Strength and Durability Studies on Concrete using Cashew Nut Shell Ash (CNSA) waste as Supplementary Materials

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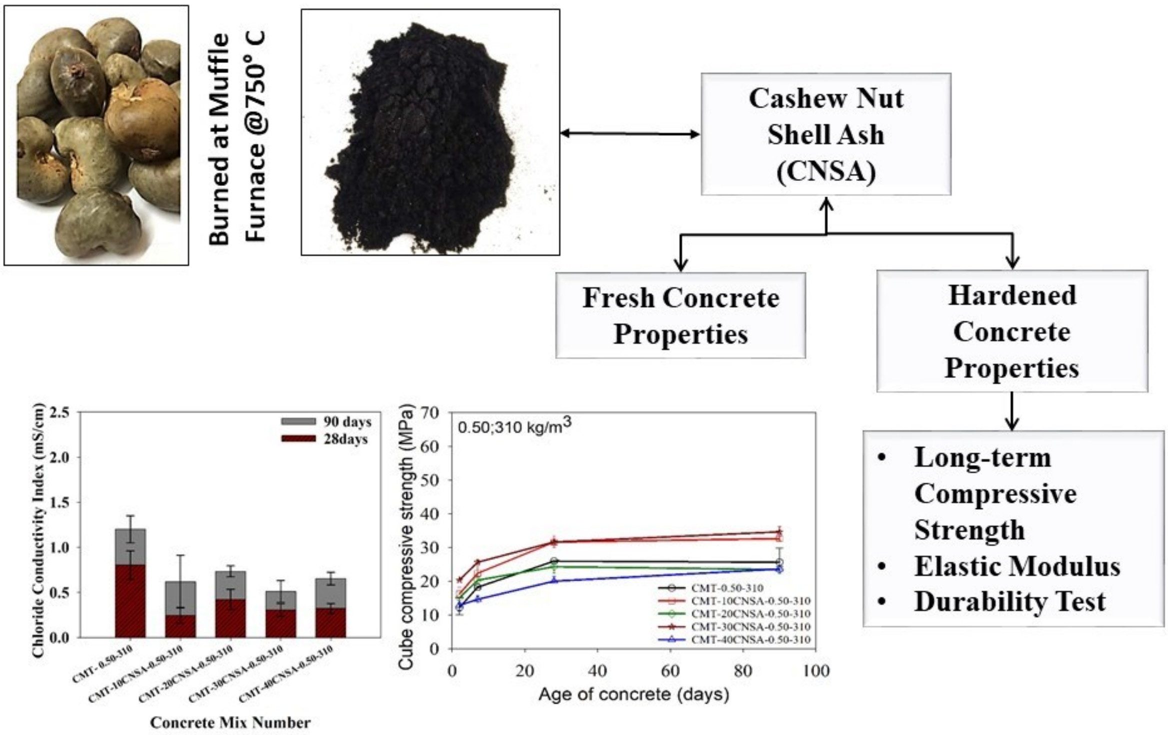
GRAPHICAL ABSTRACT



ABSTRACT:

As the world population is expected to increase significantly, there is a greater need for housing and, as a result, building materials. Conventional manufacturing methods for materials such as concrete involve substantial energy usage and substantial release of carbon emissions, which contribute to environmental deterioration. This study investigates the incorporation of Cashew Nut Shell Ash (CNSA) as a partial replacement for Ordinary Portland Cement (OPC) as primary cement, while CNSA formed binary blends. The study examined various water-to-binder ratios (0.55, 0.50, and 0.45) and a total binder content of 310 kg/m³, with replacement levels at 0%, 10%, 20%, 30%, and 40%. Compressive strength tests were performed at 2, 7, 28, and 90 days, shows a consistent increase in strength over time. Optimal CNSA content (10-30%) enhanced long-term strength due to its pozzolanic activity. Additionally, the elastic modulus was tested, indicating improved stiffness in mixes containing CNSA in comparison with the conventional concrete systems. Durability tests such as Rapid Chloride Permeability Test and carbonation depth analysis showed that CNSA addition generally decreased chloride conductivity, thereby enhancing durability. However, replacement levels (beyond 40%) exhibited diminishing returns. The results suggest that CNSA is a viable partial replacement for cement, improving concrete's workability, density, and long-term strength while enhancing durability against chloride penetration and carbonation. These findings support CNSA's potential in creating sustainable and resilient concrete systems.

Keywords: Agricultural Waste, Solid Waste Management, Cashew Nut Shell Ash, Strength, Durability.

1 INTRODUCTION

The world population is expected to increase significantly, reaching 9.70 billion in 2050 and 11.20 billion by the end of this century which will ultimately cause a substantial increase in the demand for housing. As a result, the production of building materials such as steel, concrete, etc. will increase as the industry strives to meet the demand. Similarly, the cost for processing and fabrication could also increase. In continuation, high energy demand is required for the production of conventional concrete (Nath et al., 2018; Latawiec et al., 2018). It has been well known that the production of conventional cement is one of the major sources of global CO_2 emissions which together with other greenhouse gases is considered to be responsible for 60% of global warming (Aprianti, 2017; Zhang et al., 2017; Rashad, 2015; Priya and Padmanaban, 2024). The majority of developing nations still depends on the agriculture-based economy, which results in an annual production of large amounts of solid waste that are not properly managed. Such agro-based by solid waste are typically economical, readily available, and able to reduce the level of CO_2 efficiently (Sinka et al., 2018; Martinez, 2017; Swaminathan and Bhagavathi Pushpa (2024). As a result, the use of these by-products in construction sector has taken on a greater global significance and substantial works has been carried out to make various forms of construction products to reduce environmental trash and to protect against the depletion of raw materials (Jones and Brischke, 2017; Sandak et al., 2019; Brunklaus and Riise 2018; Paramasivan, Rajagopal 2023, Nagaraju et al., 2023(a), Nagaraju et al., 2023(b). Solid waste or Agricultural by products such as ground nut, rice husk, coir fibres etc are being used as replacements for aggregate, sand, and cement in the manufacture of brick and concrete systems (Maheshwaran et al., 2023). Furthermore, past studies were carried out on the utilization of these by-products/residues in various forms to manufacture construction materials. In the recent past, usage of agriculture by product such as, groundnut shell ash, Rice husk ash, bagasse and cashew nut shell ash has been used as a supplementary binder to produce a sustainable concrete system (Sokolova et al., 2018; Memon et al., 2020; He et al, 2020). Million tonnes of nuts are being produced yearly across the world (as seen in Figure 1), and these by-products from the nut processing industries are thrown away in large quantities. Nigeria, Brazil, India, Vietnam, and Central America are the major countries that grow and produce cashew nuts a commercial crop. The Food and Agriculture Organization of the United Nations reports that Nigeria produces an average of 636,000 metric tonnes of cashew nuts annually. Cashew Nut is the major nut that has been produced in most of the countries; also, it has noted that about 68% of the total quantity of the raw cashew is generated as a byproduct called shell (nut shell). Several factors contribute to the significant generation of such wastes The large-scale production and processing of cashew nuts result in substantial quantities of shells, which are often burned to extract valuable oils, leaving behind ash. This process is widespread in major cashew-producing countries where cashew nuts are a significant agricultural product. The management of CNSA waste varies. In some regions, the ash is disposed of in landfills or used as a low-grade fertilizer. However, these methods are not environmentally sustainable and can contribute to pollution.The cashew nut shell has been used in the various industries for manufacturing/product making, such as oil extraction etc. Cashew Nut Shell Ash (CNSA) is an agro based by-products that need to go through a calcination process, to improve their properties both in fresh and hardened state. Depending on the type, these processes were typically carried out at a higher temperature of between 400 and 800 °C (Ramadhansyah et al., 2012; Memon et al., 2020; Ábrego et al., 2018). The work primarily concentrates on the applicability of the CNSAas a sustainable supplementary binder in the concrete to evaluate the pozzolanic reactivity, its long-term performance such as compressive strength development, elastic modulus, durability, shrinkage and the corrosion properties in the steel embedded systems. Also, The present work will provide a data bank for the adaptation of CNSA as binder in the general construction practice. , From the studies of Mgaya, et.al., 2019, it clears shows that the nearly 68% of raw cashew nut has generated as shell. Also, the majority of processing firms generate a cashew nutshell as a solid waste, which they then carelessly discard, or burn and some time it has adopted an uncontrolled burning technique (Saroj, 2015; Akinhanmi et al., 2008; Ogundiran et al., 2011). The carbons in these under-burnt cashew nut shells (say, < 400 °C) are more unburned. Cashew nut shell ash (CCNA) is calcined at temperatures between 400 and 800 °C, producing particles that are white and greyish which shows high silica that has been crystallized (Paper et al., 2010; Oyebisi et al., 2019). CaO-based CCNA (35.67% max) and SiO2-based CCNA (62.85% max) are the two types of CCNA that are exposed in past studies.

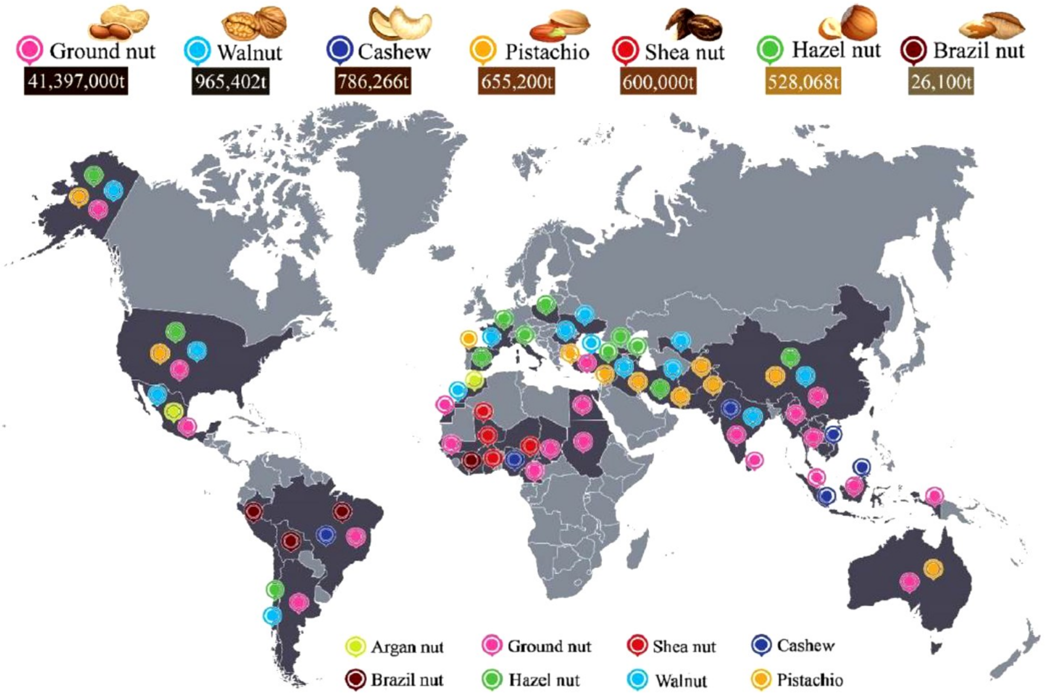


Figure 1 Worldwide yearly nut production *(The International Nut and Dried Fruit Council Foundation (INC), Nuts & Dried) Fruits Statistical Yearbook, 2020)*

The fresh and hardened properties of these two CCNA variants have different characteristics. Due to the low and absence of CaO, which indicates retarder behavior, SiO_2- based CCNA with OPC improves the slump flow and compaction factor also, the initial state of hydration. It confirms that the CNSA can be used as a pozzolanic component in blended concrete systems. Also, as the amount of CNSA in the mix increases, the fresh and hardened properties such as compressive strength, split tensile strength increases with the dosage (Saroj, 2015). In case of durability test like external sulphate attack, concrete blended with CNSA exhibited better resistance to sulphate attack than with non-blended systems. Generally, it is recommended that 15% can be replaced for structural concrete and 20% for non-structural concrete elements (Oyebisi et al., 2019). Studies form Oyebisi et al., 2019 conducted the test on CNSA from various sources. He reported that the oxide composition and the physical properties are independent to the source and the values are comparable. India is the one of the major sources of cultivating cashew nut and a substantial quantity of cashews has been exported to other countries. Studies from Tantri et al., 2022, reported that use of Un Calcined Cashew Nut-Shell Ash (UCCNA) in the ternary blend as a whole could be to be illogical, and it appeared to have a contrary effect on the mechanical performance of concrete systems UCCNA was found to be very helpful in regards to dynamic instability. The potential replacement of CNSA was found to be 30% also, when 25% of CNSA is used by replacement with conventional OPC, sorptivity and water absorption and of the blended concrete are reduced. The soprtivity index for the CNSA were in the range of 1.45 mm/min$^{0.5}$ (45% CNSA) and 0.73 mm/min$^{0.5}$ (25% CNSA), however, for conventional concrete systems, it was observed as 1.81 mm/min0.5 (Pandi and Ganesan, 2015). Past studies reported that the optimum percentage of replacement of CCNA in a cement concrete system is in the range of 20% to 30% with OPC The strength activation index has been found be increased as 75% after a standard curing condition. It was found that UCCNA evaluated SCC blends were more stable and exhibited fewer shrinkage characteristics (Tantri et al., 2022). The strength development of CNSA has been found increased with time in connection with the percentage of replacement. Pandi and Ganesan, 2015 concluded that the selected durability properties of CNSA concrete show a better performance in comparison with the non-blended concrete say OPC. The inclusion of Cashew Nut Shell Ash (CNSA) in concrete enhances its durability by improving its resistance to chemical attacks, reducing permeability, and increasing compressive strength. CNSA's fine particles fill voids within the concrete matrix, leading to a denser and more cohesive material. This reduces the ingress of harmful substances, such as chlorides and sulfates, which can cause degradation. Additionally, the pozzolanic properties of CNSA contribute to the formation of additional calcium silicate hydrate (C-S-H), further strengthening the concrete and prolonging its lifespan.

The proper utilization of CNSA in the construction industry would lower costs, mitigate the technical, and environmental risks associated with the production of OPC systems, thus in due time it could reduce solid waste, , and enhance the long term properties of hardened concrete systems.Hence, the present work focused on the potential usages of CNSA as a supplementary material and the possible replacement to the ordinary portland cement. Also, the study adopted the perception of reactivity index by examining the mineralogical and chemical constituents of CNSA, to develop the blended concrete mix proportion with the OPC systems. In addition, the data on durability parameters in different environmental condition (such as, chloride, gas, and water) are scarcely available on in connection with CNSA. The experimental outcomes will be compared with that of the conventional concrete systems and recommendations will provided to incorporate in the standards. Additionally, by eliminating the need for multiple-trial tests, the predictions from the present work would significantly improve the mix design of blended concrete systems in particular to CNSA. Initially trial mixes has been carried out to find the optimum percentage of super plasticizer, followed by the main mixes has been cast for the long-term compressive strength, elastic modulus and for the durability studies. The work consist of the above mentioned tests.

2 METHODOLOGY AND WORKFLOW

Ordinary Portland Cement (OPC) Grade 53, meeting the specifications of IS 12269, labelled as CMT, served as primary cements in this study. Cashew Nut Shell Ash (CNSA) was utilized as partial replacements in concrete mixes, resulting in the formulation of binary blends. Table 1 presents the physical properties [according to IS 1727-2004, ASTM C204-11] and oxide composition obtained from X-ray diffraction for the materials. Notably, the oxide composition of cements proved comparable and fell within the expected range and CNSA showed as a potential for supplementary cementitious materials. Crushed granite, sized between 5 - 10 mm and 10 - 20 mm, served as coarse aggregate in a 40:60 proportion, while locally sourced sand, with a maximum size of 5 mm, acted as fine aggregate. The coarse to fine aggregate ratio was fixed at 40:60. Physical properties and sieve analysis for the aggregates were conducted in accordance with IS 2386-I and III standards. The fine aggregate fell within Zone II, as per IS 383-2007 particle size distribution guidelines. To achieve the desired target slump of 100 ± 20 mm, SNF-based superplasticizers were incorporated. Mix design followed the protocol outlined in IS 10262:2009, with aggregates assumed to be in a saturated surface dry (SSD) condition. Before batching, aggregate moisture content was assessed, and necessary adjustments were made to estimate the water content required for SSD conditions. Concrete mixtures were prepared for varying water-to-binder ratios of 0.55; 0.50 and 0.45 and total binder content: 0 310 kg/m³. These mixes incorporated with 0%, 10%, 20%, 30% and 40% replacement levels of cement with CNSA as listed in Table 2.

Compressive strength tests were conducted on all concrete mixes considered in the study. For each mix, three 100 mm cube specimens were tested at ages 2, 7, 28 and 90, days of curing in a moist room. Testing utilized a compression testing frame with a 3000 kN capacity, with loading controlled at a rate of 140 kgf/cm²/min as per IS-516:1959 recommendations. ASTM C 469 procedure was adopted to determine the static elastic modulus of concrete. For each mix, three cylindrical specimens of 150 mm diameter and 300 mm height were tested for their elastic modulus at 28 days. The Rapid Chloride Permeability Test, conducted according to ASTM C1202(2012) standards, was carefully performed on cylindrical sliced specimens measuring 100 mm in diameter and 50 mm in thickness. This test plays a crucial role in evaluating concrete's ability to withstand chloride ion penetration, a critical aspect in determining its durability. Following the designated curing period, essential for allowing the concrete to achieve its desired strength, the specimens underwent further preparation. They were placed in a vacuum desiccator for approximately 24 hours, removing excess moisture from their surfaces to ensure precise and consistent test outcomes. The total charge passes was calculated based on the trapezoidal rule. This charged passed used to categorise the concrete in to various classes. The equation 1 is used to calculate the charge passed

$$Q = 900\,(I_0 + 2\,I_{30} + 2\,I_{60} + \cdots . +2\,I_{330} + I_{360}) \qquad \text{(Equation 1)}$$

where

Q = Charge passed (Coulombs)

I_0 = Current immediately after voltage is applied (Amperes)

I_t = Current at ‘t ‘minutes after voltage is applied (Amperes)

The accelerated carbonation process adhered to the guidelines outlined in RILEM TC 56 – MHM, 1988, utilizing prismatic specimens measuring 100 × 100 × 400 mm. The specimens were transferred to a carbonation chamber under conditions set to

1% CO_2 concentration. To facilitate lateral diffusion of CO_2, the side surfaces of the specimens were coated with paraffin. On specified dates, the specimens were sliced (approximately 120 mm) and sprayed with phenolphthalein indicator. In the case of carbonated concrete, the surface remained color less, while non-carbonated concrete exhibited a pink color, providing a visual indication of carbonation status. This method ensured accurate assessment of carbonation depth and the effectiveness of carbonation resistance. The measurement of carbonation depth at various time intervals allows for the calculation of the carbonation rate or carbonation velocity by applying the square root of time relationship. This relationship is expressed by the square root of time law, as shown in Equation 2.

$$x = k.\sqrt{t} \qquad \text{Equation 2.}$$

where
x = Depth of carbon dioxide penetration (mm)
k = Carbonation rate (mm/√year)
t = Time (year)

The inclusion of CNSA in concrete systems contributes to workability and overall density by improving the mixture's consistency and cohesion. Its fine particles help to create a more uniform blend, enhancing the ease with which the concrete can be mixed and poured. Additionally, CNSA fills in microscopic gaps within the concrete matrix, resulting in a denser, less porous medium. This increased density can improve the concrete's structural integrity and durability

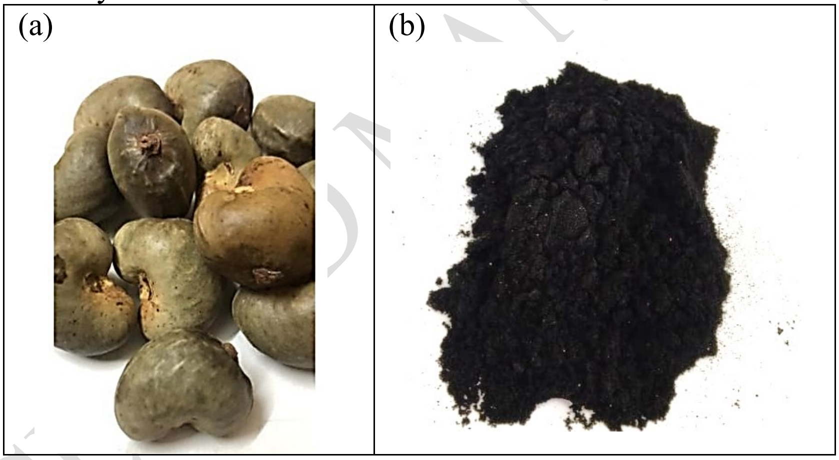


Figure 2 (a) Dry Cashew nut shell (b) Cashew Nut Shell Ash

Table 1 Oxide composition and physical characteristics of different binders

Oxide Composition (%)	**OPC**	**CNSA**
CaO	59.63	0.80
SiO_2	20.42	63.87
Al_2O_3	4.07	14.94
Fe_2O_3	5.37	12.46
MgO	0.82	1.53
K_2O	0.27	0.51
Na_2O	0.23	0.34

SO_3	0.20	1.03
Surface area (m^2/kg)	320	580
Specific gravity	3.18	3.12

Table 2 Concrete Mixture Proportioning and Fresh Concrete Properties

Mix No.	Mix ID	Concentration (kg/m^3)	SP (%)	Slump (mm)	Measured unit weight (kg/m^3)
1	CMT-0.55-310	FA:744 CA (10 mm): 477 CA (20 mm): 716 Water: 182	0.00	90	2385
2	CMT-10CNSA-0.55-310		0.04	135	2400
3	CMT-20CNSA-0.55-310		0.05	80	2400
4	CMT-30CNSA-0.55-310		0.05	95	2385
5	CMT-40CNSA-0.55-310		0.06	95	2410
6	CMT- 0.50-310	FA: 684 CA (10 mm): 529 CA (20 mm): 793 Water: 155	0.02	100	2400
7	CMT-10CNSA-0.50-310		0.01	120	2360
8	CMT-20CNSA-0.50-310		0.02	85	2400
9	CMT-30CNSA-0.50-310		0.03	130	2405
10	CMT-40CNSA-0.50-310		0.02	100	2400
11	CMT-0.45-310	FA: 743 CA (10 mm): 477 CA (20 mm): 715 Water: 155	0.02	100	2370
12	CMT-10CNSA-0.45-310		0.20	95	2400
13	CMT-20CNSA-0.45-310		0.15	130	2370
14	CMT-30CNSA-0.45-310		0.12	100	2405
15	CMT-40CNSA-0.45-310		0.15	95	2370
16	CMT-0.40-310	FA: 743 CA (10 mm): 477 CA (20 mm): 715 Water: 155 FA: 743	0.02	100	2375
17	CMT-10CNSA-0.40-310		0.20	95	2370
18	CMT-20CNSA-0.40-310		0.15	90	2420
19	CMT-30CNSA-0.40-310		0.15	100	2430
20	CMT-40CNSA-0.40-310		0.20	95	2409

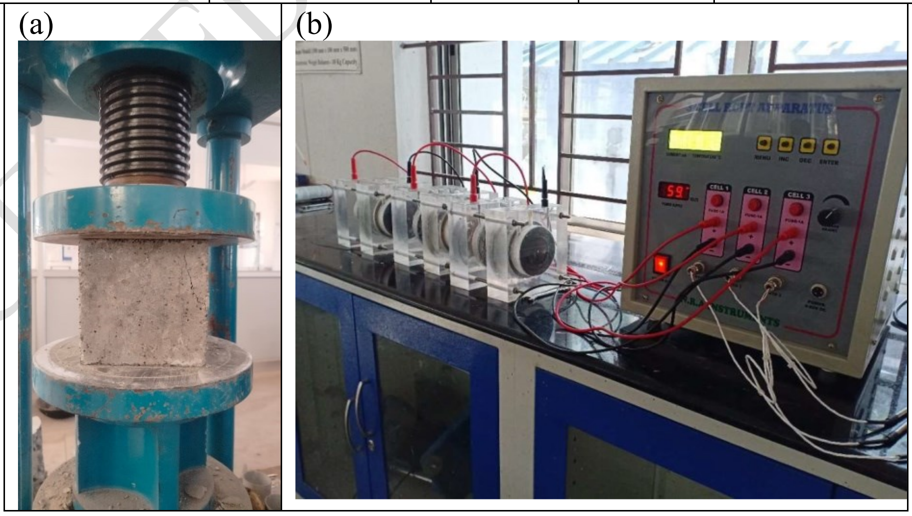


Figure 3 (a) Compressive Strength Test Setup (b) Test setup of rapid chloride permeability of concrete

3 RESULTS AND DISCUSSION

The compressive strength of concrete exhibited a consistent increase across all mixtures over time, owing to the ongoing hydration processes. Notably, the rate of strength gain appeared to vary, with a slower progression observed during the early ages (specifically at 2 and 7 days), followed by more significant improvements at 28 and 90 days of curing as provided in Figure 4. Conventional concrete containing only cement demonstrated the highest early age strength at 2 and 7 days, attributed to the hydration of cement. However, its long-term strength gain at 28 and 90 days proved to be comparatively lower than that of blends incorporating CNSA. Mixtures incorporating 10%, 20%, and 30% CNSA initially exhibited a slight reduction in strength at 2 and 7 days compared to the control mix. Nevertheless, due to the pozzolanic activity of CNSA, they eventually surpassed the control mix in strength at later ages of 28 and 90 days. Conversely, replacements with 40% CNSA experienced a more pronounced decrease in early age strength at 2 and 7 days compared to mixtures with lower CNSA contents. Furthermore, the long-term strength gain at 28 and 90 days was either lowers than that of the control mix or showed minimal improvement. Substantial increase in strength was noticed at later ages with CNSA blends. This could be due to the pozzolanic reactions between the silica in CNSA and the calcium hydroxide. Raju et al.,2023(a) and Saroj, 2015 finding showed similar result and supported the present work. These findings suggest an optimal range for CNSA content (approximately 10-30% replacement) to enhance compressive strength, potentially due to CNSA's role as a pozzolanic material. This indicates its ability to react with calcium hydroxide, a by-product of cement hydration, to form additional compounds contributing to strength development in concrete.

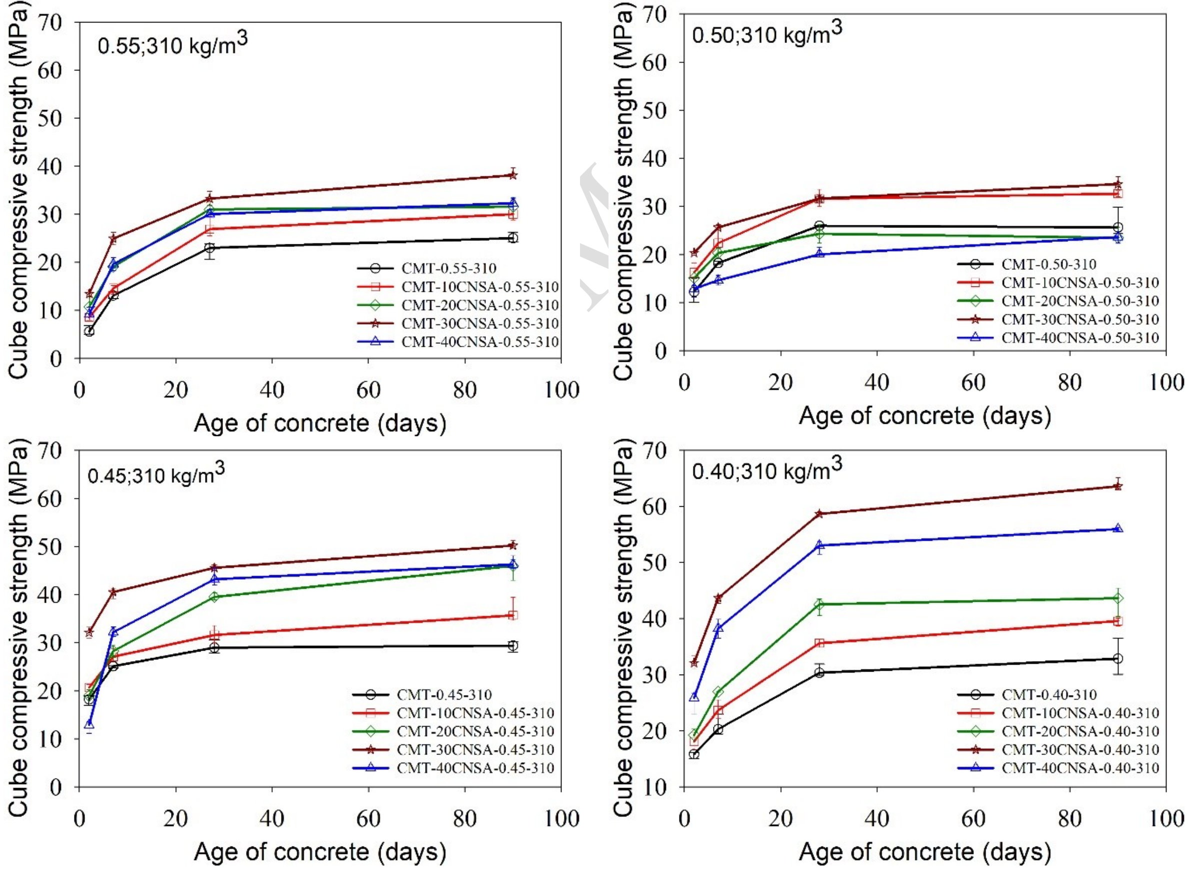


Figure 4 Compresssive strength of the concrete with CNSA at different curing age.

The elastic modulus, also known as the modulus of elasticity, of concrete with varying replacement levels of CNSA - 0%, 10%, 20%, 30%, and 40% - was investigated in this study. The elastic modulus represents the material's ability to deform under stress and is a crucial parameter in assessing concrete's structural performance. As CNSA was used in the concrete mix at different replacement levels, the mechanical properties, including the elastic modulus, were expected to vary accordingly. Typically, higher replacement levels of CNSA might lead to changes in the concrete's microstructure, affecting its overall reduction in stiffness and elasticity. Based on the test, it can be inferred that the elastic modulus of concrete increases as the concrete mix proportion increases. The present work are in supported by the previous work of Memon et al., 2020; Ábrego et al., 2018 and confirmed that the concrete mix composition highly influence the elastic modulus of concrete. For example, the elastic modulus for CMT-0.55-310 is around 10 GPa, while the elastic modulus for CMT-40CNSA-0.55-310 is around 40 GPa as seen in Figure 5. The e-modulus at 28 days is higher for concrete mixes containing CNSA compared to those without CNSA. This is because the e-modulus for mixes containing CNSA (CMT-10CNSA-0.40-310, CMT-20CNSA-0.40-310, CMT-30CNSA-0.40-310, and CMT-40CNSA-0.40-310) is higher than the e-modulus for the mix without CNSA (CMT-0.40-310).

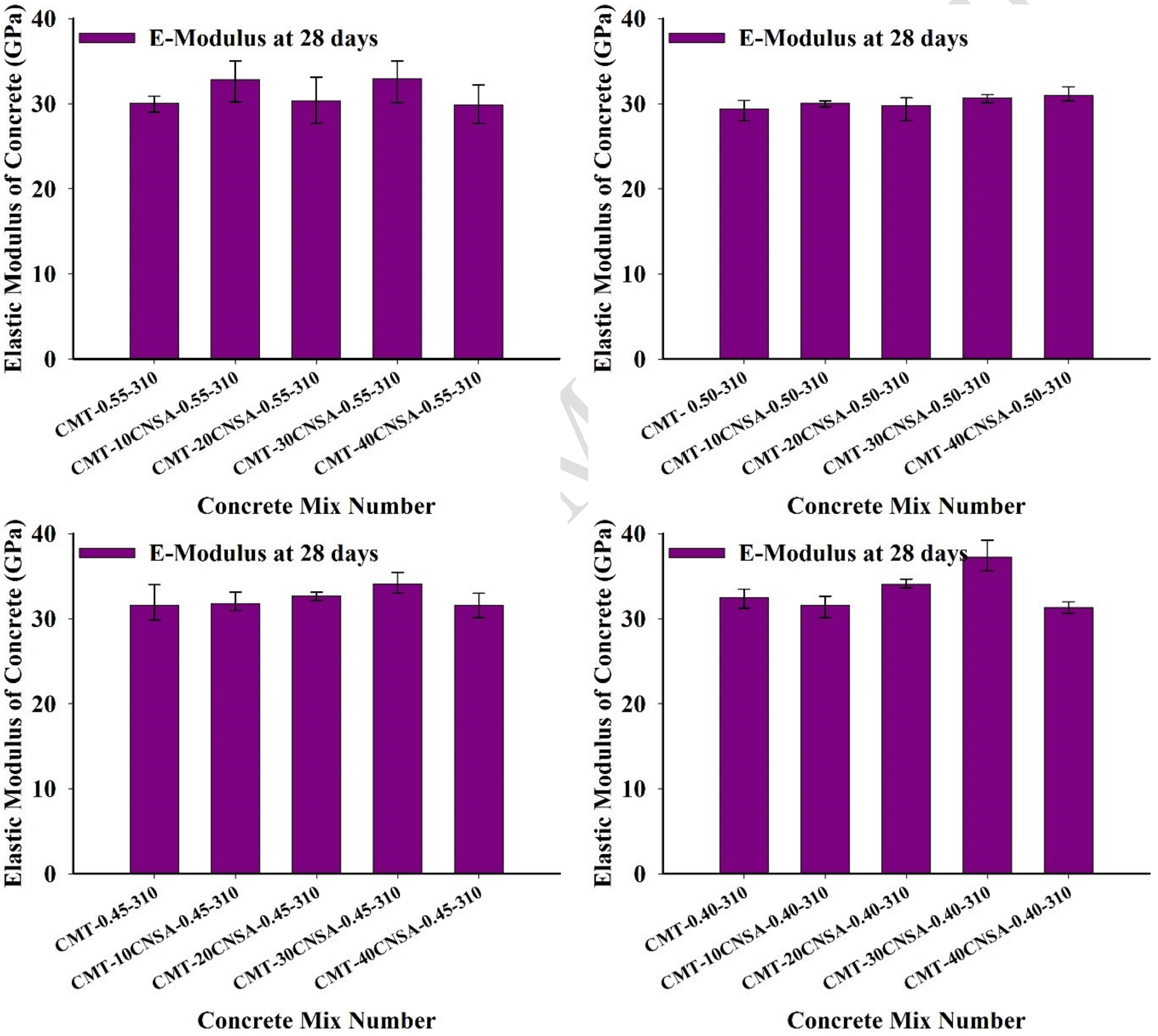


Figure 5 Elastic Modulus of the concrete with CNSA

The effect of CNSA on the carbonation depth of concrete at various replacement levels - 0%, 10%, 20%, 30%, and 40% was investigated in this study as seen from the Figure 6. Carbonation depth refers to the penetration of carbon dioxide into concrete, which can lead to the deterioration of concrete structures over time. The inclusion of CNSA in concrete mixes at different replacement levels could potentially influence the concrete's porosity, permeability, and microstructure, subsequently affecting its susceptibility to carbonation. Higher replacement levels of CNSA might result in changes to the concrete's composition and properties, altering its resistance to carbonation. By assessing the carbonation depth at different replacement levels, the study aimed to provide insights into the durability and long-term performance of concrete incorporating CNSA. Understanding how CNSA affects carbonation depth is crucial for designing sustainable and resilient concrete structures, particularly in environments where carbonation-induced deterioration is a concern. The incorporation of CNSA affects the permeability and porosity in the concrete systems as cited by Tantri et al., 2022; Pandi and Ganesan, 2015Higher the replacement levels may alter these properties and thus influencing the depth of carbonation. The present study has been supported by recommendation by Raju et al., 2023 (b).

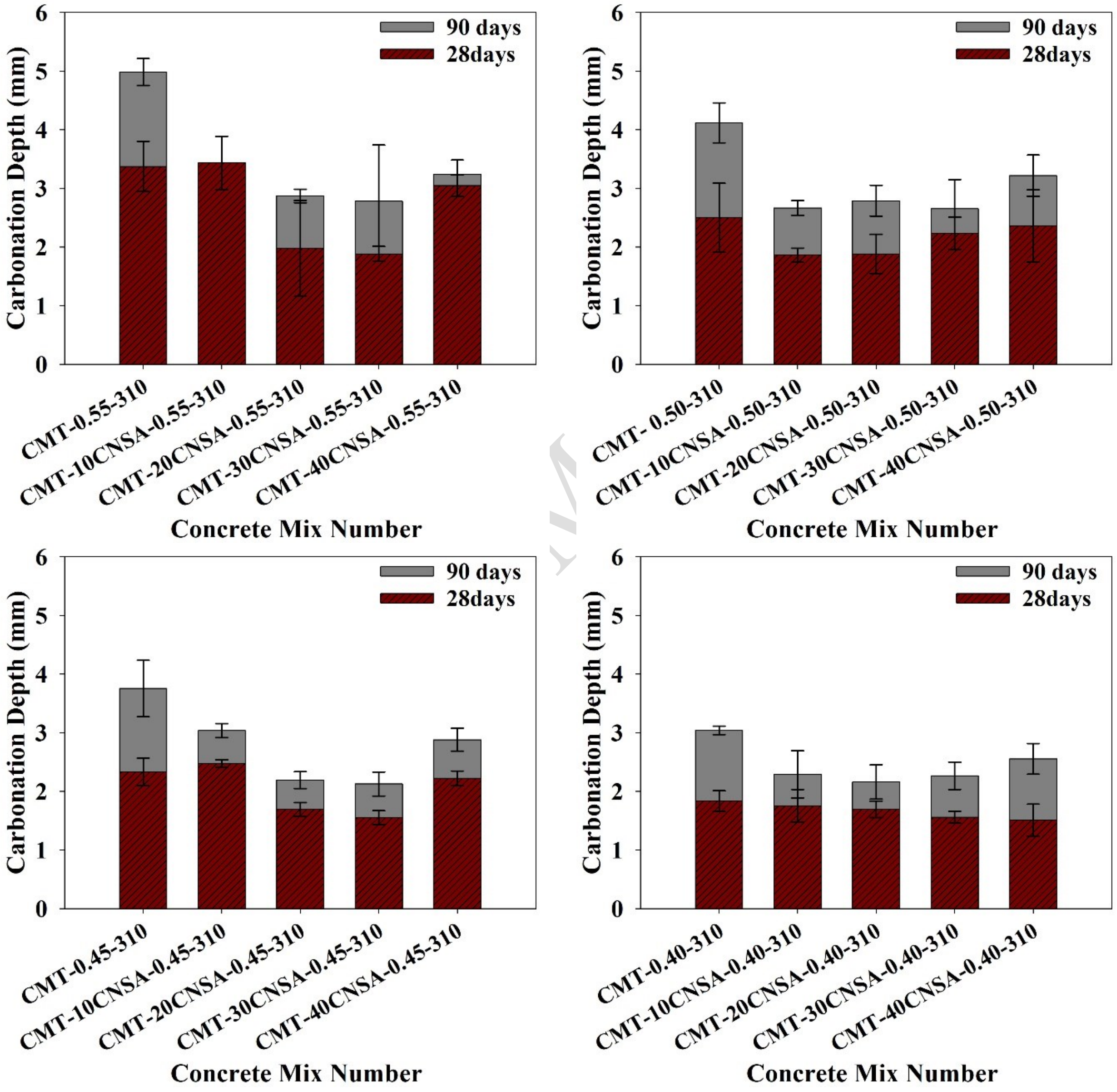


Figure 6 Carbonation Depth of concrete with CNSA

The use of cashew nut shell ash (CNSA) as a partial cement replacement in concrete has been studied for its performance enhancements. Studies by Rao et al., 2023 also supported similar kind ofresults One aspect of concrete performance that is often examined is its resistance to chloride ion penetration, as chloride ingress can lead to corrosion of reinforcement steel and ultimately degrade the structural integrity of concrete in marine or chloride-rich environments. Generally, the addition of CNSA tends to decrease the chloride conductivity of concrete compared to conventional concrete without CNSA. This is attributed to the pozzolanic reactions of CNSA, which can lead to denser microstructures and reduced permeability. The present study shows that different optimal replacement levels of CNSA for achieving the best balance between mechanical properties and durability performance, including chloride conductivity. The optimal replacement level may vary depending on factors such as the specific characteristics of the CNSA, mix design, curing conditions, and environmental exposure. As the replacement level of CNSA increases as 10%, 20%, 30%, 40%, there is typically a trend of decreasing chloride conductivity up to a certain level of replacement. However, beyond a 40% replacement level, there are a diminishing returns or even adverse effects on concrete property in terms of chloride conductivity

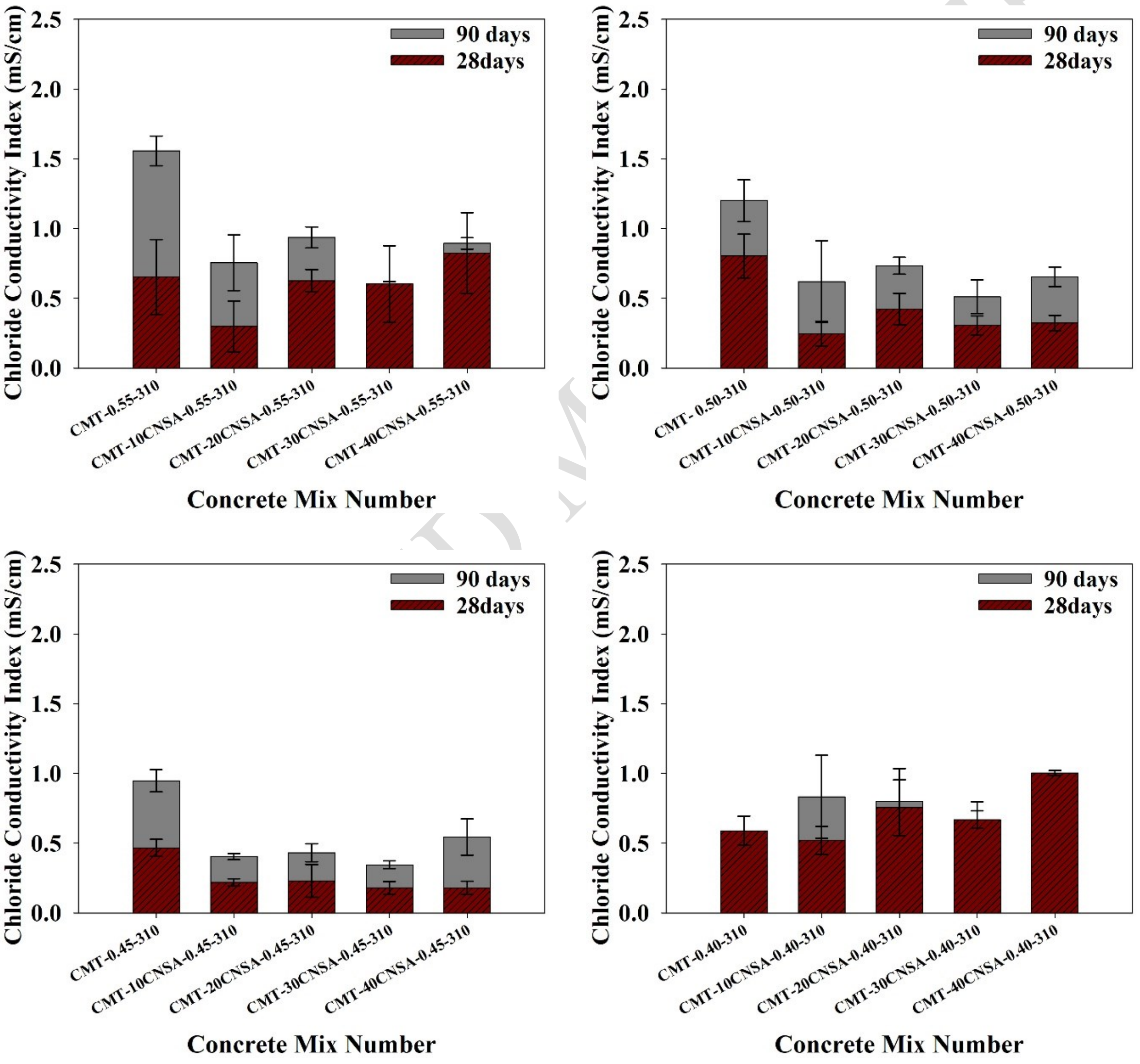


Figure 7 Chloride Conductivity of concrete with CNSA

4 CONCLUSION

Cashew Nut Shell Ash (CNSA) is increasingly being explored as a supplementary cementitious material (SCM) in concrete due to its potential performance enhancement.

Adopting CNSA helps manage waste from the cashew nut industry and reduces the carbon footprint of concrete production, contributing to more sustainable construction. CNSA's pozzolanic activity enhances long-term concrete strength and durability. Economically, CNSA is a cost-effective alternative to traditional SCMs, especially in regions with abundant cashew processing. However, successful adoption requires proper mix design, careful curing, and consistent quality control to ensure optimal performance and durability in the concrete sytems.

1. . The strength gain of concrete is typically slower at early ages when incorporate with CNSA. Conventional concrete, made primarily with OPC, often shows higher early age strength due to the rapid hydration rate. However, prolonged curing time, the pozzolanic reaction in CNSA blends contribute to a higher long-term strength gain compared to conventional concrete systems. This could be because of calcium hydroxide in the presence of water to form C-S-H, which is responsible for the strength and durability of concrete. This activity is optimal within the 10-30% replacement range.
2. Elastic modulus increases with higher CNSA replacement levels, indicating a stiffer material. CNSA-containing mixes exhibited higher elastic modulus compared to those without CNSA, particularly at 28 days. This is due to the enhanced microstructure and denser packing resulting from pozzolanic reactivity, which contribute to stiffer concrete systems.
3. Inclusion of CNSA at different replacement levels influenced carbonation depth, potentially due to changes in concrete's porosity and permeability. Higher replacement levels might alter concrete's resistance to carbonation, impacting long-term durability. This improves the density and reduces the permeability, which helps resist carbonation; excessive replacement levels could make a negative impact this balance.
4. CNSA addition generally decreases chloride conductivity, attributed to pozzolanic reactions leading to denser microstructures and reduced permeability. Optimal replacement level varies depending on CNSA characteristics, mix design, curing conditions, and environmental exposure. Increasing CNSA replacement up to 40% typically decreases chloride conductivity, but beyond this level, there may be diminishing returns or adverse effects on concrete properties. The optimal level of replacement to minimize chloride conductivity depends on various factors, such as characteristics of the CNSA used, and the environmental exposure. Typically, increasing CNSA replacement up to 40% decreases chloride conductivity. However, beyond 40%, the benefits may diminish, and other concrete properties might be adversely affected.

Overall, the study provides the potential benefits of incorporating CNSA in concrete mixes, including improved mechanical properties, durability, and sustainability. However, careful consideration of replacement levels is crucial to optimize performance while ensuring desired properties are maintained.

5 REFERENCE

1 Ábrego, J., Plaza, D., Luno, F., Atienza-Martínez, M., Gea, G., (2018). Pyrolysis of cashew nutshells: characterization of products and energy balance. *Energy,* (158), 72–80. https:// doi. org/ 10. 1016/j. energy. 2018. 06. 011

2 Tantri, A., Nayak, G., Shenoy, A., Shetty, K. K., Achar, J., Kamath, M., (2022). Implementation assessment of calcined and uncalcined cashew nut-shell ash with total recycled concrete aggregate in self-compacting concrete employing Bailey grading

technique. *Innovative Infrastructure Solutions,* 7, 305, https://doi.org/10.1007/s41062-022-00907-8

3 Akinhanmi T.F, Atasie V.N., Akintokun P.O., (2008). Chemical composition and physicochemical properties of cashew nut (Anacardium occidentale) oil and cashew nut shell liquid. *Journal of Agricultural, Food and Environmental Sciences*, 2 (1), 1–10.

4 Aprianti S, (2017). A huge number of artificial waste material can be supplementary cementitious material (SCM) for concrete production–a review part II. *Journal of Cleaner Production*, 142, 4178–4194, https://doi.org/ 10.1016/jjclepro.2015.12.115.

5 ASTM C1202 (2010). Standard test method for electrical indication of concrete's ability to resist chloride penetration. *American Society for Testing and Materials*, USA

6 ASTM C204 (2011). Standard test methods for fineness of hydraulic cement by air permeability apparatus. *American Society for Testing and Materials*, USA

7 ASTM C469 (2010). Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression. *American Society of Testing and Materials*, USA.

8 Broitman, D., Raviv, O., Ayalon, O., Kan I., (2018). Designing an agricultural vegetative waste-management system under uncertain prices of treatment-technology output products. *Waste Management,* 75, 37–43, https://doi.org/10.1016/j wasman.2018.01.041.

9 Brunklaus, B., Riise, E., (2018) Bio-based Materials within the Circular Economy: Opportunities and Challenges. *Designing Sustainable Technologies, Products and Policies,* pp. 43–47.

10 Das, P., Sreelatha, T., Ganesh, A., (2004). Bio oil from pyrolysis of cashew nut shell characterisation and related properties. *Biomass Bioenergy,* 27 (3) 265–275, https://doi.org/10.1016/j.biombioe.2003.12.001

11 He. J., Kawasaki, S., Achal, V., (2020). The utilization of agricultural waste as agro-cement in concrete: a review. *Sustainability*, 12, 6971, https:// doi. org/ 10. 3390/ SU121 76971

12 He K., Zhang J., Zeng Y., (2019). Knowledge domain and emerging trends of agricultural waste management in the field of social science: *A scientometric review. Sci Total Environ.* Jun 20; 670:236-244. doi: 10.1016/j.scitotenv.2019.03.184.

13 Daniel, H., Perinaz, B.T., (2012). What a waste: a global review of solid waste management. *Urban development series*, knowledge papers no. 15, World Bank 15 116, http://hdl.handle.net/10986/17388.

14 IS 10262 (2009). Indian Standard methods for Concrete Mix Proportioning – Guidelines, *Bureau of Indian Standards*, New Delhi. India.

15 IS 12269 (2013). Indian Standard Ordinary Portland Cement, 53 GRADE — Specification, *Bureau of Indian Standards*, New Delhi, India.

16 IS 1727 (2004). Indian Standard methods of test for pozzolanic materials, *Bureau of Indian Standards*, New Delhi, India.

17 IS 383 (2007). Indian Standard methods of test for Specification for Coarse and Fine Aggregates from Natural Sources for Concrete, *Bureau of Indian Standards*, New Delhi, India.

18 IS 516 (2004) Indian standard methods of tests for strength of concrete, *Bureau of Indian Standards*, New Delhi, India.

19 Mgaya, J., Shombe, G.B., Masikane, S.C., Mlowe, S., Mubofu E.B., Revaprasadu N., (2018). Cashew nut shell: a potential bio-resource for the production of bio-sourced chemicals, materials and fuels, *Green Chemistry*. doi: 10.1039/c8gc02972e

20 Jones, C., Brischke, C., (2017). Performance of bio-based building materials, *Woodhead Publishing.*

21 Latawiec, R., Woyciechowski, P., Kowalski, K.J., (2018). Sustainable concrete performance CO2 emission, *Environments,* 5 (2) 27, https://doi.org/10.3390/environments 5020027.

22 Maheshwaran, J., Regin, J. J., Ilanthalir, A., (2023). Influence of chemical and thermal treatment methods on the mechanical and micro-structural characteristics of coconut shell based concrete, *Global NEST Journal*, 25(10), 56-64.

23 Martinez, R. G, (2017). Hygrothermal assessment of a prefabricated timber-frame construction based in hemp. *Procedia Environmental Sciences,* 38 729–736, https://doi.org/10.1016/j.proenv.2017.03.155.

24 Memon, S.A., Khan, S., Wahid, I., Shestakova, Y., Ashraf, M., (2020). Evaluating the effect of calcination and grinding of corn stalk ash on pozzolanic potential for sustainable cement-based materials. *Advances in Materials Science and Engineering*. https:// doi. org/ 10. 1155/ 2020/ 1619480

25 Nagaraju, T. V., Mantena, S., Azab, M., Alisha, S. S., El Hachem, C., Adamu, M., Murthy, P. S. R. (2023). Prediction of high strength ternary blended concrete containing different silica proportions using machine learning approaches. *Results in Engineering*, 17, 100973.

26 Nagaraju, T. V., Bahrami, A., Azab, M., Naskar, S. (2023). Development of sustainable high performance geopolymer concrete and mortar using agricultural biomass—A strength performance and sustainability analysis. *Frontiers in Materials*, 10, 1128095.

27 Nath, A.J, Lal, R, Das, A.K., (2018). Fired bricks: CO_2 emission and food insecurity. *Global Challenges*, 2, https://doi.org/10.1002/gch2.201700115.

28 Ogundiran, M.B., Babayemi, J.O., Nzeribe, C.G., (2011). Application of waste cashew nut shell ash showed significant reduction in mobility of pb and cd in waste battery contaminated soil, *Pacific Journal of Science and Technology*. 12 (2), 121–126.

29 Oyebisi, S., Igba, T., Oniyide, D., (2019). Performance evaluation of cashew nutshell ash as a binder in concrete production. *Case Studies in Construction Materials.* 11:e00293. https:// doi. org/ 10. 1016/j. cscm. 2019. e00293

30 Pandi, K., Ganesan, K., (2015). Effect of Water Absorption and Sorptivity of Concrete with Partial Replacement of Cement by Cashew Nut Shell Ash. *Australian Journal of Basic and Applied Sciences,* 9(23), 311-316

31 Paper, C., Ara, S., Gerais, M., (2010) Analysis of the cashew nut production *I pro-Africa conference*

32 Paramasivan, S., Rajagopal, T., (2023). Strength studies on concrete using e-plastic waste as coarse aggregate. *Global NEST Journal*, 25(10), 212-215.

33 Priya, S.S., Padmanaban, I., (2024). Effect of coconut shell ash as an additive on the properties of green concrete. *Global NEST Journal*, 26(1), 05413.

34 Raju, G. K., Nagaraju, T. V., Jagadeep, K., Rao, M. V., & Varma, V. C. (2023). Waste-to-energy agricultural wastes in development of sustainable geopolymer concrete. *Materials Today: Proceedings.*

35 Raju, J. N. S. S. N., Nagaraju, T. V., Varma, V. C., Alisha, S. S., Jagadeep, K., (2023). Eco-efficient biowaste and aqua waste as cementitious material in high performance concrete. *Materials Today: Proceedings*.

36 Ramadhansyah, P.J., Mahyun, A.W., Salwa, M.Z.M., Abu, B.B.H., Megat, J.M.A., Wan I.M.H. (2012). Thermal analysis and pozzolanic index of rice husk ash at different grinding time. *Proc Eng* 50:101–109. https:// doi. org/ 10. 1016/j. proeng. 2012. 10. 013

37 Rao, M. V., Sivagamasundari, R., & Nagaraju, T. V. (2023). Achieving strength and sustainability in ternary blended Concrete: Leveraging industrial and agricultural By-Products with controlled Nano-SiO_2 content. *Cleaner Materials*, 9, 100198.

38 Rashad, A.M, (2015). A brief on high-volume Class F fly ash as cement replacement–A guide for Civil Engineer, *International Journal of Sustainable Built Environment*. 4 278–306, https://doi.org/10.1016/j.ijsbe.2015.10.002.

39 RILEM TC 56 – MHM (1988). CPC-18 Measurement of hardened concrete carbonation depth, *Materials and structures*, 21, 453 – 455.

40 Sandak, A., Sandak, J., Brzezicki, M., Kutnar, A., (2019). Bio-based building skin, *Springer Nature, Singapore*.

41 Saroj, P.L., (2015) Advances in cashew production technology. http:// www. cashew. res. in

42 Sinka, M, Korjakins, A., Bajare, D., Zimele, Z., Sahmenko, G., (2018). Bio-based construction panels for low carbon development, *Energy Procedia*, 147 220–226, https://doi.org/10.1016/j.egypro.2018.07.063.

43 Sokolova L.N.S., Ermakova, E.V, Rynkovskaya, M., (2018) A review of agro-waste materials as partial replacement of fine aggregate in concrete. *IOP Conference Series: Materials Science and Engineering* https:// doi. org/ 10. 1088/ 1757- 899X/ 371/1/ 012012

44 Swaminathan, S. Bhagavathi Pushpa, T.., (2024), Utilization of cement power plant beds for aerated concrete thermal blocks, *Global NEST Journal*, 26(2), 05432.

45 United Nations, Peace, dignity and equality on a healthy planet. https://www.un.org/en/sections/issues-depth/population/

46 Zhang, X., Shen, J., Wang, Y., Qi, Y., Liao, W., Shui, W., Li, L., Qi, H., Yu, X., (2017). An environmental sustainability assessment of China's cement industry based on emergy, *Ecological Indicators*. 72, 452–458, https://doi.org/10.1016/jecolind.2016.08.046.

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