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Sustainable Concrete with Wood Ash and Recycled Clay Block Aggregate

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Abstract: Various environmentally friendly binders have been used to mitigate the negative environmental impacts of cement production and the negative effects of waste and construction materials being disposed of in landfills. Wood ash (WA) is one such alternative binder, which is extracted from fish grills and restaurants that dispose of it in landfills, causing environmental pollution. Studies have shown that, based on the chemical composition of WA, the strength and durability properties of concrete can be slightly improved by using WA as a cement substitute, with an ideal replacement ratio of 10% to 20% to achieve the highest compressive, tensile and flexural strength within this range. Additionally, Crushed Clay Blocks (CCB) can be used to replace Normal Coarse Aggregate (NCA) at replacement at rates of 0%, 50%, and 100%. This is to meet sustainable development requirements and maintain a clean and pollution-free environment. This paper provides a comprehensive overview of the properties of WA and its potential applications in conventional concrete using alternative, environmentally friendly materials such as CCB. The highest compressive, tensile, and flexural strengths were achieved at 10% WA substitution with 50% CCB, reaching (41.45, 3.47, and 4.90) MPa, respectively. It was observed that as the WA substitution ratio increased with the CCB substitution ratio, the strength properties of the concrete mixtures decreased, although they improved over time due to pozzolanic effects. This study recommends an optimal mixture of S6 (10% WA + 50% CCB), which exhibits a proficient balance between strength and resource efficiency. In conclusion, this research aims to use WA in the manufacture of non-load-bearing insulating building units.

Keywords: Crushed clay blocks waste, Supplementary cementitious materials, Wood ash, Strength properties, Density, Water absorption.

1. Introduction

A main global challenge is finding an alternative material for cement, which is a major source of pollution to the environment because it emits greenhouse gases. Investigators play a significant role in global waste disposal by developing appropriate methods for its effective utilization [1]. Worldwide, 0.74 kg of solid trash is produced per capita daily, with national figures varying from 0.11 to 4.54 kg per capita daily, contingent upon urbanization levels and income brackets [2, 3].

The waste composition predominantly consists of organic and green materials. Waste treatment primarily emphasizes recycling 20% and incineration 17.8%, which facilitate the repurposing of materials post-consumption and guarantee their appropriate final disposal [4]. This aligns with the adoption of the circular economy as a novel, eco-friendly industrial paradigm. In recent years, an environmental concern has emerged, characterized by the accumulation of debris and demolition trash, which needs the development of alternative methods to mitigate its adverse effects. The integration of these wastes into the building sector is a crucial strategy to mitigate their detrimental impact on the environment [5, 6].

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In the construction business, a portion of the environmental impact arises from the demolition of structures, resulting in various forms of solid waste. Conversely, the incorporation of cement in the manufacturing of bricks, blocks, and concrete, it enhances durability results in a substantial anthropogenic emission of carbon dioxide (CO2) amounting to 5-8% globally. Projections suggest this could escalate to 27% by 2050, particularly given that one cubic meter of concrete is produced annually per capita [7-9].

Given this context and anticipated developments, the objective is to produce WA as an alternative material to partially substitute ordinary Portland cement (OPC) in building, by combining two or more varieties of coarse aggregate with chemically stable ash [10]. This material may decrease CO2 emissions while preserving or enhancing its mechanical qualities (e.g., porosity, structure, compressive strength, water absorption, durability) [11, 12].

Many researchers have devoted themselves to using different raw materials for concrete production, for example wood waste ash as a good option for partial replacement [13, 14], where they found good results in concrete properties [15]. On the other hand, these wastes are given an alternative use, and potential environmental pollution is reduced [13, 16] by entering the environment, which directly contributes to sustainable development [17, 18].

In this study aims to investigate the possibility of using crushed clay blocks (CCB) aggregates as a sustainable additive to concrete by considering how it affects performance and environment. This is done by replacing cement with wood waste ash at varying rates ranging from (10-30) % with the use of CCB waste at rates of (0, 50 and 100) % in order to reduce the environmental impact resulting from dumping construction materials in landfills and protect the environment from pollution. In order to verify the mechanical properties, workability, density, water absorption, compressive strength, splitting strength and flexural strength tests are conducted.

2. Materials and Methods

2.1 Materials

This study utilizes ordinary Portland cement (OPC) (Type I). The Badosh cement facility in Mosul manufactured the cement, with coarse aggregate passing through a sieve size of 19 mm. It is naturally sourced from Mosul quarries and is pulverized by laboratory crushers into pointed, uneven, and fragmented forms; fine aggregates from the Kanhash district of Mosul City, which has a specific gravity of 2.62, a water absorption rate of 2.9%, and a bulk density of 1728 kg/m³ and passes through a sieve size of 4.75 mm; and wood ash is used in concrete production with a weighted replacement ratio instead of cement. In this research, wood ash (WA) from fish restaurants as wastes, which is disposed of in landfills, causing environmental pollution, was used. Preliminary tests found that WA had a specific gravity of 2.30, a water absorption of 1.81%, a bulk density of 630 kg/m³, and a fineness of WA of 320 m²/kg. Based on a laboratory test conducted in Northern Technical University's (NTU's) Concrete Laboratory according to ASTM C618 [19]. To verify the pozzolanic activity of pozzolanic materials, the Strength Activity Index (SAI) was performed to determine the strength development at the age of 28 days. The strength activity index of WA was calculated according to ASTM C311-16 [20] as in equation (1), and the strength activity index values of WA are shown in Table 1. Using crushed hollow insulating clay blocks (CCB) from construction and household waste, water absorption of 15.1%, a bulk density of 1.856 kg/m³, a specific gravity of 2.000, and a sieve size of 19 mm, as shown in Fig. 1(a) and Fig. 1(b).

$$SAI=\frac{SP}{P}*100 \qquad (1)$$

Where; SP = Average compressive strength of WA cement-reference cement mortar cubes at designated ages, and P = Average compressive strength of reference cement mortar cubes at designated age.

Table 1. Activity index of WA.

Pozzolanic activity index	Value (%)	(%) Limits of ASTM C311-16 [20]
At 7 days	76	Min. 75
At 28 days	81	Min. 75

Fig. 1. (a) Shows Wood Ash.

Fig. 1. (b) Shows Crushed Clay Blocks.

2.2 Mix proportions

The first substitution includes (0,50, and 100) % of crushed clay blocks as a substitute for Normal Coarse Aggregate (NCA). The second substitution includes (0,10,20, and 30) % of cement weights to determine the optimum ratio of cement replacement with wood ash (WA) to enhance the sustainability of building materials. Fine aggregate (sand content) is estimated at 1.5 as weight ratio from weight method of 1:1.5:3. Table 2 shows the mixing ratios. The symbols (W0, W10, W20, W30) % refer to the mixing ratios of ordinary Portland cement (OPC) mixes with wood ash replacement at 0, 10, 20, and 30%. The symbols (B0, B50, B100) refer to the mixtures of ordinary Portland cement with crushed clay blocks (CCB) as a substitute for gravel. Moreover, the use of Superplasticizer (SP) type Sika® ViscoCrete®-180 GS at a fixed ratio of 1% and a fixed ratio of water content to cement w/c estimated at 0.3 based on the experimental mixes, as shown in Table 3.

Table 2. Concrete mixtures with replacements ratios.

Mixes	Cement with WA (%)	Crushed Gravel (%)	CCB (%)	Water	SP (%)	Symbol
S1	0	100	0	0.30	1	W0B0
S2	10	100	0	0.30	1	W10B0
S3	20	100	0	0.30	1	W20B0
S4	30	100	0	0.30	1	W30B0
S5	0	50	50	0.30	1	W0B50

S6	10	50	50	0.30	1	W10B50
S7	20	50	50	0.30	1	W20B50
S8	30	50	50	0.30	1	W30B50
S9	0	0	100	0.30	1	W0B100
S10	10	0	100	0.30	1	W10B100
S11	20	0	100	0.30	1	W20B100
S12	30	0	100	0.30	1	W30B100

*Wood ash is obtained from restaurants after processing, grinding and screening

Table 3. Mix proportion of OPC with WA.

Mixes	Cement (Kg/m³)	Sand (Kg/m³)	Crushed Gravel (Kg/m³)	Water (Kg/m³)	WA (Kg/m³)	CCB (Kg/m³)	SP (g/m³)	Symbol
S1	431	646	1293	129	-	-	4.3	W0B0
S2	388	646	1293	129	32	-	4.3	W10B0
S3	345	646	1293	129	63	-	4.3	W20B0
S4	302	646	1293	129	94	-	4.3	W30B0
S5	431	646	646	129	-	485	4.3	W0B50
S6	388	646	646	129	32	485	4.3	W10B50
S7	345	646	646	129	63	485	4.3	W20B50
S8	302	646	646	129	94	485	4.3	W30B50
S9	431	646	-	129	-	970	4.3	W0B100
S10	388	646	-	129	32	970	4.3	W10B100
S11	345	646	-	129	63	970	4.3	W20B100
S12	302	646	-	129	94	970	4.3	W30B100

2.3 Pre-Experimental Tests

2.3.1 Preparation of Molds and Casting

Mixing of ingredients is a key aspect of concrete manufacturing. The total weight of the materials is combined individually, and the binders (cement and wood ash) are the binder and fine aggregate are mixed separately under dry conditions to ensure uniform mixing. A concrete mixing machine thoroughly mixes the binder and fine aggregate under dry conditions. Followed by the coarse aggregate. The mixing process continues, after which water is added before the superplasticizer is added and mixed thoroughly for up to 5 minutes to ensure consistency, followed by the addition of water containing the superplasticizer. Finally, the mixing process is repeated for 10 minutes to ensure homogeneity [21]. Six cubes of 100 mm were constructed to test the compressive strength and water absorption for 7 and 28 days. Five cylindrical specimens with diameters of 100 mm and heights of 200 mm were cast to test the splitting tensile strength. Three prismatic molds with a length of 400 mm, a width of 100 mm, and a height of 100 mm were cast to test the flexural strength, as shown in Fig. 2. Before adding water, the cement, sand, gravel, and wood ash were mixed well. Water was then added to the dry mix in the mixer, and it was mixed for five minutes before the superplasticizer was added. The superplasticizer was then added after being mixed with a small amount of water. The mixing continued for ten minutes to achieve homogeneity [21]. The trial mixes are shown in Table 4, and after obtaining the test results for the mixes, mix M8 was chosen because it is the best in terms of materials and compressive strength and the most economical. Mix M8 was selected due to its highest cement content of 431 kg/m³, which provides sufficient binder for optimal hydration and results in the maximum 28-day compressive strength of 40 MPa. Its mix proportions also ensure proper workability and material efficiency, making it the most effective and economical choice among the trial mixes.

Fig. 2. Shows preparation of molds and castings.

Table 4. Trial Mixes for OPC at 28 Day.

Mixes	Mix ratio	Cement (Kg/m³)	Sand (Kg/m³)	Gravel (Kg/m³)	Water* (Kg/m³)	SP (%)	Com-pressive Strength (MPa)
M1	1:2:4	318	636	1272	178	-	26.3
M2	1:2:3	362	724	1086	203	-	31.5
M3	1:1.5:2	375	653	1125	210	-	33.8
M4	1:1.5:3	388	582	1164	217	-	34.7
M5	1:2:4	345	690	1380	104	1	35.2
M6	1:2:3	398	796	1194	119	1	37.6
M7	1:1.5:2	414	721	1243	124	1	38.5
M8	1:1.5:3	431	646	1293	129	1	40

* Water to cement ratio (W/C) estimated at 0.3

2.3.2 Preparation of WA and CCB

Various trial mixes were conducted before work began to determine the most resistant mixes in terms of compressive strength. These mixtures were made with two different amounts of water: 0.56 without a superplasticizer and 0.3 with a superplasticizer. The mixture M8 with the superplasticizer was chosen based on the highest compressive strength as shown in Table 4. To treat wood ash, it was dried in a hot oven at 100 °C for 24 hours, then it was ground up and put through a 325-mesh sieve, as shown in Fig. 3. Drying, grinding, and sieving improve the workability of the new mixture [22]. Different amounts of wood ash were used instead of cement in 6 different experimental mixes, as well as different amounts of coarse blocks being replaced with CCB as shown in Fig. 4. The mixture had to be in a state of saturated surface dryness (S.S.D.) so that it wouldn't absorb water while it was being mixed. The optimum mix was selected based on the results obtained.

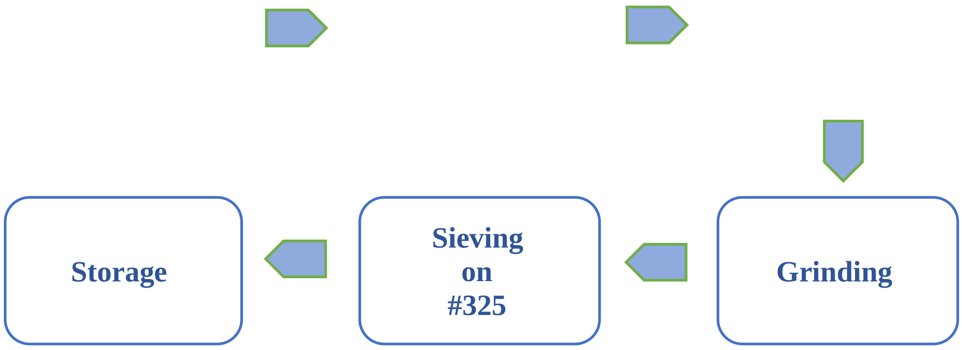

Fig. 3. Shows the WA preparation.

Fig. 4. Shows the preparation of OPC, WA and CCB.

2.4 Experimental Tests

Seven experimental tests were conducted for each of the twelve mixtures shown in Table 3, and these tests are:

The slump, compressive strength, splitting tensile strength, flexural strength, density, water absorption and thermal conductivity. The details of the experimental tests are as follows:

2.4.1. Slump Test

After mixing the wood ash concrete, the concrete slump test was performed using a metal slump cone conforming to ASTM C143/C143-15a [23]. Since proper workability is related to consistency, fluidity, pumpability, and finishing ability, it improves strength and durability [24]. A slump cone of 300 mm height, 200 mm diameter at the bottom, and 100 mm diameter at the top was used to test the workability of both wood ash and conventional concrete. Three layers were placed in the cone, and a steel rod was used to densify each layer 25 times.

2.4.2. Compressive Strength Test

The compressive strength test was carried out at ages 7 and 28 days under displacement-controlled loads at a rate of 0.3 mm/min in accordance with BS 1881, part 116 [25]. For this test, 100×100×100 mm cube specimens were employed. The average of three specimens for each mix was used to determine the compressive strength, and data was taken from the machine for every specimen.

The following formula was used to calculate the specimens' compressive strength as in equation (2):

$$f_{cu} = \frac{P}{A} \quad (2)$$

Where; f_{cu}: Compressive Strength (MPa), P: Ultimate Load (N), and A: Cross Sectional Area (mm²).

2.4.3. Splitting Tensile Strength Test

Testing was conducted on cylinder specimens that were 7 and 28 days old, in compliance with ASTM C496/C496M-11[26] and BS 1881: Part 117 (100 mm in diameter and 200 mm in height). Test specimens' splitting tensile strength is determined using equation (3).

$$fT = \frac{2P}{\pi LD} \quad (3)$$

Where; fT: Splitting Tensile Strength (MPa), P: Ultimate applied load(N), L: Length of cylinder (mm), and D: Diameter of cylinder (mm).

2.4.4 Flexural Strength Test

The flexural strength test was performed at ages 7and 28 days using prism specimens with dimensions (400×100×100) mm, in compliance with ASTM C78-15a [27]. The flexural strength of the test specimens is calculated using equation (4).

$$FT = \frac{PL}{bd^2} \quad (4)$$

Where; FT is Modulus of Rupture, P: Ultimate applied load (N), L: Length of span (mm), b: Width of specimen (mm), and d: Depth of specimen (mm).

2.4.5. Density and Water Absorption

2.4.5.1 Density

The hardened density test was performed according to ASTM C642 [28] at 28 days. The density of concrete containing wood ash depends on the specific gravity and fineness of the binder materials that fill the pores. Use cubes of size (100 × 100 × 100) mm to perform the density test. The equation (5) is used to calculate the dry density.

$$Dry\ density\ Dd = \frac{W1}{W2-W3} * D_w \quad (5)$$

Where; W1: the oven dry weight of cube in the air (g), W2: Weight of the surface-dry sample following immersion in water. (g), W3: the apparent weight of sample in water (g), and D_w: the density of water (g).

2.4.5.2 Water Absorption

The water absorption of the concrete was evaluated in accordance with ASTM C642 [28]. This test utilized three cube specimens per mix (100x100x100) mm for concrete after 28 days. The equation (6) is used to calculate water absorption.

$$Water\ absorption\ ratio = \frac{W2-W1}{W1} \quad (6)$$

Where; W1: the oven dry weight of cube (g), and W2: Weight of the surface-dry sample following immersion in water (g).

2.4.6. Thermal Conductivity

To make the needed specimen, a special plastic disc mold with a diameter of 100 mm and a thickness of 20 mm was made depending on the specifications of the thermal insulation device. At 28 days, the specimen was tested for thermal conductivity. This test was conducted to comply with ASTM C518 (2017) standards [29]. Thermal conductivity samples are depicted in Fig. 5.

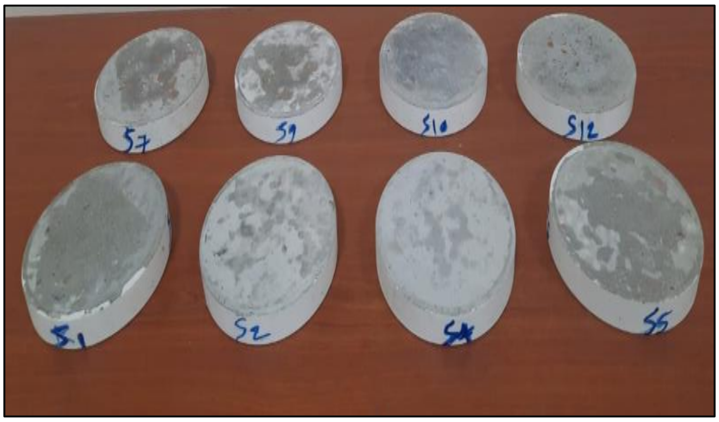

Fig. 5. Shows specimens for the thermal conductivity test.

Thermal conductivity is the amount of heat that moves through a unit thickness perpendicular to a unit-area surface when there is a unit temperature gradient. In steady-state conditions, heat transfer is solely dependent on the temperature gradient [30]. The thermal conductivity test was conducted using the Lee's disc method at the University of Mosul, College of Science, Physics Department. Lee's disc method uses the idea of thermal equilibrium to figure out how heat moves through a material that doesn't conduct heat well. For this test, the specimen is heated with steam, a certain amount of heat is applied to one side, the heat transferred to the other side is measured, and then a graph is made to show the disc's cooling rate [31], as shown in Fig. 6.

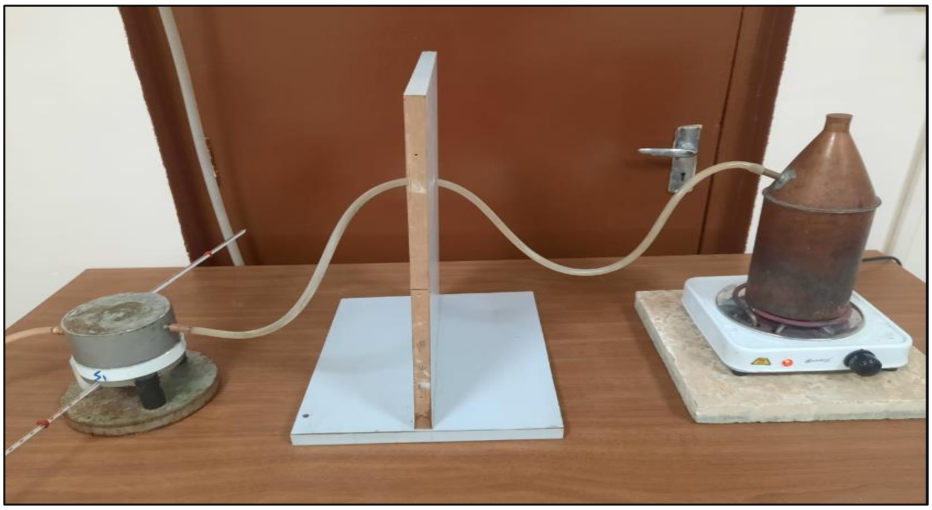

Fig. 6. Shows Lee’s disc apparatus.

3. Results and Discussions

3.1 Slump Test

The slump test is a key measure of concrete workability, reflecting its cohesion and ease of placement. The use of materials such as wood ash (WA) as a partial cement replacement and crushed clay blocks (CCB) as a replacement for ordinary aggregates can significantly affect these properties. Fig. 7 shows the slump values for different mixes:

Comparison of S1, S5, and S9:

Replacing ordinary aggregates with CCB affects particle shape and surface texture, resulting in differences in workability. CCB typically have a more angular shape and coarser texture compared to ordinary aggregates, which can increase internal friction and reduce shrinkage by indirect deduction from the mechanical and physical properties of crushed clay brick (CCB) aggregate. As a result, the slump slowly goes down as the percentage of aggregate replacement with CCB rises from 0% (S1) to 50% (S5) and then to 100% (S9). This trend is consistent with the results of studies conducted on lightweight aggregate concrete, where the use of materials with higher porosity and surface roughness resulted in decreased workability [32].

Comparison between S2, S6, and S10:

The use of wood ash as a partial cement replacement may have a greater impact on slump. Wood ash particles are typically finer and have a larger surface area compared to cement, which can increase water consumption and reduce workability. Blaine's fineness test was performed for both materials (wood ash = 320 m²/kg and cement = 310 m²/kg) in the laboratories of the Technical Engineering College of Mosul. Therefore, mixes with 10% WA (S2, S6, and S10) exhibit lower slump values than the reference mix (S1). Adding 10% WA and raising the CCB levels (from 0% in S2 to 100% in S10) together causes a compound decreases in a slump because the WA uses more water and the CCB makes the mixture less workable. This finding fits with research that says using wood ash instead of cement makes the mixture harder to work with because the particles aren't all the same size and shape [33].

Comparison of S3, S7, and S11:

Increasing the wood ash content to 20% enhances the effects observed at 10% replacement. Consequently, augmenting the dimensions of fine WA particles escalates water requirements, leading to a substantial decrease in slump. This reduction becomes more pronounced in S7 and S11 as the CCB content increases. The cumulative effect of higher WA content and increased CCB replacement leads to a significant reduction in workability. Research has shown that beyond certain limits, adding wood ash can significantly reduce slump due to increased water absorption and surface area [34].

Comparison of S4, S8, and S12:

Wood Ash Replacement of 30% of Cement At 30% replacement, the effect on workability becomes more pronounced. The increase in wood ash fine particles significantly raises water demand, leading to a notable reduction in slump. S4 has a much lower reduction than S1, and this effect gets worse when 50% and 100% CCB are added to S8 and S12. When high amounts of WA and CCB are mixed together, they make a very hard-to-work-with concrete mix. To get the right consistency, superplasticizers or more water must be added. According to studies, wood ash can improve some properties of concrete, but adding too much of it can make it much harder to work with, which shows how important it is to carefully plan the mix [35].

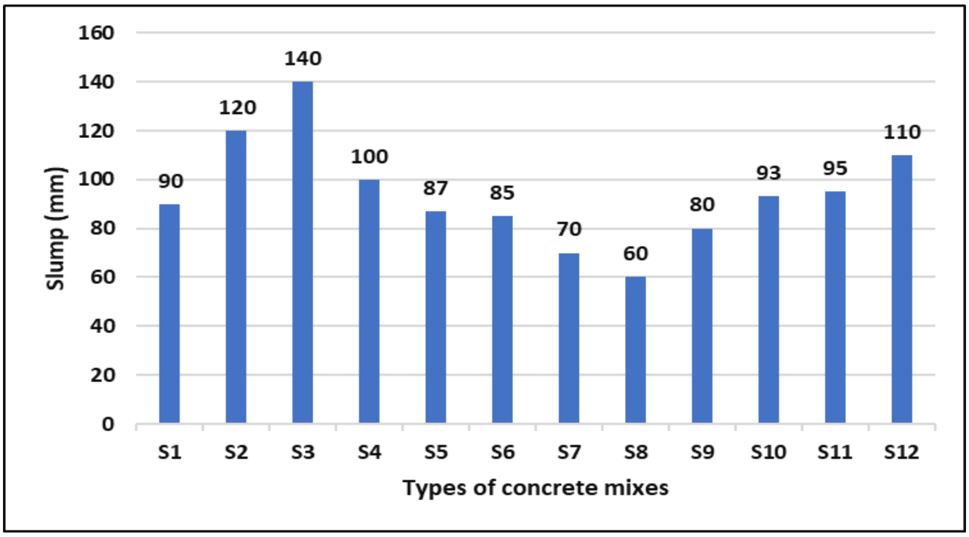

Fig. 7. Illustrates the effect of WA on the slump test.

3.2 Compressive Strength

When analyzing the compressive strength results shown in Fig. 8, the effect of varying levels of cement replacement with wood ash and replacing ordinary aggregate with crushed clay blocks. These mixtures are classified as follows:

Comparison of Mixes S1, S5, and S9:

Replacing natural aggregate with crushed clay blocks can affect the compressive strength of concrete. Research shows that using recycled materials like crushed clay bricks instead of natural aggregate can lower compressive strength because the materials behave differently. Studies have shown that using crushed clay bricks as aggregate can reduce compressive strength by approximately 20–30%, depending on the level of replacement and the material quality [36]. So, both S5 and S9 have less compressive strength than S1, and S9 shows a bigger drop because it has a higher replacement rate.

Comparison of Mixes S2, S6, and S10:

Studies have found varying effects on compressive strength when partially replacing cement with wood ash. Some studies indicate that replacing up to 10% of wood ash can maintain and even slightly improve concrete strength, thanks to the pozzolanic activity of the ash, which contributes to the formation of more calcium silicate hydrates (C-S-H) [37]. But when aggregates are replaced with crushed clay blocks, the overall effect is that the compressive strength goes down [35]. Therefore, S2 exhibits greater strength than S1, while S6 exhibits greater strength than S1, and S10 exhibits lower strength than S1, influenced by the extent of aggregate replacement.

Comparison of Mixes S3, S7, and S11:

Increasing the wood ash content to 20% typically results in a decrease in compressive strength. Research shows that when 20% of the material is replaced with wood ash, the negative impact is greater than the positive effects, leading to lower strength [34]. Consequently, S3 has a lower strength than S1. Adding more crushed clay blocks instead of aggregates in S7 and S11 will make the strength decrease even more, with S11 being the weakest of the three [38].

Comparison of Mixes S4, S8, and S12:

At a 30% replacement level, compressive strength decreases significantly. Studies have shown that these high levels of wood ash can result in a decrease in compressive strength of up to 30% compared to reference mixes [39]. Therefore, the compressive strength of S4 is significantly lower than that of S1. Adding crushed clay aggregates to S8 and S12 makes this effect worse. Of all the mixes we talked about, S12 has the lowest compressive strength [35].

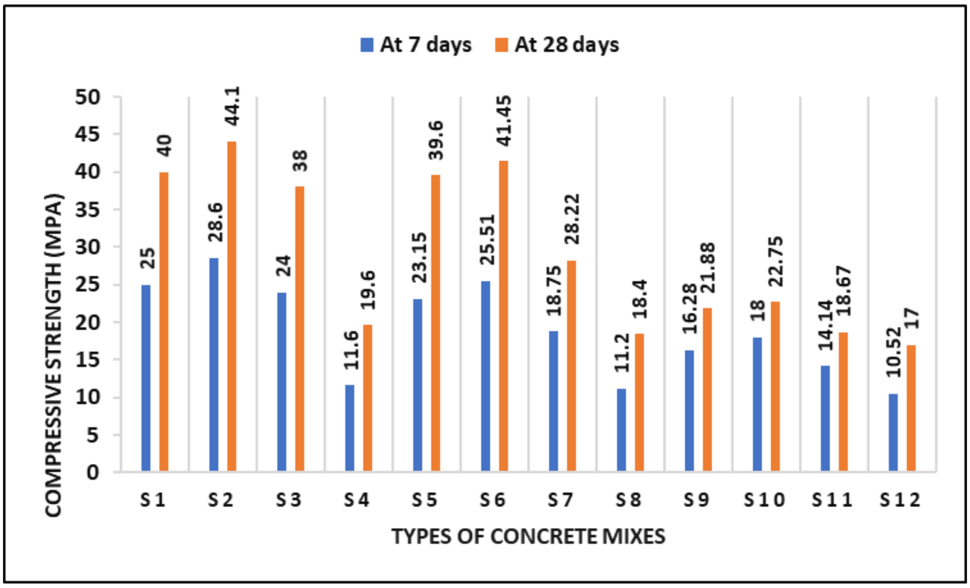

Fig. 8. Illustrates the compressive strength of PC with a WA replacement.

3.3 Splitting Tensile Strength

By analyzing the splitting tensile strength results shown in Fig. 9, the effect of varying levels of wood ash (WA) cement replacement and of replacing ordinary aggregate with crushed clay brick (CCB) on concrete performance can be evaluated.

Comparison of Mixes S1, S5, and S9:

Mix S1, which contains 0% WA and 0% CCB, exhibits the highest splitting tensile strength among the three mixes. Using CCB as a partial (S5: 50%) and full (S9: 100%) replacement for aggregates results in a gradual decrease in tensile strength. This trend is consistent with the findings of Karvic et al., who observed that the addition of wood ash resulted in a decrease in tensile strength in the early stages of aging due to increased water demand and porosity. Similarly, the use of crushed clay brick as aggregate was associated with decreased mechanical properties due to its high porosity and lower strength compared to natural aggregate [40].

Comparison between S2, S6, and S10:

S2, with 10% WA and without CCB, shows a slight decrease in tensile strength compared to S1. This observation is consistent with research indicating that replacing up to 10% of cement with wood ash can maintain or slightly reduce tensile strength. However, as CCB replaces aggregates in S6 (50%) and S10 (100%), a more pronounced decrease in tensile strength is evident. The combined effect of WA and CCB contributes to this decrease, as both materials can increase porosity and reduce the density of the concrete matrix [39].

Comparison between S3, S7, and S11:

At a 20% WA replacement level, S3 shows a further decrease in tensile strength compared to S2. Studies have shown that higher WA content can lead to a significant decrease in tensile strength due to increased porosity and weaker cohesion within the concrete matrix. The addition of CCB in S7 and S11 exacerbates this decrease, as the porous nature of the crushed clay aggregates weakens the structural integrity of the concrete [41].

Comparison between S4, S8, and S12:

S4, which contains 30% WA without CCB, recorded the lowest tensile strength among mixes containing only WA. This significant decrease is consistent with findings that indicate that increasing WA content negatively affects mechanical properties. The use of calcium carbonate (CCB) in S8 (50%) and S12 (100%) further reduced tensile strength, highlighting the combined negative effect of high WA and full replacement of aggregates with CCB on concrete performance [42].

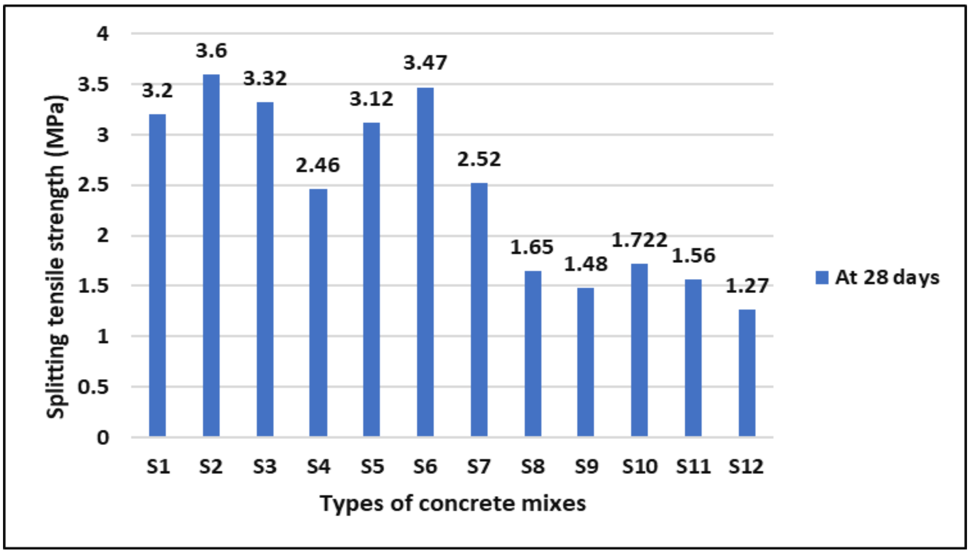

Fig. 9. Illustrates the splitting tensile strength of PC with WA replacement.

3.4 Flexural Strength

The flexural strength test results shown in Fig. 10 reveal valuable insights into the effect of replacing cement with wood ash and replacing ordinary gravel with crushed clay blocks. The data indicate differences in flexural strength between the different mixes, highlighting the influence of material composition on concrete performance.

Compared to 0% cement replacement (S1, S5, S9):

S1 (4.32 MPa) is the reference mix.

S5 (4.57 MPa) shows a slight increase in strength, suggesting that crushed clay blocks may improve performance even without cement replacement. The increase in flexural strength can be attributed to the morphological properties of crushed clay blocks (CCB), particularly their angular shape and rough texture. These characteristics enhanced mechanical interlocking with the cement paste and strengthened the Interfacial Transition Zone (ITZ), thereby improving crack resistance and flexural performance at partial replacement levels.

S9 (3.65 MPa) shows a decrease, suggesting that 100% gravel replacement negatively impacts flexural strength.

Compared to 10% cement replacement (S2, S6, S10):

S2 (5.18 MPa) shows an improvement in strength, likely due to the beneficial properties of wood ash. The improvement in strength is primarily due to the combined effect of wood ash at 10% replacement. Its pozzolanic reactivity generated additional C-S-H gel, while its fine particle size contributed to a filler effect, leading to a denser microstructure and a stronger ITZ. This refinement in the matrix structure directly enhanced flexural performance.

S6 (4.90 MPa) maintains strong performance, supporting the idea that partial cement replacement may be beneficial.

S10 (3.80 MPa) shows a decrease, reinforcing the idea that excessive aggregate replacement may weaken structural integrity.

Compared to 20% cement replacement (S3, S7, S11):

S3 (4.88 MPa) demonstrates balanced performance, indicating optimal conditions for wood ash use.

S7 (4.15 MPa) shows a decrease, which may be attributed to aggregate replacement.

S11 (2.73 MPa) shows a marked weakening, highlighting the risks of excessive aggregate replacement.

Compared to 30% cement replacement (S4, S8, S12):

S4 (2.94 MPa) shows a significant decrease in strength, suggesting that higher wood ash content may not be beneficial.

S8 (2.82 MPa) confirms this trend, indicating that crushed clay aggregate does not compensate for the loss of cement.

S12 (1.85 MPa) highlights the negative effects of excessive replacement on flexural strength.

Several studies have investigated the effect of wood ash (WA) as a partial cement replacement on the flexural strength of concrete. It can enhance flexural strength up to a certain replacement level, after which the strength begins to decline. More specifically, replacing 10% of cement with wood ash resulted in an increase in flexural strength compared to plain concrete [34].

Additionally, a study available on PubMed evaluated concrete in which cement was replaced with WA at ratios ranging from 5% to 20%. The results showed a slight decrease in flexural strength with increasing WA content, but strength improved over time. The study concluded that WA can be mixed with cement without adversely affecting the strength properties of concrete [35].

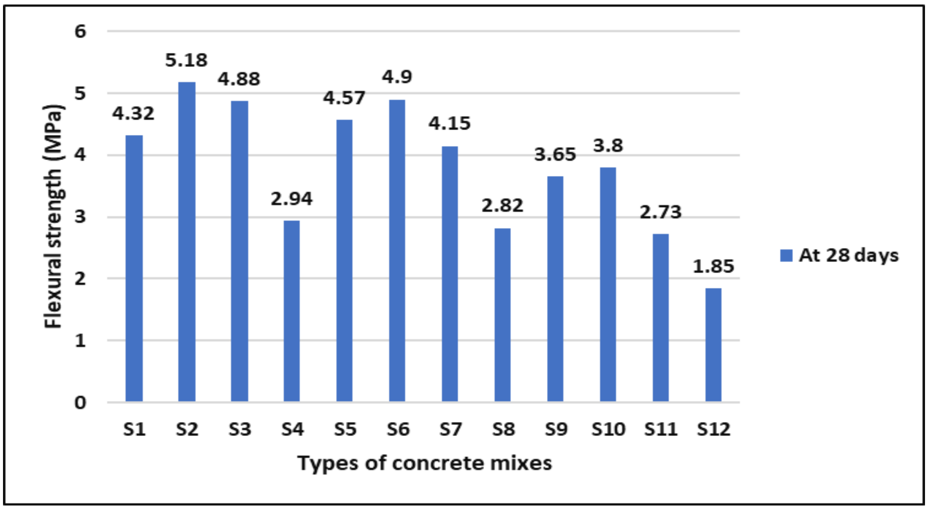

Fig. 10. Illustrates the flexural strength of PC with a WA replacement.

3.5 Density

Fig. 11 illustrates the effect of concrete density as a critical factor on its structural performance and durability. Using wood ash as a partial cement substitute and replacing ordinary gravel with crushed clay aggregates can significantly affect concrete density [43]. A detailed analysis based on the specific classifications is provided below:

Comparison between S1, S5, and S9:

S1 (Reference Mixture): This mixture, which contains 100% ordinary gravel, serves as a baseline for density comparison.

S5 (50% Gravel Replacement): Replacing 50% of ordinary gravel with crushed clay blocks typically results in a lower concrete density. Crushed clay blocks generally have a lower density than natural gravel, resulting in an overall decrease in the mixture's density. The overall reduction in mixture density is primarily attributed to the partial replacement of natural gravel with crushed clay blocks (CCB), which possess a lower specific gravity. This substitution decreases the unit weight of the concrete and introduces additional micro-voids within the matrix, thereby reducing bulk density. While this reduction can enhance thermal insulation properties, it may simultaneously compromise mechanical durability due to weaker interfacial bonding and lower load-bearing capacity.

S9 (100% Gravel Replacement): Replacing ordinary gravel with crushed clay blocks entirely results in a further decrease in concrete density. While this may improve certain properties, such as thermal insulation, it may also result in a significant decrease in compressive strength, warranting careful study in construction applications.

These observations are consistent with the findings of Naaman et al., who reported that partial replacement of natural aggregate with crushed clay brick aggregate resulted in a decrease in concrete density, affecting its structural performance [44].

Comparison of S2, S6, and S10:

S2 (10% wood ash, 0% gravel replacement): Using 10% wood ash as a cement replacement may result in increased density.

The fine wood ash particles fill voids within the concrete matrix, resulting in a denser and more compact structure. This densification may enhance some mechanical properties [45].

S6 (10% wood ash, 50% gravel replacement): Combining 10% wood ash and 50% gravel replacement with crushed clay bricks may result in a density comparable to that of the reference mix. The densifying effect of wood ash can compensate for the density loss caused by the lighter crushed clay aggregates, maintaining the overall density balance.

S10 (10% wood ash, 100% gravel replacement): In this mixture, completely replacing the gravel with crushed clay aggregates, despite the presence of wood ash, is likely to result in a density decrease compared to the reference mixture. The significant decrease resulting from the lighter weight of the crushed clay aggregates outweighs the densifying effect of the wood ash.

A study by Vijay et al. explored the effect of wood ash as a partial replacement for cement on concrete performance. The study concluded that adding wood ash improved the overall performance of concrete, which can be attributed to the densification resulting from the fine ash particles filling the voids within the concrete matrix [46].

Comparison of S3, S7, and S11:

S3 (20% wood ash, 0% aggregate replacement): Increasing the wood ash content to 20% consistently improves concrete density due to its grouting effect. However, excessive use of wood ash may increase water consumption and lead to workability problems, which may affect final density and durability.

S7 (20% wood ash, 50% aggregate replacement): This mix may produce a density similar to or slightly lower than the reference mix. The increased densifying effect of wood ash may not fully compensate for the density reduction resulting from partial replacement of aggregates with crushed clay aggregates.

S11 (20% wood ash, 100% aggregate replacement): With the use of 20% wood ash and full replacement of aggregates with crushed clay aggregates, a significant density reduction is expected.

The lightness of the crushed clay aggregates dominates, resulting in a lighter concrete mix.

Studies have shown that although wood ash can act as a filler and increase density up to a certain replacement level, high proportions may have negative effects on workability and durability [34].

Comparison between S4, S8, and S12:

30% cement replacement with wood ash and 0%, 50%, and 100% aggregate replacement with crushed clay blocks.

S4 (30% wood ash, 0% aggregate replacement): At 30% replacement, wood ash may cause a decrease in density. Increasing the ash content can lead to increased porosity and reduced compaction, negatively impacting density and mechanical properties.

S8 (30% wood ash, 50% aggregate replacement): The combination of 30% wood ash and 50% crushed clay blocks is likely to result in a significant decrease in density. Both substitutions contribute to a lighter concrete mix, which may affect structural integrity.

S12 (30% wood ash, 100% aggregate replacement): This mixture is expected to be the least dense of the series. High levels of wood ash and crushed clay blocks significantly reduce the weight of the concrete, which may impair its strength and durability.

Research indicates that higher wood ash ratios may increase porosity and reduce density, resulting in reduced strength and durability [34].

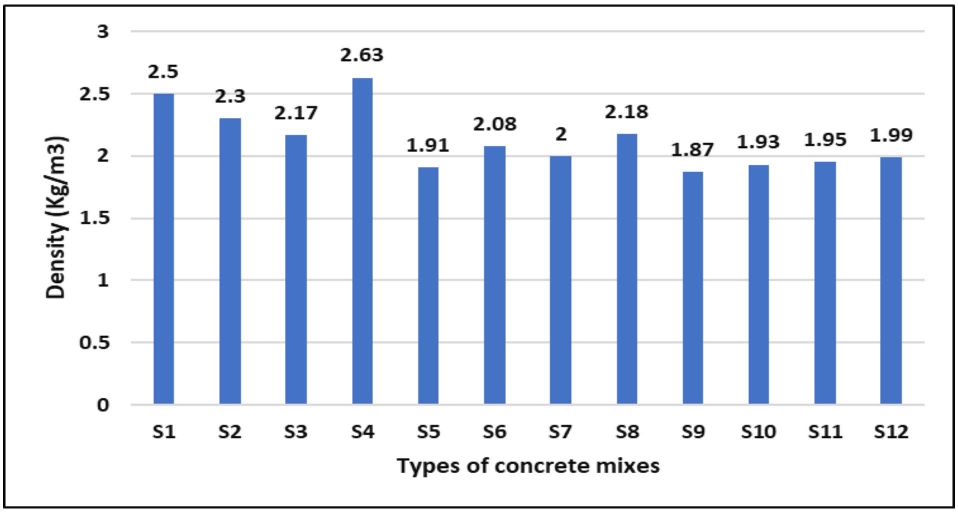

Fig. 11. Illustrates the density of PC with WA replacement.

3.6 Water Absorption

Fig. 12 shows varying proportions of wood ash as a cement substitute and crushed clay as a gravel substitute:

Comparison of mixes S1, S5, and S9:

S1 (reference): 2.27% water absorption. S5 (0% cement replacement, 50% crushed clay): 4.65% water absorption. S9 (0% cement replacement, 100% crushed clay): 4.93% water absorption.

Using crushed clay as a replacement for regular gravel increases water absorption. This trend is consistent with findings that the addition of materials such as crushed clay enhances water absorption in concrete mixes due to its porous nature [47].

Comparison of mixes S2, S6, and S10:

S2 (10% cement replacement, 0% crushed clay): 4.3% water absorption. S6 (10% cement replacement, 50% crushed clay): Water absorption 5.58%. S10 (10% cement replacement, 100% crushed clay): Water absorption 6.14%.

With the replacement of 10% cement with wood ash, water absorption increases compared to the reference standard (S1). This trend continues with the replacement of gravel with crushed clay (S6 and S10). Studies have shown that wood ash can act as an internal curing agent, affecting the water absorption properties of concrete [33].

Comparison between S3, S7, and S11:

S3 (20% cement replacement, 0% crushed clay): Water absorption 6.45%. S7 (20% cement replacement, 50% crushed clay): Water absorption 6.75%. S11 (20% cement replacement, 100% crushed clay): Water absorption 7.47%.

Increasing the wood ash content to 20% results in higher water absorption [39]. The addition of crushed clay improves this property. This behavior is consistent with observations that higher wood ash content can lead to increased porosity and water absorption in concrete [48].

Comparison between mixes S4, S8, and S12:

S4 (30% cement replacement, 0% crushed clay): Water absorption 3.72%. S8 (30% cement replacement, 50% crushed clay): Water absorption 3.9%. S12 (30% cement replacement, 100% crushed clay): Water absorption 4.15%.

At a 30% replacement of wood ash, water absorption decreases compared to 20% replacement mixes. The addition of crushed clay slightly increases water absorption due to the micro-filler effect, enhanced pozzolanic activity, and partial internal curing, all of which refine the pore structure and improve ITZ density. Nevertheless, absorption remains higher than the reference concrete because of the inherent porosity of wood ash and the introduction of crushed clay aggregates. This outcome confirms that the optimal wood ash content lies within the 10–20% range. Research indicates that the optimum wood ash ratio to maintain desired properties in concrete is between 10% and 20% [39].

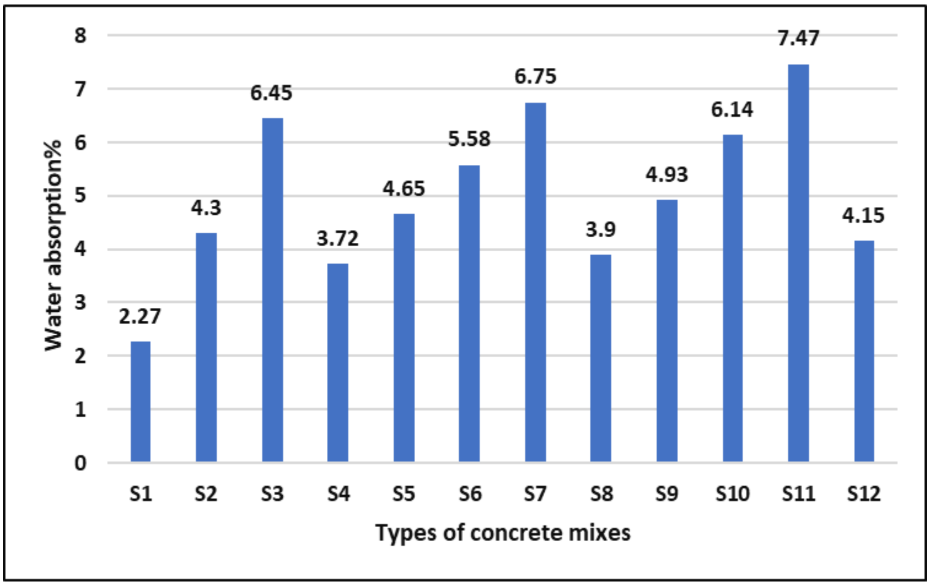

Fig. 12. Illustrates the water absorption of PC with WA replacement.

3.7 Thermal conductivity

The results shown in Fig. 13 showed that the addition of wood ash (WA) and the replacement of natural aggregates (NA) with crushed clay blocks (CCB) significantly affected the mechanical and thermal properties of concrete. After 28 days, the compressive strength of mixes containing 10% wood ash (S2: 44.1 MPa) improved compared to the reference mix (S1: 40 MPa), indicating that lower wood ash content enhances cement hydration and pozzolanic activity [22].
However, higher wood ash replacement (e.g., 30% in S4: 19.6 MPa) resulted in a sharp decrease, likely due to the increased porosity of unreacted wood ash particles and matrix weakening. Replacing wood ash with crushed clay blocks (CCB) (50% or 100%) further reduced the compressive strength, especially in mixes with higher wood ash content (S7-S12). For example, S12 (30% WA + 100% CCB) showed only 17 MPa, highlighting the negative impact of the porous structure of CCB and the dilution effect of WA on the cement [22].

Thermal conductivity (k values) shown in Figure 10 gradually decreased with increasing WA and CCB content. Mixture S11 (20% WA + 100% CCB) achieved the lowest thermal conductivity (0.366 W/m°C), a 71% decrease compared to control mix S1 (1.272 W/m°C). This trend is consistent with the increased porosity of WA and CCB, which traps air and enhances thermal insulation [49]. The decrease in thermal conductivity (k) with increasing WA and CCB content is attributed to the higher porosity of these materials, which traps air and reduces heat transfer. Replacing dense cement and natural aggregates with porous WA and CCB lowers the solid heat-conducting fraction and increases the tortuosity of thermal paths, while the lighter density of CCB further reduces k. In mixture S11 (20% WA + 100% CCB), these combined effects result in a significant reduction in thermal conductivity, enhancing the concrete's insulating performance. Decreasing WA content improves compressive strength due to enhanced pozzolanic interactions and filler effects, which is consistent with the study by (Yang et al., 2020) [49]. Studies indicate that a WA content of 10% is associated with significant improvements in strength. Research indicates that using CCB in concrete has been shown to lower thermal conductivity, enhance insulation, and reduce energy costs in buildings. Increased porosity in aggregates is associated with decreased thermal conductivity, as shown in studies that relate grain size and porosity to heat transfer efficiency [50].

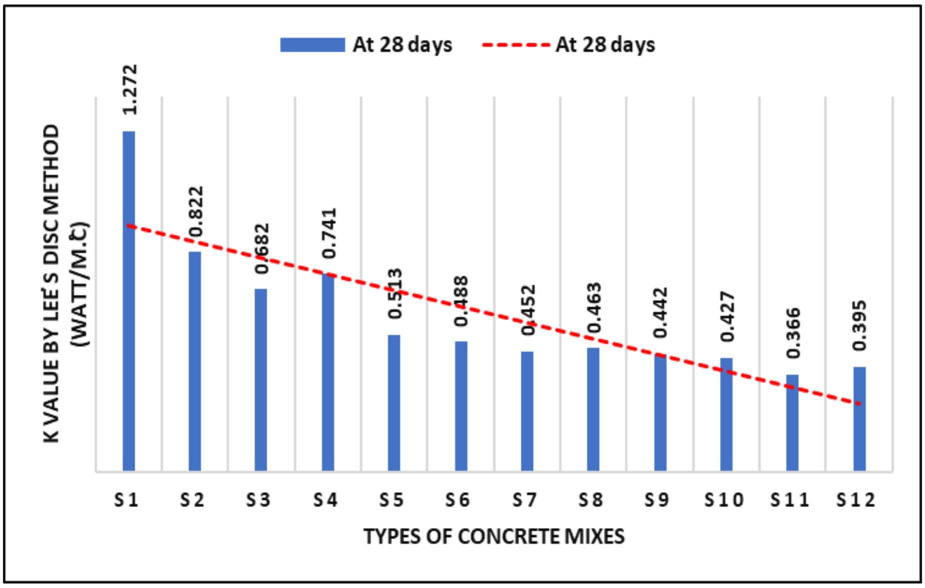

Fig. 13. Illustrates the thermal conductivity of PC with a WA replacement.

4. Conclusions

The possibility of using wood ash as a sustainable concrete additive has been evaluated by considering how it affects performance and environment. A total of seven tests have been conducted by replacing cement with WA waste as well as replacing ordinary gravel with CCB in different proportions. workability, density, water absorption, compressive strength, splitting strength, flexural strength and thermal conductivity tests were conducted, and the finding can be summarized as follows:

1. The use of wood ash as a partial cement replacement and crushed clay aggregates as replacements for ordinary aggregates contributes to reduced workability in concrete mixes, as evidenced by lower slump values. The WA and CCB ratios used directly influence the extent of this reduction, with higher replacement levels are leading to greater slump reductions. This is evident in the S8 mix, where the reduction is lowest, at 33.33% compared to the S1 reference mix. S3 mix exhibits the highest value, with a 55.56% increase compared to the reference mix S1. These results show how important it is to make the best mix designs when using other materials so that sustainability goals are met while still getting the properties that fresh concrete needs.

2. While partial replacement of cement with wood ash may be beneficial at low levels (around 10%), with compressive strength peaking at S2, an average increase of 76.40% compared to the reference mix S1, higher replacement levels, especially when combined with the replacement of natural aggregates with alternative materials such as crushed clay aggregates, tend to result in reduced compressive strength, with compressive strength reaching its lowest at S12, an average decrease of 32% compared to the reference mix. When designing concrete mixes for specific construction applications, these results align with previous studies and warrant consideration.

3. While partial replacement of cement with wood ash up to 10% may have a negligible effect on tensile strength, higher levels of replacement and replacement of crushed clay aggregates with natural aggregates tend to deteriorate concrete's mechanical properties. The highest tensile strength was recorded at S2, with an increase of 12.50% compared to the reference mix S1, while the lowest tensile strength was recorded at S12, with a decrease of 60.31% compared to the reference mix S1. These results are consistent with previous studies, emphasizing the need to carefully consider the materials when incorporating them into concrete mixes to balance sustainability goals with structural performance.

4. These studies suggest that while moderate WA replacement can enhance or maintain flexural strength, excessive replacement may lead to decreased mechanical performance. The highest flexural strength was recorded at S2, with an increase of 19.91% compared to the reference mix S1, while the lowest flexural strength was recorded at S12, with a decrease of 57.18% compared to the reference mix S1. Therefore,

careful material selection and optimization of replacement levels are essential to achieve optimal concrete performance.

5. The incorporation of wood ash and crushed clay aggregates affects concrete density in different ways. While wood ash acts as a filler and increases density at lower replacement levels, higher ratios may increase porosity and decrease density. Similarly, replacing aggregates with crushed clay aggregates typically reduce density due to the aggregates' lighter weight. The highest density was recorded at S4, with an increase of 5.20% compared to the reference mix S1, while the lowest density was recorded at S9, with a decrease of 25.20% compared to the reference mix S1. These modifications may enhance some properties, such as thermal insulation, but they can negatively impact mechanical strength and durability, requiring a balanced approach to mix design.
6. Both wood ash and crushed clay aggregate replacements tend to increase water absorption in concrete mixes. This is due to their porous nature, which enhances the overall porosity of the material. The highest water absorption was recorded at S4, with an increase of 63.88% compared to the reference mix S1, while the lowest water absorption was recorded at S11, with a decrease of 229% compared to the reference mix S1. Paying attention to replacement ratios is crucial to balancing the potential benefits and drawbacks to concrete performance.

WA can be used in the manufacture of insulating and non-load-bearing blocks.

Findings of this study recommends the use of OPC in the construction field to manufacture load-bearing insulating blocks using WA with CCB. It will enable the production of concrete masonry units at low cost without compromising the structural properties and durability.

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Data Availability

Data that support the findings of this study are available from the corresponding author upon reasonable request.

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