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Research article

Eco-efficient structural concrete: Mechanical and durability properties of mixes with cashew nutshell ash and waste foundry sand

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ABSTRACT

The construction industry is facing rising issues related to sustainability and resource depletion, mostly due to the extensive use of conventional materials such as cement and fine aggregates. Cement manufacture emits a substantial amount of carbon, and mining natural aggregates can be harmful to the environment. This study investigates the use of Cashew Nutshell Ash (CNA) and Waste Foundry Sand (WFS) as partial substitutes for cement and fine aggregates in concrete, with the objective of increasing sustainability. In this study, cement was replaced with CNA at varied percentages of 0%, 5%, 10%, 15%, and 20%, while fine aggregate was replaced with WFS at 0%, 10%, 20%, 30%, and 40%. The mechanical, durability, and microstructural properties of the modified concrete were evaluated. The tests involved assessing compressive strength, flexural strength, split tensile strength, acid resistance, water absorption, and chloride ion penetration. The study looked at the combined effect of CNA's pozzolanic activity and WFS's packing efficiency. The results revealed that the combination with 10% CNA and 20% WFS (C10%W20%) had the greatest results, with a 12% improvement in compressive strength, a 15% increase in flexural strength, and a 10.5% increase in split tensile strength compared to the control mix (C0%W0%). Durability tests found that the material is more resistant to acid assaults, has lower water absorption, and has less chloride ion penetration. Finally, the study concludes that CNA and WFS are effective sustainable options for concrete manufacturing, improving both performance and environmental sustainability.

1. Introduction

As a cornerstone in modern infrastructure, the global construction industry functions as an essential force for economic and societal progress through urban development However, the exponential growth of this sector has brought about significant environmental and resource challenges. The primary raw materials for concrete such cement and fine aggregates are responsible for severe environmental issues [1,2]. Cement manufacturing alone accounts for approximately 7% of global carbon dioxide emissions [3,4], a figure that underscores the pressing need for sustainable alternatives. The excessive mining of natural aggregates simultaneously disrupts landscapes while accelerating the land deterioration and causing biodiversity loss [5,6]. In this context, exploring alternative materials that can partially replace cement and aggregates in concrete mixes has emerged as an area of paramount importance in sustainable construction practices. The necessity arose from mounting environmental issues to study agricultural waste [7–9] and industrial by-products [10–12] as concrete components alternatives. Cashew nutshell ash (CNA) from agricultural waste combines with waste foundry sand (WFS) from industries to present a sustainable solution for addressing construction problems. The ash generated through cashew nut processing waste combustion transforms into a silica-rich pozzolanic material suitable for cement substitutes [13,14]. Mendu Pannem (2021) reported CNA as an effective pozzolan since its strength activity index (SAI) exceeds 75% and improvement in strength properties with the addition of 15% of CAN [15] Similarly, waste foundry sand, a by-product of metal casting industries demonstrates excellent distribution efficiency and its small-sized particles produce good possibilities for aggregate substitution [16–20]. This study addresses two critical global challenges: sustainability in construction and effective

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waste management. This research applies agricultural and industrial waste products to concrete production to reduce primary material reliance and convert abundant discards into beneficial components that prevent materials from accumulating in landfills. The utilization of CNA and WFS in concrete production aligns with the principles of the circular economy, promoting resource efficiency and minimizing environmental impact. Moreover, the findings of this study have the potential to revolutionize the construction industry by enhancing the performance of concrete. By leveraging the pozzolanic activity of CNA and the particle packing efficiency of WFS, this research seeks to improve the mechanical and durability properties of concrete. The insights gathered help create novel affordable sustainable construction materials with limited environmental impact and extended durability [21]. The ongoing depletion of natural resources together with the environmental deterioration from conventional concrete production proves that sustainable replacements must become an immediate necessity. Large quantities of waste emerge from agricultural and industrial activities although many waste streams receive inadequate management or find limited utilization. The production of cashew nuts creates extensive amounts of shells and metal casting facilities generate enormous quantities of foundry sand. These waste materials generate adverse environmental impact when disposed of incorrectly. Adding industrial residues into concrete manufacturing offers potential for managing waste stream issues while benefiting concrete behaviour along with environmental outcomes. This dual benefit aligns with global efforts to transition toward sustainable construction practices and achieve the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action) [22]. The construction industry faces a dual challenge: the environmental consequences of conventional material usage and the escalating demand for high-performance construction materials. The production of cement and fine aggregates for traditional concrete components requires significant energy consumption while causing both resource shortage and environmental deterioration. The problem of managing agricultural and industrial wastes, including cashew nutshells and foundry sand has limited processing options for their beneficial utilization. Studies [23–25] proved that concrete production benefits from agricultural and industrial by-products. The existing research have primarily focused on effects of agricultural and industrial residues in concrete production yet fails to investigate combined material impacts on single mixes. Realizing the complete properties of concrete made with CNA and WFS requires a specific examination of chemical interactions and material strength alongside durability assessment to achieve sustainable concrete materials that manage both environmental needs and structural conditions. A systematic analysis of mechanical and durability aspects with microstructural evaluation is conducted in this research to examine the combined effects of CNA and WFS within concrete mixtures. This research evaluates various CNA and WFS replacement levels to find an optimal mix design that delivers exceptional performance for concrete.

2. Materials and methodology

2.1. Materials

The primary ingredients used to make concrete test specimens are Ordinary Portland Cement OPC-53 grade, Cashew Nutshell Ash (CNA), Waste Foundry Sand (WFS) as fine aggregate, coarse aggregate, water and superplasticizer. The OPC-53 grade exhibits high strength properties combined with small particle dimensions to achieve faster strength development at a specific gravity of 3.15 and 1440 kg/m^3 unit weight. CNA functions as a pozzolanic ingredient because of its specific gravity 2.2 and its combined silica and calcium oxide content enables better durability and strength. Waste Foundry Sand (WFS) served as an environmentally friendly fine aggregate material with specific gravity 2.45 with a unit weight of 1700 kg/m^3 and fineness modulus measuring 1.8. The crushed gravel aggregates function as coarse material with a specific gravity value of 2.65 and unit weight at 1500 kg/m^3 while delivering sustaining strength and resistance properties. Productivity through hydration became possible due to the use of clean potable water while a high-range superplasticizer enhanced workability by reducing the water-cement ratio to achieve superior concrete performance [26].

2.2. Methodology

2.2.1. Mechanical properties

The compressive strength of CNA and WFS added concrete was determined using 100 mm cubic specimens subjected to uniaxial compression with a UTM of 2000 kN capacity at 7, 14, and 28 days of curing, as per IS: 516–1959. The modulus of elasticity was measured using cylindrical specimens (100 mm diameter, 200 mm height) subjected to compression after curing for 7, 14, and 28 days. Strain was calculated using dial gauges, and stress was derived from the applied load and cross-sectional area, with the modulus calculated from the stress-strain curve's slope. The energy storage capacity was also determined. Tensile strength was measured using cylindrical specimens (200 mm height, 100 mm diameter) tested at 7, 14, and 28 days using a UTM with a 2000 kN capacity, as per IS: 5816–1959. Flexural strength was assessed using a 100 mm × 100 mm x 500 mm prism placed in a 2000 kN UTM under a single-point loading system with a simply supported span of 650 mm, according to IS: 516–1959.

2.2.2. Durability properties

For acid resistance (ASTM C267), 100 mm cube samples were submerged in 3% H_2SO_4 solutions after a curing period of 28 days. Weight loss and reduction in compressive strength were assessed following time intervals of 30, 60, 90, 120, 150, and 180 days. Weight loss was determined by weighing samples before and after immersion, whereas strength loss was assessed with a Universal Testing Machine (UTM). Cylindrical samples (100 mm × 200 mm) were utilized to evaluate the chloride penetration ability of concrete according to ASTM C1202. Following 28 days of curing, the samples were sliced into 50 mm pieces, covered with epoxy, and tested with RCPT using 3% NaCl and 0.3 M NaOH solutions under a 60 V DC voltage. Current was gauged every 30 min over six hours, and average values were documented from three samples to assess chloride ion infiltration. Water absorption tests included drying cured samples at 105°C until they reached a constant weight, followed by soaking them in water for 24 h. Weight increase was assessed to determine water uptake as a percentage of the dry weight. These assessments offered an in-depth insight into chloride infiltration, acid durability and water absorption resistance properties of CAN and WFS added concrete. The observed durability behaviour and permeability characteristics are consistent with the established principles of concrete transport properties reported by Neville [27].

2.2.3. Microstructural analysis

The microstructural and material analysis of concrete containing Cashew Nutshell Ash (CNA) and Waste Foundry Sand (WFS) utilizes multiple techniques. Concrete samples with specific CNA and WFS proportions are prepared, cured for 28 days, and analysed. Scanning Electron Microscopy (SEM) examines surface morphology and the distribution of CNA and WFS particles, focusing on the Interface Transition Zone (ITZ). Prior to imaging, the samples are cleaned and coated with a conductive layer. Energy-Dispersive X-ray Spectroscopy (EDS), integrated with SEM, determines the elemental composition of key regions. Phase analysis is conducted using X-ray Diffraction (XRD) by grinding the concrete into fine powder and identifying crystalline phases. Thermogravimetric Analysis (TGA) measures weight loss of a sample as it is heated, providing insights into thermal stability and composition. A small sample is placed in a crucible and heated in a controlled atmosphere. The resulting weight vs. temperature curve shows decomposition stages. For TGA, use 5–20 mg of finely ground, uniform sample in a crucible suited for the temperature range (e.g., platinum, alumina). Set up the Thermogravimetric Analyzer, ensuring mass change is measured in a controlled atmosphere (inert or reactive). Choose an appropriate temperature range (25˚C-1000˚C) and heating rate (5–20 ˚C/min). Optionally, hold temperature at specific points to observe decomposition events. SEM imaging and elemental analysis are performed using a MINI-SEM 3200 M equipped with an EDS system, and XRD data is analysed using Xpert High Score Plus software, with diffraction patterns measured over a 2θ range of 0˚ to 100˚ at 10˚ intervals. This integrated approach provides comprehensive insights into the chemical composition, microstructure, hydration, and thermal properties of the concrete, revealing the impact of CNA and WFS on its durability and performance.

2.3. Experimentations

Table 1a presents 16 mix proportions were designed as per IS: 10262–2019 with cement was replaced partially with CNA at levels of 0%, 5%, 10%, 15% and 20%, whereas fine aggregates were replaced partially with WFS at 0%, 10%, 20%, 30% and 40%. The concrete mix was made with respective mix proportions and make test specimen for compressive strength, split tensile and flexural strength. After 28 adays of curing, the test specimen was tested as IS: 516–1959 and IS: 5816–1959 to determine the compressive strength, split tensile and flexural strength of CNA and WFS added concrete as well as control concrete. According to ASTM C267, the acid resistance of CNA and WFS modified concrete, along with control concrete, was tested by measuring weight loss and compressive strength reduction after exposure to acid solutions. The tests were conducted on 100 mm cube samples after 28 days of curing. The cubes were weighed before immersion in the acid solutions and measure the weight loss between 0 and 180 days with 30 days interval. Additionally, 100 mm× 200 mm cylindrical specimens were used to assess chloride penetration as per ASTM C1202. After 28 days of curing, these specimens were cut to 50 mm thickness, coated with epoxy resin, and subjected to RCPT testing.

3. Mechanical properties of CNA and WFS added concrete

3.1. Compressive strength

Fig. 1**.** illustrates the variation of compressive strength of concrete modified with various level of CNA and WFS at 28 days.

The compressive strength results show a positive relationship between the increased CNA content and compressive strength as the mix percentage rises from 0% to 10%. A substantial portion of cement replaced with CNA significantly increases the compressive strength of concrete. This increase in strength is attributed to the pozzolanic reaction of CNA, which reacts with calcium hydroxide (Ca $(OH)_2$) produced during cement hydration to form additional calcium silicate hydrate (C-S-H) gel. The pozzolanic reaction can be expressed as;

$$SiO_2 + CaOH_2 + H_2O \rightarrow C - S - H \quad (gel)$$

$$Al_2O_3 + Ca(OH)_2 + H_2O \rightarrow C - A - H \quad (gel)$$

Where C-A-H refers to calcium aluminate hydrate. These secondary hydration products improve the microstructure of the concrete and contribute to its compressive strength. The control mix C0W0 achieves a compressive strength of 40 N/mm^2 while C10W20 achieves a compressive strength of 50.4 N/mm^2, showcasing the strengthening effect of CNA. Besides CNA, Waste Foundry Sand (WFS) contributes to strength development, particularly when utilized at a replacement level of 20%. Concrete mixes such C5W20 (5% CNA, 20% WFS) and C10W20 (10% CNA, 20% WFS) demonstrate a steady enhancement in compressive strength. This enhancement is mainly attributed to the filling impact of fine WFS particles, which lower porosity in the concrete matrix, along with the partial pozzolanic activity of silica present in WFS. Reactive silica in WFS interacts with calcium hydroxide to produce additional C-S-H gel, as described by the reaction;

$$SiO_2 + Ca(OH)_2 + H_2O \rightarrow C - S - H \quad (gel)$$

However, with increased replacement levels of WFS, such as mixes C5W40 and C10W40 (40% WFS), the compressive strength decreases. This decrease can be linked to the inherent properties of WFS such as irregular particle shapes compared to natural sand. It was observed that the concrete mixes containing WFS up to 20% (C5W20 & C10W20) demonstrate a progressive improvement in strength whereas higher WFS levels (C5W40 & C10W40) lead to reduced strength. This could be due to the inherent properties of WFS, which might lack the ideal char-

Table 1a
Mix proportions.

Mix-ID	Cement (kg/m^3)	CNA (kg/m^3)	Fine Aggregate (Sand) (kg/m^3)	WFS (kg/m^3)	Coarse Aggregate (kg/m^3)	Water (kg/m^3)	Admixture (kg/m^3)
C0W0	400	0	700	0	1200	152	2
C0W10	400	0	630	70	1200	152	2
C0W20	400	0	560	140	1200	152	2
C0W30	400	0	490	210	1200	152	2
C0W40	400	0	420	280	1200	152	2
C5W0	380	20	700	0	1200	152	2
C5W10	380	20	630	70	1200	152	2
C5W20	380	20	560	140	1200	152	2
C5W30	380	20	490	210	1200	152	2
C5W40	380	20	420	280	1200	152	2
C10W0	360	40	700	0	1200	152	2
C10W10	360	40	630	70	1200	152	2
C10W20	360	40	560	140	1200	152	2
C10W30	360	40	490	210	1200	152	2
C10W40	360	40	420	280	1200	152	2
C15W0	340	60	700	0	1200	152	2
C15W10	340	60	630	70	1200	152	2
C15W20	340	60	560	140	1200	152	2
C15W30	340	60	490	210	1200	152	2
C15W40	340	60	420	280	1200	152	2

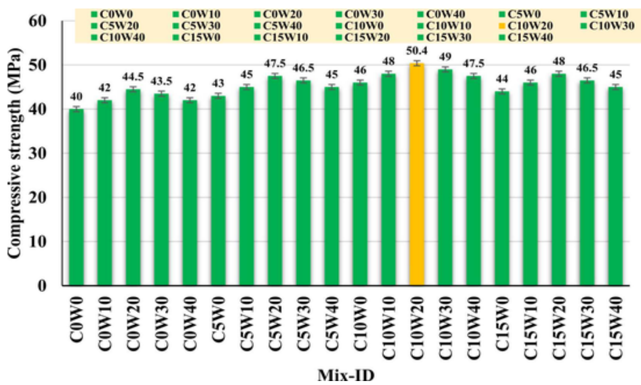

Fig. 1. Compressive strength of various concrete mixes.

acteristics of natural sand, such as gradation and particle shape, at higher replacement levels.

3.2. Flexural strength and split tensile strength

Fig. 2**.** illustrates the variation of flexural strength and split tensile strength of concrete modified with various level of CNA and WFS at 28 days.

It was observed that the concrete mix with higher CNA content led to increased split tensile strength. The split tensile strength of the C0W0 (control mix) was found to be 3.80 N/mm², however with the inclusion of 10% CNA, the split tensile strength was reached to 4.20 N/mm² for C10W0 mix. The pozzolanic effect of CNA has led to better concrete microstructures which enhances cracking resistance. Addition of WFS shows a weaker impact on the split tensile strength measurement rather than its effect on compressive strength. The C10W20 mix attains the highest tensile strength of 4.60 N/mm² among all treatments. The enhancement in microstructure because of WFS addition to 20% resulted in improved split tensile strength which may have benefited from better bonding and lowered porosity between material components. The addition of CNA also increases the flexural strength of the concrete. The inclusion 10% CNA with 20% WFS increases the flexural strength from 5.00 N/mm² (C0W0 mix) to reach 6.25 N/mm² (C10W20 mix). This improvement suggests that the pozzolanic effect of CNA contributes to the development of stronger concrete under bending forces. The addition of WFS also contributes to flexural strength, but the effect is more moderate compared to compressive and tensile strength. The flexural strength gradually increases with WFS, peaking at C10W20 (6.25 N/mm²), and then slightly decreasing with higher WFS content, like in C10W40 (5.85 N/mm²). It was concluded that the combination of 10%

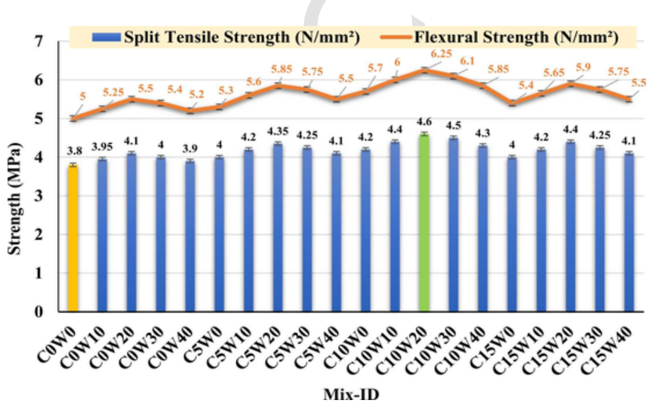

Fig. 2. Flexural strength and split tensile strength of various concrete mixes.

CNA and 20% WFS is found to be optimal mix for attaining high strength for concrete modified with CNA and WFS.

4. Durability properties of CNA and WFS added concrete

4.1. Acid resistance

Table 2a and Table 2b illustrates the acid resistance of concrete modified with various level of CNA and WFS in terms of weight loss and strength loss after exposed to acid solution. The results of the acid attack on concrete mixes with varying proportions of Cashew Nutshell Ash (CNA) and Waste Foundry Sand (WFS) exposed to 3% concentration of H_2SO_4 solution indicate that the addition of CNA and WFS improves the concrete's resistance to sulfuric acid. The control mix (C0W0) showed considerable mass and strength loss, with mass loss at 36% and strength loss at 60% after 180 days. Conversely, mix with CNA and WFS exhibited lesser loss in mass and strength, with the C10W20 blend (10% CNA and 20% WFS) revealing the least degradation. The improved acid resistance of concrete mix includes CNA and

Table 2a
Weight loss (%) against acid attack.

Mix -ID	0 Days	30 Days	60 Days	90 Days	120 Days	150 Days	180 Days
C0W0	0.00	6.00	12.00	18.00	24.00	30.00	36.00
C0W10	0.00	5.50	11.00	16.50	22.00	27.50	33.00
C0W20	0.00	5.00	10.00	15.00	20.00	25.00	30.00
C0W30	0.00	4.50	9.00	13.50	18.00	22.50	27.00
C0W40	0.00	4.00	8.00	12.00	16.00	20.00	24.00
C5W0	0.00	5.80	11.60	17.40	23.20	29.00	34.80
C5W10	0.00	5.20	10.40	15.60	20.80	26.00	31.20
C5W20	0.00	4.80	9.60	14.40	19.20	24.00	28.80
C5W30	0.00	4.30	8.60	12.90	17.20	21.50	25.80
C5W40	0.00	3.80	7.60	11.40	15.20	19.00	22.80
C10W0	0.00	6.00	12.00	18.00	24.00	30.00	36.00
C10W10	0.00	5.50	11.00	16.50	22.00	27.50	33.00
C10W20	0.00	3.10	6.20	9.30	12.40	15.50	18.60
C10W30	0.00	4.50	9.00	13.50	18.00	22.50	27.00
C10W40	0.00	4.00	8.00	12.00	16.00	20.00	24.00
C15W0	0.00	5.80	11.60	17.40	23.20	29.00	34.80
C15W10	0.00	5.20	10.40	15.60	20.80	26.00	31.20
C15W20	0.00	4.80	9.60	14.40	19.20	24.00	28.80
C15W30	0.00	4.30	8.60	12.90	17.20	21.50	25.80
C15W40	0.00	3.80	7.60	11.40	15.20	19.00	22.80

Table 2b
Strength loss (%) against acid attack.

Mix ID	0 Days	30 Days	60 Days	90 Days	120 Days	150 Days	180 Days
C0W0	0.00	10.00	20.00	30.00	40.00	50.00	60.00
C0W10	0.00	9.50	19.00	28.50	38.00	47.50	57.00
C0W20	0.00	9.00	18.00	27.00	36.00	45.00	54.00
C0W30	0.00	8.50	17.00	25.50	34.00	42.50	51.00
C0W40	0.00	8.00	16.00	24.00	32.00	40.00	48.00
C5W0	0.00	9.20	18.40	27.60	36.80	46.00	55.20
C5W10	0.00	8.60	17.20	25.80	34.40	43.00	51.60
C5W20	0.00	8.00	16.00	24.00	32.00	40.00	48.00
C5W30	0.00	7.50	15.00	22.50	30.00	37.50	45.00
C5W40	0.00	7.00	14.00	21.00	28.00	35.00	42.00
C10W0	0.00	10.00	20.00	30.00	40.00	50.00	60.00
C10W10	0.00	9.50	19.00	28.50	38.00	47.50	57.00
C10W20	0.00	6.00	12.00	18.00	24.00	30.00	36.00
C10W30	0.00	8.60	17.20	25.80	34.40	43.00	51.60
C10W40	0.00	8.00	16.00	24.00	32.00	40.00	48.00
C15W0	0.00	9.30	18.60	27.90	37.20	46.50	55.80
C15W10	0.00	8.70	17.40	26.10	34.80	43.50	52.20
C15W20	0.00	8.00	16.00	24.00	32.00	40.00	48.00
C15W30	0.00	7.50	15.00	22.50	30.00	37.50	45.00
C15W40	0.00	7.00	14.00	21.00	28.00	35.00	42.00

WFS is due to the pozzolanic reaction of CNA along with the finer particle size of WFS, which collectively decrease porosity and increase density. The pozzolanic compound involves the reaction of silica (SiO_2) and alumina (Al_2O_3) from CPA with calcium hydroxide ($CaOH_2$) (a product of cement hydration) to from $C-S-H$ and $C-A-H$ gel. These compounds enhance the concrete structure by filling voids and improving bonding. These reactions are as follows;

Formation of $C-S-H$ gel$SiO_2 + CaOH_2 + H_2O \rightarrow C-S-H \quad (gel)$

Formation of $C-A-H$ gel$Al_2O_3 + Ca(OH)_2 + H_2O \rightarrow C-A-H \quad (gel)$

These secondary hydration products improve the durability of the concrete and lessen its vulnerability to acid attack by decreasing the availability of free, which highly reactive with sulphuric acid. In the control mix, the subsequent reaction takes place, resulting in considerable mass loss caused by the formation of gypsum and ettringite as observed in SEM as presented in Fig. 5a, which expand and weaken the structure;

$$Ca(OH)_2 + H_2SO_4 \rightarrow CaSO_4.2H_2O + H_2O$$

$$C_3A + 3CaSO_4 + 32H_2O \rightarrow C_3A.3CaSO_4.32H_2O$$

The mix with CNA and WFS, especially C10W20, resist this degradation because of their more compact microstructure and lower porosity. The small particle size of WFS additionally improves the packing density of the concrete matrix, limiting acid penetration and minimizing the formation of expansive products such as gypsum and ettringite as observed in SEM as presented in Fig. 5b. These findings concluded that the C10W20 mix outperforms other mixes, establishing it as the optimal combination for improved acid resistance due to the synergistic impacts of CNA and WFS, which render the concrete denser, stronger, and more resilient under acidic conditions.

4.2. Chloride resistance

The RCPT results reveal that all concrete mixes fall within the category of low chloride penetration with the change passing in the range of 1000–2000 Coulombs signifying the moderate resistance to chloride ion penetration. Of the various mixes, C10W20, containing 10% Cashew Nut Shell Ash (CNA) and 20% Waste Foundry Sand (WFS), showed the lowest RCPT value of 1650 Coulombs, making it the optimal mix for chloride ion resistance. Other mixtures, including C5W0, C15W0, and various combinations of CNA and WFS, exhibited slightly higher RCPT values, suggesting that although they perform better than the control, they did not achieve the same level of resistance as C10W20 mix. The improved chloride resistance of concrete mix includes CNA and WFS is due to the pozzolanic reaction of CNA along with the finer particle size of WFS, which collectively decrease porosity and increase density. The pozzolanic compound involves the reaction of silica and alumina from CPA with calcium hydroxide ($CaOH_2$) (a product of cement hydration) to from $C-S-H$ and $C-A-H$ gel. These compounds enhance the concrete structure by filling voids and improving bonding. These reactions are as follows;

Formation of $C-S-H$ gel$SiO_2 + CaOH_2 + H_2O \rightarrow C-S-H \quad (gel)$

Formation of $C-A-H$ gel$Al_2O_3 + Ca(OH)_2 + H_2O \rightarrow C-A-H \quad (gel)$

WFS, with its fine particle size, enhances the packing density of the concrete matrix, reducing voids and increasing resistance to chloride ion penetration. This improvement in the concrete's microstructure decreases its permeability, thereby limiting the diffusion of chloride ions. Similar improvements in durability and chloride resistance due to pore refinement and microstructural densification in sustainable concrete incorporating industrial by-products were also reported by Zhang et al. [28]. Additionally, the fine particles of WFS improve the packing density of the concrete, further minimizing voids and limiting pathways for acid penetration The combined effect of CNA and WFS enhances the chloride ion resistance of concrete, with the 10% CNA and 20% WFS mix offering the best balance of strength and durability. This suggests that the optimal chloride resistance is achieved when both CNA and WFS are incorporated at moderate levels, improving concrete's performance against chloride-induced corrosion. Fig. 3. illustrates the variation of Chloride resistance of concrete modified with various level of CNA and WFS tested using RCPT.

4.3. Water absorption resistance

It was found that the C10W20 mix containing 10% CNA along with 20% WFS absorbed the least water among all compositions with a rate of 5.5%. The water resistance properties of this mix appears remarkably superior to all other mixes tested. Concrete structure densification emerges from the combined action of Cashew Nutshell Ash and Waste Foundry Sand that decreases porosity in the material. CNA, being rich in silica, enhances the formation of a compact microstructure that reduces water ingress.

WFS acts as a fine aggregate which performs the distribution task of filling concrete matrix voids to achieve overall porosity reduction. The control mix C0W0 containing no CNA or WFS displays the highest absorption rate of water at 7.5%. Structural porosity increases when supplementary materials such as CNA and WFS are absent in the mix which results in improved water flow through the material. An increase in CNA and WFS concentration leads to overall water absorption reduction. Mixes containing C5W0, C5W10 and C10W10 demonstrate enhanced water resistance performance. The mix incorporating C15W40 demonstrates suitable water absorption capability at 7.4% yet shows less performance than C10W20.

Water absorption resistance reaches its peak with C10W20 but CNA and WFS together result in an improvement to water resistance capabilities. The results concluded that combined use of CNA and WFS in concrete mix significantly enhances water resistance capacity. The C10W20 concrete mix containing 10% CNA and 20% WFS demonstrates optimal performance by reducing water absorption which improves concrete durability through reduced penetration. Fig. 4. illustrates the variation of water absorption rates of concrete modified with various level of CNA and WFS.

5. Microstructural analysis

From the mechanical and durability properties of the concrete modified with various level of CNA and WFS, it was observed that the concrete modified with 10% CNA and 20% WFS (C10W20) was optimum which give optimum performance. Hence, the C10W20 mix samples

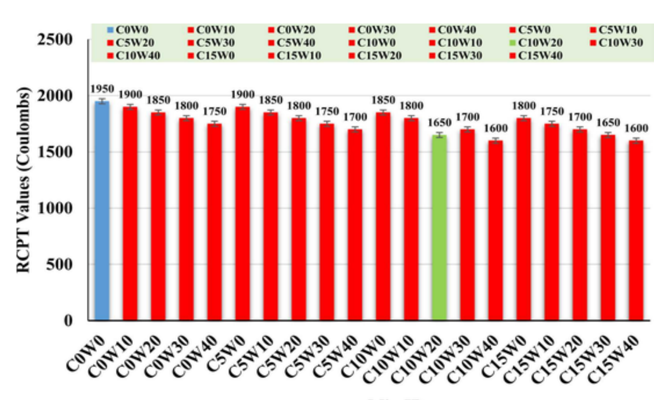

Fig. 3. RCPT value of concrete modified with various level of CNA and WFS.

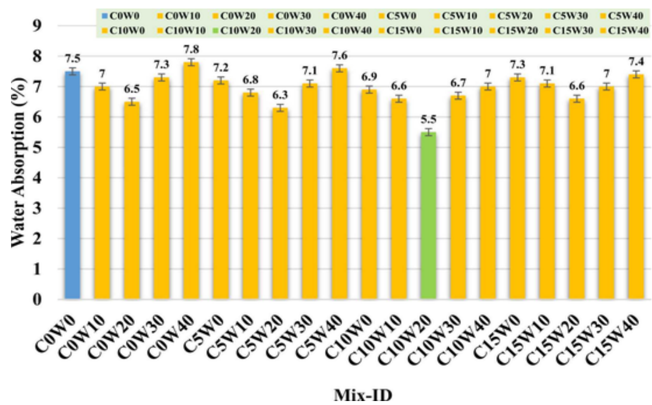

Fig. 4. Water absorption rates of concrete modified with various level of CNA and WFS.

were tested for microstructural analysis to obtain insights on microstructural changes occurred with the addition of CNA and WFS into the concrete mix.

The SEM images present in Fig. 5. revealed distinct microstructural features between control mix (C0W0) and optimized mix (C10W20) which contains 10% Cashew Nut Shell Ash (CNA) and 20% Waste Foundry Sand (WFS). The SEM image from the control mix shows notable void spaces with ettringite along with a porous structure. The control mix shows initial signs of chemical reaction along with expansive product development leading to gypsum and ettringite formation. Internal stress from these products builds up inside the material structure while simultaneously creating expansion and structural weakening and enhancing porosity which promotes mix degradation. The SEM image of C10W20 mix reveals a compact microstructure which contains minimal voids along with reduced formation of expansive crystalline products. This improvement is attributed to the synergistic effects of CNA and WFS. The pozzolanic properties of CNA lead to the formation of secondary cementitious products, which refine the concrete matrix, reduce porosity, and enhance durability. Comparable microstructural densification and hydration enhancement using agricultural ash-based binders were reported in [30]. Additionally, the fine particles of WFS improve the packing density of the concrete, further minimizing voids and limiting pathways for acid penetration. Comparable enhancement in matrix densification and durability performance using recycled foundry sand in cementitious composites was reported by Smith and Johnson [29]. The Interfacial Transition Zone (ITZ) in the C10W20 mix is also better developed, contributing to its enhanced resistance against acid attack. Overall, the SEM analysis confirms the superior performance of the C10W20 mix compared to the control mix. While the control mix (C0W0) exhibits higher porosity and significant degradation due to expansive reactions, the C10W20 mix resists these effects through its compact microstructure and reduced vulnerability, making it more durable under aggressive environmental conditions.

The EDS analysis reveals significant compositional differences between samples C0W0 and C10W20 as presented in Fig. 6. The C0W0 primarily composed of oxygen (82.70%) and calcium (10.53%) and silicon (5.48%) while displaying only a small amount of iron (1.28%). C10W20 demonstrates a substantial material composition change because with 18.55% iron alongside reduced calcium (0.60%) and silicon (0.31%) content. High levels of oxygen in both samples confirm the presence of oxide phases. These differences imply potential changes in material properties, with high iron content in C10W20 possibly enhancing strength, thermal stability, or magnetic properties while its reduced calcium and silicon content could influence durability and chemical activity.

The X-Ray Diffraction (XRD) patterns in Fig. 7. compare the crystalline phases of the control mix (C0W0) and the optimized mix (C10W20), which contains 10% Cashew Nut Shell Ash (CNA) and 20% Waste Foundry Sand (WFS). The C0W0 mix shows peaks of less durable phases and unreacted materials, including Calcium Hydroxide (C), Periclase (P), Hematite (H), Nesquehonite (N), Quartz (Q), and Kaolinite (K), indicating a less compact and less durable microstructure vulnerable to chemical attacks. In contrast, the C10W20 mix shows prominent peaks of durable phases, including Alite (A), Belite (B), Calcium Silicate Hydrate (C-S-H), Ferrite (F), and Gypsum (G). These phases enhance the strength and durability of the concrete. The presence of C-S-H, Alite, and Belite suggests a more complete hydration process, aided by CNA's pozzolanic reaction. WFS's fine particles improve packing density, resulting in a denser structure with fewer voids. The XRD pattern of C10W20 mix indicates superior microstructure, with more stable and durable phases, compared to the control mix, confirming the benefits of CNA and WFS in enhancing concrete's durability, strength, and resistance to degradation.

The TGA (Thermogravimetric Analysis) and DTGA (Derivative Thermogravimetric Analysis) graphs for C0W0 and C10W20 offer information regarding the thermal stability and decomposition behaviour of the samples, as shown in Fig. 8. The blue lines illustrate TGA, demonstrating mass reduction with temperature, whereas the orange lines depict DTGA, showing the rate of mass loss. In both samples, the TGA curves (blue lines) demonstrate stability until 200°C, indicating low moisture or volatile content. A significant mass reduction takes place between 300°C and 450°C, attributed to the decomposition of organic matter, probably from CNA. Above 450°C, both samples achieve stability, with C10W20 preserving a higher residual mass, probably because of its higher inorganic content from WFS. The DTGA curves (orange lines) show decomposition peaks around 400°C in both samples, signifying the highest decomposition rate. The more defined DTGA peak in

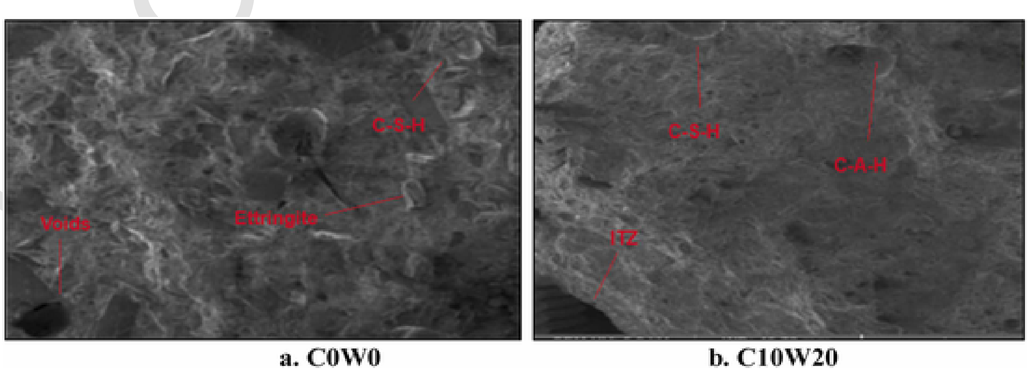

Fig. 5. SEM image.

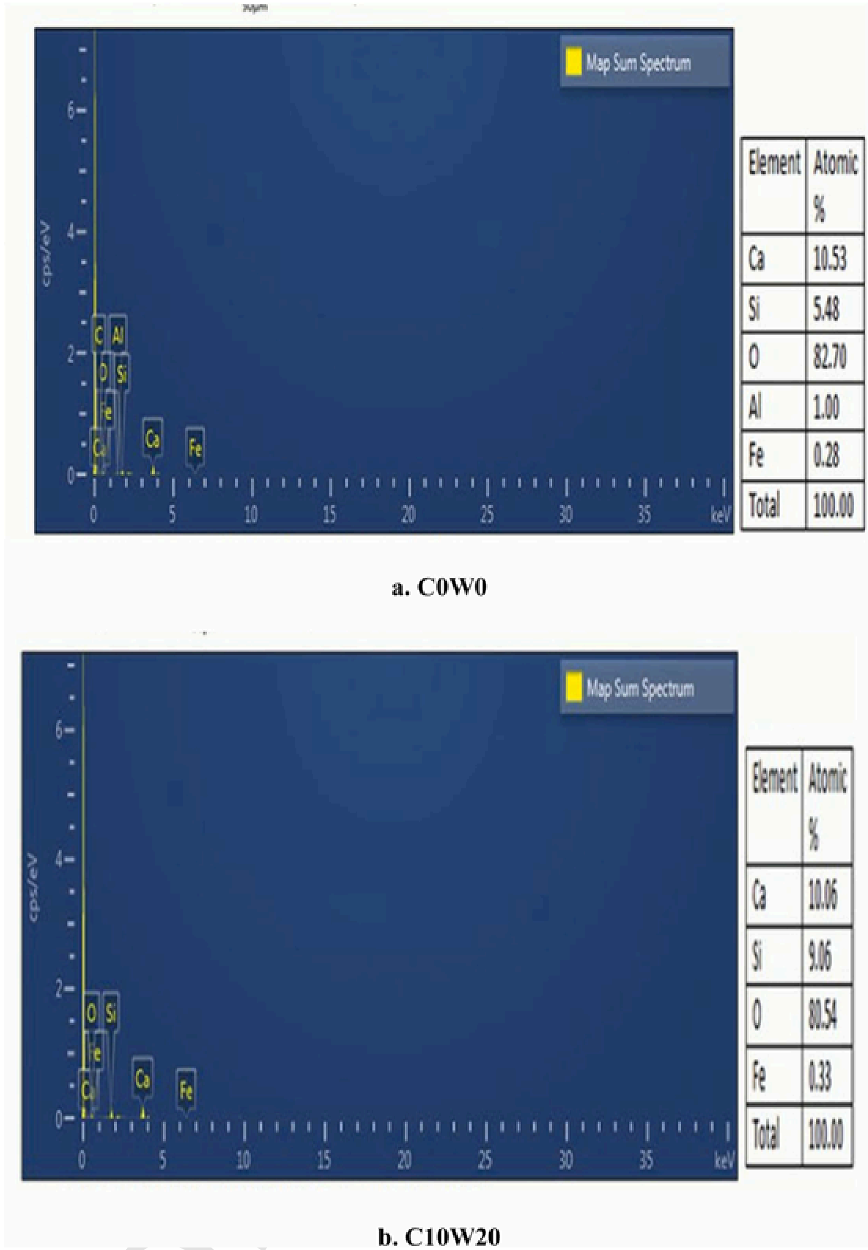

Fig. 6. EDS of C0W0 and C10W20.

C10W20 indicates more significant thermal events, likely resulting from interactions between WFS and CNA. In contrast to C0W0, the greater higher mass in C10W20 highlights the contribution of WFS in increasing the inorganic content and enhancing thermal stability, indicating enhanced suitability for heat-resistant uses.

6. Conclusions

This extensive study demonstrates that the combined use of cashew Nutshell Ash (CNA) and waste Foundry Sand (WFS) as partial substitutes for cement and fine aggregate respectively, can result in the production of eco-efficient, high performing structural concrete. The optimized mixture of 10% CNA and 20% WFS (C10W20) outperformed the control mix in terms of mechanical strength, durability and microstructural refinement.

1. The trial findings showed a 12% improvement in compressive strength, a 15% rise in flexural strength and a 10.5% increase in split tensile strength.
2. Significant reduction in acid-induced bulk and strength loss, lower chloride ion permeability and reduced water absorption, all showing strong tolerance to harsh environmental conditions.
3. SEM, EDS, XRD and TGA/DTGA tests demonstrated a denser matrix, more stable phase composition and improved thermal stability, all of which contribute to long-term material integrity.
4. These advantages are related to the pozzolanic activity of CNA and the filler effect of WFS, which improves the concrete structure and minimizes porosity.

This study not only confirms with the ideals of the circular economy and the UN Sustainable Development Goals by incorporating agricultural and industrial byproducts into concrete formulations, but it also

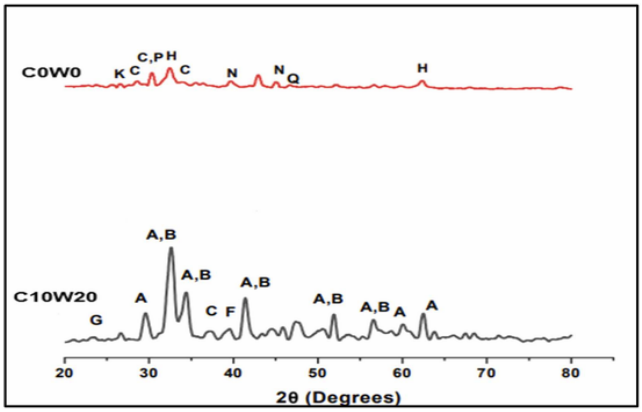

Fig. 7. XRD of C0W0 and C10W20.

presents a scalable, cost effective solution for next-generation building. The information provided offers a convincing argument for using CNA and WFS-based concrete as a sustainable alternative to standard mixes with bold applications in infrastructure development and green construction efforts across the world.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

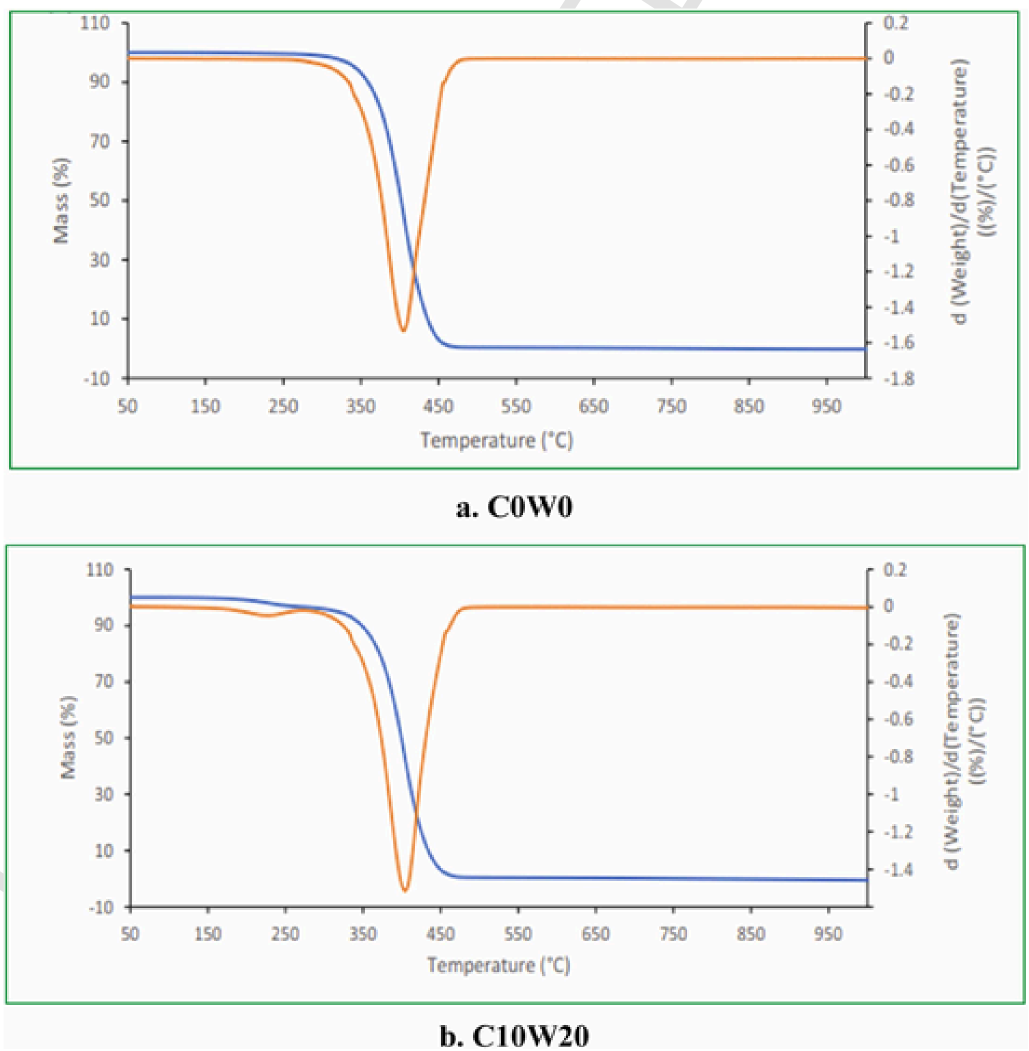

Fig. 8. TGA and DTGA of C0W0 and C10W20.

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