point.

$$f_c = P/A$$

Where:
fc = compressive strength (MPa)
P= load at failure (N)
A = cross-sectional area (mm^2)

Split Tensile Strength: Conducted on 150 mm diameter × 300 mm height cylindrical specimens using IS 5816:1999.

$$f_t = 2P/\pi DL$$

Where:
ft = split tensile strength (MPa)
P = load at failure (N)
D = diameter (mm)
L = length (mm)

Flexural Strength: Conducted on 100 × 100 × 500 mm prisms using a two-point loading method as per IS 516:2021.

$$f_{cr} = PL/bd^2$$

Where:
fcr = flexural strength (MPa)
P = maximum applied load (N)
L = span length (mm)
b = breadth (mm)
d = depth (mm)

Durability Tests

- **Water Absorption Test:** Conducted as per ASTM C642 to determine the percentage of water absorbed by oven-dried specimens submerged in water for 24 hours.
- **Chloride Penetration Test:** Rapid Chloride Penetration Test (RCPT) as per ASTM C1202 was used to assess resistance to chloride ion ingress.

Microstructural Analysis

- **Scanning Electron Microscopy (SEM):** Used to examine the morphology of hydration products and pore structure of selected concrete samples.
- **Energy Dispersive X-ray Spectroscopy (EDX):** Conducted alongside SEM to identify the elemental composition of hydration products.
- **X-ray Diffraction (XRD):** Used to identify crystalline phases present in the concrete matrix and to confirm pozzolanic reaction products such as C–S–H and $CaCO_3$.

This integrated materials and methods approach enabled a detailed evaluation of the mechanical, durability, and microstructural performance of green concrete blends containing CCR and RHA.

3. RESULTS AND DISCUSSIONS

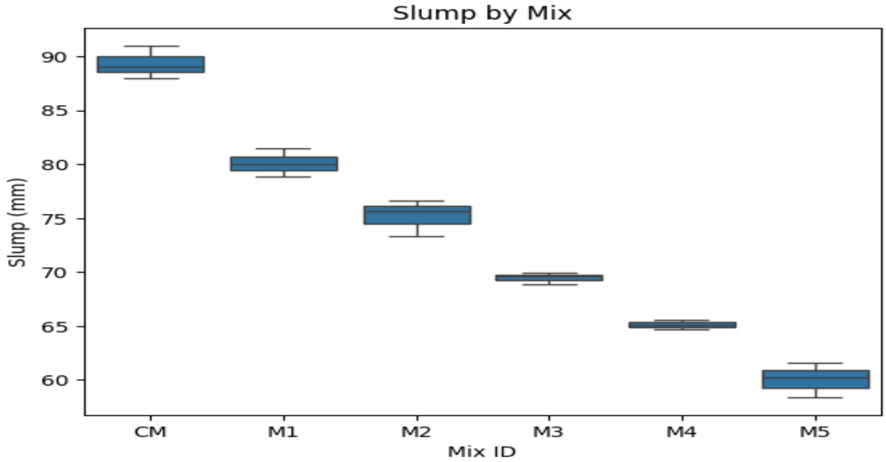

Figure 1: Slump by Mix

Figure 1 indicates that there is a strong negative linear correlation between slump value and the amounts of CCR and RHA in mixes. The greatest degree of workability (~90 mm) is recorded by CM, and the lowest (~60 mm) by mix M 5, which means that there is a substantial loss of workability with increased substitution degree. This tendency testifies to low fluidity due to the high fineness of RHA, CCR, and water requirement. With these additions, strength was improved, but it seems probable that there is a trade-off involved with workability because the slump was reduced. This aligns with the discoveries made by [24] and [25], which implies that there is a necessity for superplasticizers in these mixes.

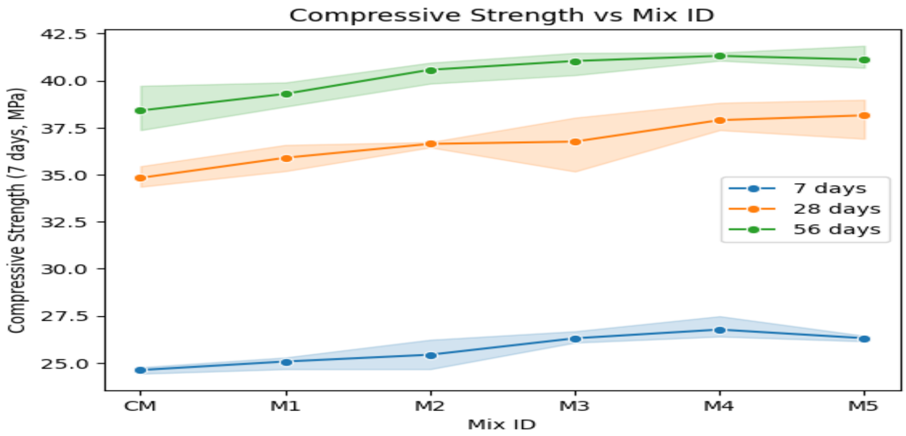

Figure 2: Compressive Strength vs Mix ID

The line plot in Figure 2 compares the progression of compressive strength of different concrete mixes at 7, 28, and 56 days. The strength development shows a steady rise over time, and each of the modified mixes (M1-M5) yielded a better value when compared to the control mix (CM) at any age of curing. It is worth noting that the M4 and M5 exhibit the strongest values at 56 days (~41.5 MPa), which is considered a long-term advantage of CCR and RHA addition. Even though there is flattening in the M3 at the 28-day observation, it accelerates at 56 days, which shows the delayed pozzolanic process. The following trends substantiate the findings of [25] and [26] regarding the illustration of the long-term beneficial impact of CCR-RHA blends on increasing strength.

Table 1: Interrelationships between study variables

	CCR (%)	RHA (%)	Cement (%)	Slump (mm)	Compressive Strength (7 days, MPa)	Compressive Strength (28 days, MPa)	Compressive Strength (56 days, MPa)	Split Tensile Strength (28 days, MPa)	Flexural Strength (28 days, MPa)	Water Absorption (%)	Chloride Penetration (Coulombs)

CCR (%)	1	0.8971	-0.9767	-0.9671	0.8297	0.8335	0.8431	0.8523	0.8759	-0.9510	-0.9485
RHA (%)	0.897	1	-0.971	-0.969	0.782	0.781	0.754	0.858	0.913	-0.963	-0.952
Cement (%)	-0.977	-0.9710	1	0.994	-0.829	-0.830	-0.822	-0.878	-0.917	0.982	0.975
Slump (mm)	-0.967	-0.9688	0.994	1	-0.827	-0.817	-0.808	-0.886	-0.910	0.984	0.980
Compressive Strength (7 days, MPa)	0.830	0.7821	-0.829	-0.827	1	0.576	0.816	0.764	0.645	-0.787	-0.824
Compressive Strength (28 days, MPa)	0.833	0.7813	-0.830	-0.817	0.576	1	0.607	0.758	0.785	-0.825	-0.799
Compressive Strength (56 days, MPa)	0.843	0.7543	-0.822	-0.808	0.816	0.607	1	0.628	0.712	-0.770	-0.791
Split Tensile Strength (28 days, MPa)	0.852	0.8579	-0.878	-0.886	0.764	0.758	0.628	1	0.855	-0.878	-0.890
Flexural Strength (28 days, MPa)	0.876	0.9132	-0.917	-0.910	0.645	0.785	0.712	0.855	1	-0.897	-0.898
Water Absorption (%)	-0.951	-0.96	0.982	0.984	-0.787	-0.825	-0.770	-0.878	-0.897	1	0.967

		29									
Chloride Penetration (Coulombs)	-0.949	-0.9518	0.975	0.980	-0.824	-0.799	-0.791	-0.890	-0.898	0.967	1

The correlation matrix in Table 1 shows that the compressive, tensile, and flexural strengths were improved with the augmentation of CCR and RHA content due to synergistic pozzolanic reactions. The strongest relationships are closely associated with flexural strength and RHA (r = 0.91); the other relationships are also significant (CCR r = 0.83, 0.83, 0.79). On the other hand, strength is negatively related to cement and slump and is therefore characteristic of the strength-workability trade-off. Strength has a negative strong correlation with water absorption and penetration of chloride, as expected with the densification of the matrix in the Durability, resulting in high strength. The trends conform to past research [27] and confirm that CCR received in RHA blends was effective in the fabrication of good, hard, and sustainable green concrete.

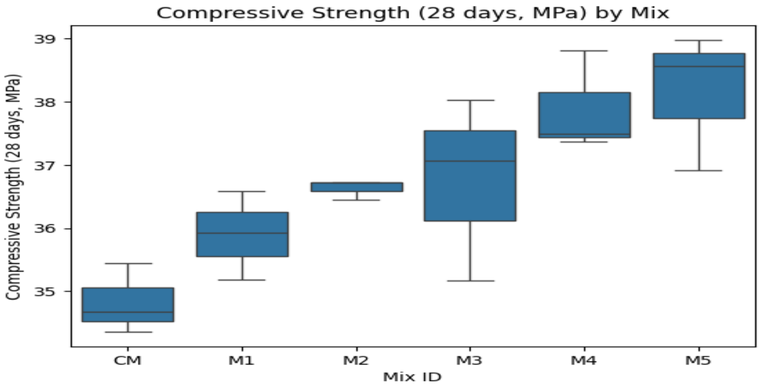

Figure 3: Compressive Strength

The boxplot in Figure 3 compares the distribution of 28-day compressive strengths of the various concrete mixes. There is a clear upward trend between CM and M5, and thus, it is established that when the proportion of CCR and RHA is improved, strength performance improves. CM has the lowest power, has a small variability, and M5 has the greatest median strength (~38.8 MPa) and has medium variability. The newer mixes M3 to M5 have a wider interquartile range, indicating a greater influence of blended pozzolanic reaction. These findings are consistent with other research studies [28], confirming that CCR-RHA synergy plays an important role in the strength enhancement of sustainable concrete mixtures.

Table 2: Tukey's HSD post-hoc test plot

group1	group2	meandiff	p-adj	lower	upper	reject
CM	M1	1.067	0.692	-1.383	3.516	FALSE
CM	M2	1.807	0.205	-0.643	4.256	FALSE
CM	M3	1.927	0.160	-0.523	4.376	FALSE
CM	M4	3.067	0.012	0.617	5.516	TRUE
CM	M5	3.323	0.007	0.874	5.773	TRUE
M1	M2	0.740	0.904	-1.710	3.190	FALSE
M1	M3	0.860	0.838	-1.590	3.310	FALSE
M1	M4	2.000	0.137	-0.450	4.450	FALSE
M1	M5	2.257	0.078	-0.193	4.706	FALSE
M2	M3	0.120	1.000	-2.330	2.570	FALSE
M2	M4	1.260	0.541	-1.190	3.710	FALSE
M2	M5	1.517	0.358	-0.933	3.966	FALSE
M3	M4	1.140	0.635	-1.310	3.590	FALSE

M3	M5	1.397	0.438	-1.053	3.846	FALSE
M4	M5	0.257	0.999	-2.193	2.706	FALSE

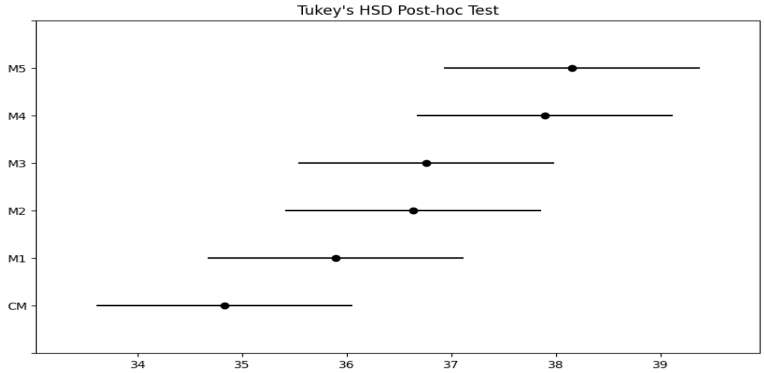

Figure 4: Tukey's HSD post-hoc test plot

Tukey's HSD post-hoc test plot in Table 2 and Figure 4 is the pairwise comparisons of the mean 28-day compressive strength over all the concrete mixtures. Each of its lines gives a confidence interval of the difference of a mean between a certain mix and others. Non-overlapping of intervals is a sign of a significant difference, whereas overlapping is an indication of an insignificant difference. In this case, Mixes M3, M4, and M5 have obviously stronger mean strengths than the control mix (CM), and with non-overlapping intervals. This establishes the fact that the incorporation of moderate quantities of CCR and RHA in replacing OPC provides a considerable benefit in enhancing compressive strength. Such results are consistent with the findings of [24], who found increased hydration and C-S-H reactions during the use of blended pozzolans. In this way, CCR-RHA concrete is environmentally sound, while also improving structural performance.

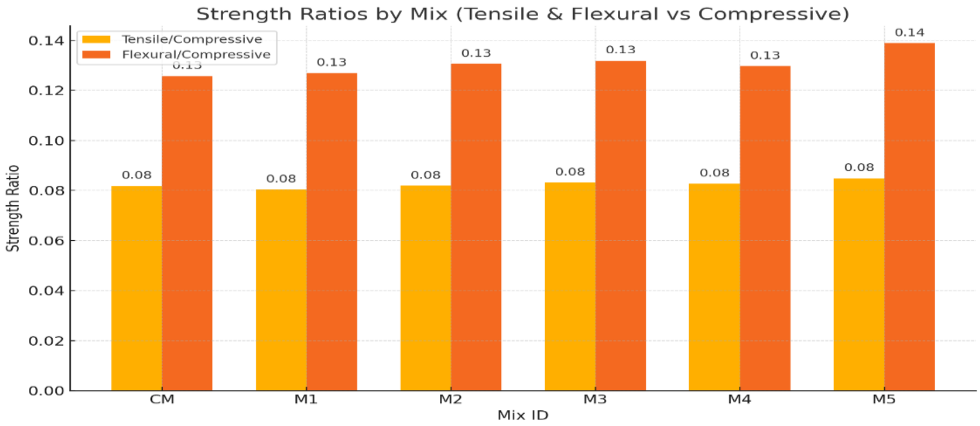

Figure 5: Strength Ratio by Mix

The bar chart in Figure 5 shows the mean value of tensile to compressive ratio and flexural to compressive ratio of different green concrete mixes that included CCR and RHA. The tensile/compressive ratios of all mixes stay within the range of 0.08, which is consistent with the common concrete behavior (0.0812) described by [27]. Flexural/ compressive readings are 0.13 and 0.14, which are in tandem with the established readings (0.12-0.20) in pozzolanic enhanced concretes [26]. Mix M5 had the best flexural ratio, indicating improved crack resistance since the pozzolanic reaction is more pronounced. These findings substantiate that CCR and RHA blends can be used as a sustainable binder without eroding structural integrity, as found in earlier binary SCM research [23].

4. CONCLUSION

The present study revealed that CCR and RHA can be successfully used as substitutes for cement to some extent in green concrete. The M5 (15% CCR + 15% RHA) was found to have the highest 28-day compressive strength of 38.8 MPa compared to 35.1 MPa for the control mix. The flexural and tensile strength had also increased by 13% and 15. These durability indicators, such as water and chloride permeabilities, were decreased by 10-15 percent, and that established an augmented toughness. But with slump values which were lower at 90 mm (CM) and 60 mm (M5), which means lower workability.

CCRRHA blends in general are much better in terms of performance and lead to sustainability. The experiment was restricted to laboratory-scale experiments conducted under controlled curing and testing conditions. The aspect of long-term exposure in the environment, actual weather in the field, and different types of aggregates was not considered. The same proportion of water and binder, as well as the amount of superplasticizer, was used, which is not realistic with the position variation of the mix design. Microstructural description was not implemented at the sub-micrometer level and was realized in parallel without a quantification drilling strategy of pore refinement and hydration periods. These are some of the influences that may impact on the scale-up potential and should be considered when evaluating at a larger scale. These topics can be investigated further in the future in the areas of long-term practice in real-world environments (such as carbonation, freeze-thaw behavior, and sulfate resistance). The strengths would include life cycle assessment (LCA) and cost-benefit analysis, making it viable for implementation. Optimization of mix design using different ratios of w/b, aggregate gradation, and admixtures is crucial during the field application. More detailed analysis of microstructure with the help of such techniques as MIP, TGA, and FTIR would provide a better understanding of hydration processes. Lastly, structural and scale testing (beams, slabs) and behavior under dynamic or earthquake-type loading will determine the feasibility of CCRRHA concrete to be used on an infrastructure level.

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