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Durability Properties of Ambient-Cured Metakaolin Stabilized Compressed Earth Blocks

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Abstract

This study assessed the durability of compressed earth blocks (CEBs) stabilized with 0-19% metakaolin (CEB_MKX) and cured at ambient temperature (26 ± 0.2 °C) for 28 and 180 days. Materials were characterized mineralogically, chemically, mechanically, and physically. Metakaolin was produced by calcining kaolin at 700 °C for 3h and activated with 12M NaOH. The optimum content was 11%, in accordance with the African Standard. Abrasion resistance of CEB_MK11% (2.73 cm^2/g) was markedly higher than unstabilized CEBs (0.35 cm^2/g). In wetting-drying cycles, CEB_MK11% exceeded the 15% mass loss limit after five cycles (17.18% after twelve), indicating moderate durability. Capillary absorption reached 3.42 g/cm^2 after 72 h, slightly higher than OPC-stabilized blocks (3.12 g/cm^2), showing greater early-stage uptake but comparable long-term behavior. Erosion drip tests showed no visible surface erosion, though moisture penetration was higher in CEB_MK11% (21.1 mm) than OPC8% (16.3 mm), yet all values were < 90 mm, confirming adequate durability. Under water spray (0.5 bar), CEB_MK11% had an erosion rate of 38.5 mm/h (EI2), higher than OPC8% (3.9 mm/h, EI1) but clearly outperforming unstabilized CEBs (> 120 mm/h, EI5). Overall, 11% metakaolin significantly enhanced abrasion resistance and moisture durability, supporting its potential for sustainable construction.

Keywords: sustainable materials, stabilized earth blocks, capillary absorption test, durability performance, wetting-drying cycles, Erosion drip test, water spray test.

1. Introduction

The rising need for sustainable and economical building materials has sparked renewed interest in Compressed Earth Blocks (CEBs) as an alternative to traditional masonry units. Compressed earth blocks (CEB) have garnered considerable interest as a sustainable and economical alternative building material in areas where conventional construction materials are costly or limited. Notwithstanding these benefits, their mechanical strength and durability are significantly compromised when subjected to degrading conditions. To prevent this degradation, various stabilizers have been employed to enhance their function.

CEBs consist predominantly of natural soils that are compacted to create solid blocks. The ideal soil composition for CEBs often comprises 10-30% clay, 50-75% sand, with the remainder consisting of silt and gravel. Clay is crucial for imparting cohesion and binding characteristics, guaranteeing that the blocks retain their form and integrity (Avizovas et al., 2022; Bredenoord & Kulshreshtha, 2023;

Mousavi et al., 2021). Silt affects workability and compactness, hence influencing the density and strength of the blocks (Pu et al., 2020; Zheng et al., 2024). Simultaneously, sand and gravel improve mechanical stability and diminish shrinking, hence enhancing the overall durability of the blocks (Baldovino et al., 2020; Shi et al., 2023). Furthermore, stabilizers including cement, lime, and pozzolanic compounds such as metakaolin are utilized to enhance strength and durability, with their type and quantity varied according to the required qualities and environmental circumstances (Djibo et al., 2023; Omar Sore et al., 2018). The meticulous equilibrium of components is essential for generating superior CEBs that adhere to construction standards.

In recent years, geopolymer binders have emerged as a promising alternative to cement for stabilizing compressed earth bricks (SCEB). By definition, geopolymers are aluminosilicate materials belonging to the family of alkali-activated materials which, unlike cementitious materials, require alkalis to harden (Pouhet, 2015). The synthesis of geopolymers is obtained by polycondensation and can be made from materials rich in aluminosilicates including a wide range of industrial wastes as fly ash, blast furnace slag, rice husk ash, kaolin, metakaolin.

Geopolymerization process occurs when aluminosilicate materials are synthesized resulting in the formation of viscous cementitious slurry which upon hardening forms strong, durable, and compact geopolymeric material (Chuewangkam et al., 2024). The geopolymerization process activators are NaOH, Na_2SO_4, waterglass, Na_2CO_3, K_2CO_3, KOH, K_2SO_4 or a little amount of cement clinker (Mousavi et al., 2021). This process results to formation of geopolymers. Geopolymers as binder offers several advantages, including lower environmental impact and improved thermal properties in geopolymer concrete compared to cement concrete.

In previous studies, CEBs were stabilized with geopolymer material in proportions varying between 5% and 20%, using increments of 5%. The current research considered expanding this range by employing 2% increments from 5% to 19%, including 10%, which (Dabakuyo et al., 2022) identified as the optimal content, when the SCEBs are cured under ambient temperature. Additionally, (Omar Sore et al., 2018) found that a 15% geopolymer content, with curing done at 60°C resulted in CEBs with properties similar to those stabilized with Portland cement, particularly regarding water stability. The difference in optimum values of metakaolin content is due to the variation in sources of materials and curing conditions.

Omar Sore et al., (2018) assessed the viability of stabilizing compressed earth blocks with a geopolymer binder, which is less environmentally harmful than Portland cement. The performance of the geopolymer-stabilized CEBs was compared with non-stabilized CEBs and Portland cement-stabilized CEBs. The geopolymer binder was produced by combining metakaolin with a sodium hydroxide solution. Laterite served as the primary matrix material for the blocks. CEBs were produced with 5%, 10%, 15%, and 20% geopolymer stabilization and compared to both CEBs stabilized with 8% Portland cement and those without any stabilizer. After curing, the blocks were subjected to various characterization tests to evaluate their physical, mechanical and thermal properties. The results showed that geopolymerization of CEBs significantly improved their mechanical performance and gave them thermal properties very similar to those of non-stabilized blocks. The study concludes that geopolymer stabilization is a feasible and more eco-friendly option than cement for enhancing the properties of compressed earth blocks in Burkina Faso (Omar Sore et al., 2018).

Djibo et al., (2023) carried out a similar study on the physico-mechanical performances of compressed earth blocks stabilized with a calcined clay-based geopolymer. The geopolymer binder was produced from locally sourced kaolin-rich clay, calcined at 700°C for 3 hours to convert it into amorphous and reactive metakaolin. The lateritic soil material had a particle size of 0/5 mm. An alkali solution of sodium hydroxide (NaOH, 12 M) was added to the dry mixtures to activate the metakaolin and create wet mixtures. These mixtures were then manually and statically compressed (~35 bar) in a mold (295 x 140 x 95 mm^3) using a Terstaram machine to form the CEB. The stabilized CEBs were cured for 14 days, with 7 days at room temperature (30 ± 5°C) and 7 days in an oven at 60°C, while the cement-stabilized CEBs were cured at room temperature (30 ± 5°C) for 28 days. The CEBs were dried and tested for their physico-mechanical properties, revealing a significant improvement in performance for those stabilized with up to 20% geopolymer, with water-accessible porosity of 27.4% for CEBs stabilized with 15% geopolymer, compared to 26% for those stabilized with 8% cement. The dry and wet compressive strengths were 9.8 MPa and 4.8 MPa for CEBs stabilized with 15% geopolymer, compared to 6.6 MPa and 4.7 MPa for CEBs stabilized with 8% cement (Djibo et al., 2023).

CEBs, made from natural materials, offer an eco-friendly alternative to traditional building materials. However, their performance under various environmental conditions must be thoroughly understood. CEBs are prone to cracking and deterioration due to abrasion and erosion, moisture exposure and water ingress, wetting and drying cycles, as depicted in Figure 1. Sustained exposure to these conditions considerably compromises their mechanical integrity and longevity.

Fig. 1. CEB buildings damaged over time by environmental factors

Incorporating metakaolin as a stabilizer in compressed lateritic earth blocks significantly enhances their water resistance, reducing their tendency to crumble when exposed to moisture and achieving a water absorption rate of 14.81%. This level of water absorption meets the requirements set forth by (BS EN 771-1, 2016) standard, which recommends that structural clay masonry units should ideally have a water absorption rate of 20% or lower, depending on exposure conditions. Meeting these standards indicates that stabilized earth blocks with metakaolin are suitable for structural applications, particularly in environments where durability against moisture is essential.

Metakaolin is a pozzolanic material obtained by calcination of kaolinitic clay at temperature between 600 and 800°C (Ilić et al., 2010), equation 1. Metakaolin has demonstrated considerable potential in enhancing the performance of CEBs. Stabilizing CEBs with metakaolin improves their resistance to water absorption, erosion, and cracking, thereby extending their service life in both indoor and outdoor environments. Despite the promising benefits, limited research has focused on the long-term durability of metakaolin-stabilized CEBs, particularly under ambient curing conditions.

$$Al_2Si_2O_5(OH)_4 \xrightarrow{600-800^{\circ}C} Al_2O_3.2SiO_2 + 2H_2O \ldots\ldots\ldots (1)$$

This study sought to evaluate the mechanical and environmental durability properties of ambient-cured metakaolin-stabilized CEBs at 180 days of age. The block properties such as compressive strength, water absorption by capillarity and immersion, and resistance to erosion and weathering are assessed.

2. Materials and Methods

2.1 Material Acquisition and Preparation

The material utilised in the study were laterite soil, metakaolin clay, sodium hydroxide flakes and Ordinary Pozzolanic Cement (OPC). The laterite soil was sourced at Juja Sub-County, Kenya. The soil was allowed to dry, pulverized, and sieved though a 5 mm sieve, as per the recommendations of the "African Standard WD-ARS 1333:2018" (WD-ARS 1333 Edition, 2018). The soil was obtained from subsoil layers beneath the organic topsoil; at a thickness of 100 mm.

Metakaolin was obtained through calcination of kaolin at 700°C for three hours. The preparation procedure is as indicated in **Fig**.

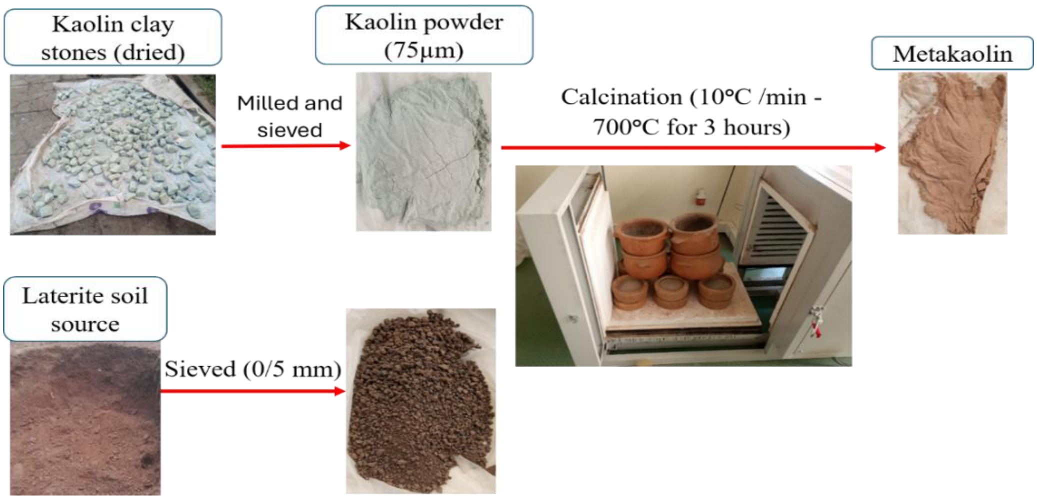


Fig. 2: Preparation flow chart for Metakaolin and laterite soil

Bags of sodium hydroxide flakes of 99.5% purity were sourced from Insulation World Kenya Ltd, Nairobi. A 12 M solution of sodium hydroxide (NaOH) was then prepared by dissolving NaOH in distilled water.

Ordinary Portland Cement (CEM I 32.5N) was purchased from Thika, Sub-County, Kenya. The cement was used as a block stabilizer to test the durability properties of the stabilized blocks. The cement was compliant with the Kenya Standard (KS EAS 18-1, 2001).

2.2 Material characterization and sample testing

The mineralogical composition and crystalline phases analysis for laterite soil and Metakaolin were done through X-ray diffraction (XRD) (device used: "PANayltical X'Pert Pro powder diffractometer").

Scanning electron microscopy (SEM) was utilized (device used: "JCM 6000 Plus from JEOL, Tokyo, Japan") to examine the microstructure, providing insights into surface morphology and particle arrangement.

The elemental composition of the laterite soil and Metakaolin was determined (device used: "Bruker S1 Titan 600 XRF Analyzer") using X-ray fluorescence (XRF).

2.3 Production of the Compressed Earth Blocks

The stabilization levels were designated as CEB_MKX, where X represents metakaolin content. The metakaolin replacement percentages were 0, 5, 7, 9, 10, 11, 13, 15, 17 and 19% of the total mass of laterite soil in the mix (Table 1). Blocks were pressed using a manual press machine (Compaction force ≈ 100 kN), Fig. *1*. The fresh blocks were initially cured under polyethylene plastic sheets for 24 hours (Fig. *2*a) then followed by ambient temperature (26.0 ± 0.2°C) curing for 27 days (Fig. *2*b). Five (5) samples of CEBs for each metakaolin content and for each test were prepared and subjected to physico-mechanical tests, as per (WD-ARS 1333 Edition, 2018). The amount of water added to the laterite soil-metakaolin blend was established by performing compaction tests on the various samples. The length, width and height of the blocks were 290, 140 and 120 mm, respectively. The SCEB were subjected to various tests including compressive strength, dry density, capillarity and erosion resistance.

Table 1: Summary of Mix Proportions for laterite soil-metakaolin blocks

Mix design					
CEB type	**^{a}Laterite soil content (%)**	**^{a}Cement content (%)**	**^{a}Metakaolin content (%)**	**b**	**Water / solid (%)**
CEB_0%	100	//	0	-	17.3
CEB_MK5%	95	//	5	0.8	16.6
CEB_MK7%	93	//	7	0.8	17.0
CEB_MK9%	91	//	9	0.8	17.4
CEB_MK10%	90	//	10	0.8	18.7
CEB_MK11%	89	//	11	0.8	18.2
CEB_MK13%	87	//	13	0.8	18.7
CEB_MK15%	85	//	15	0.8	19.0
CEB_MK17%	83	//	17	0.8	19.2
CEB_MK19%	81	//	19	0.8	19.5
CEB_OPC8%	92	8	//	//	19.0

In Table 1: ^{a}Percentage of dry mix; b = NaOH solution / metakaolin ratio; OMC = optimum moisture content; NMC = natural moisture content


(a) Mixing of materials

(b) Manual pressing of blocks

Fig. 1: Blocks production


(a) Block curing for 24 hours

(b) Block curing for 27 days

Fig. 2: Curing of CEBs

2.3.1 Blocks Durability Tests

The mechanical and durability properties of the CEBs were assessed at 180 days of age to evaluate the performance and stability changes that occurred beyond the 28-day curing period.

(i) Compressive Strength

Five (5) blocks were randomly selected for carrying out the compression strength test in accordance to African Standard WD-ARS 1333:2018. Blocks were placed between the platens of a universal testing machine (Figure 5) and the load applied uniformly. The maximum load (P) at failure and the cross-sectional area of the specimens were recorded. The average compressive strength for the blocks was calculated using equation 1.2. Where σ is compressive strength, P is the maximum load and A is the cross-sectional area.

$$\sigma = \frac{P}{A} \dots\dots\dots\dots (2)$$

Fig. 3: Compressive strength test on the blocks at 180 days.

(ii) Capillarity

Before testing, the specimens were previously oven-dried at 70 ± 5°C until constant mass was achieved. The lateral surfaces of the blocks were then sealed by aluminium tape (Figure 6). The test was performed in accordance with (XP P13-901, 2022) standard.

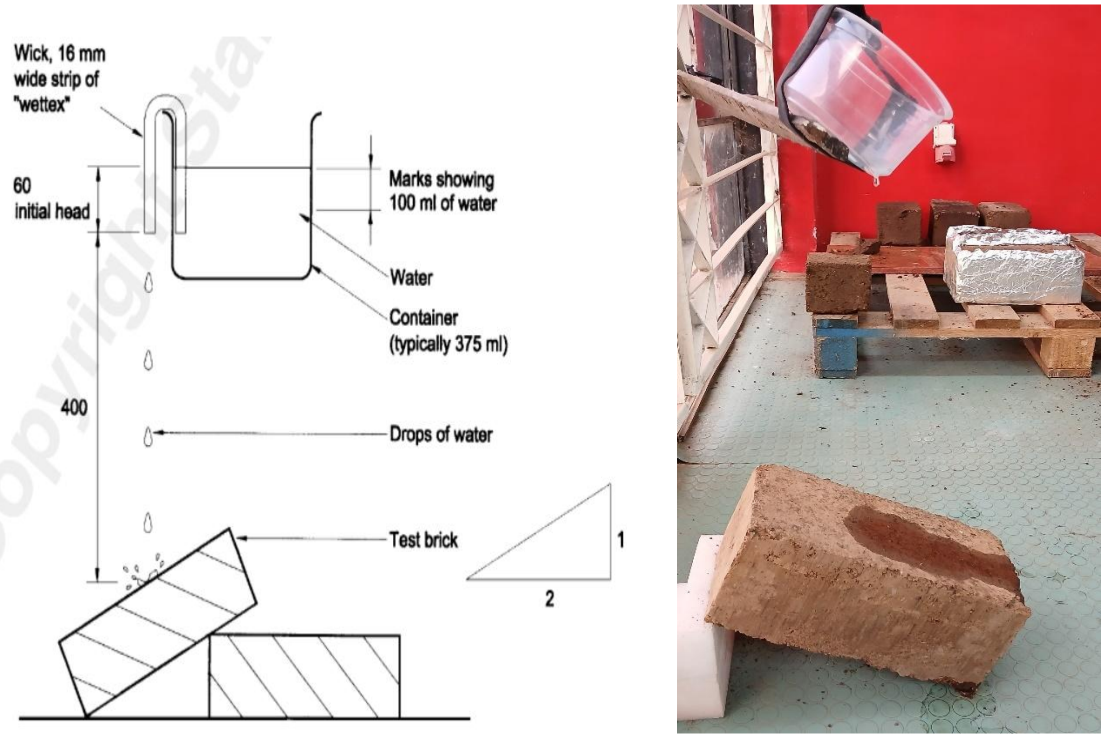
(a) Capillary absorption test setup

(b) Capillary absorption test

Fig. 4: Setup for capillarity assessment of CEBs

(iii) Erosion resistance, The drip test

The drip test, which simulated light rain erosion, consisted of dropping 100ml of water in droplets onto the surface of blocks set at a 27º angle, from a height of 400mm (Figure 7). After 30min, the erosion depth (DE) and moisture depth penetration (DP) was measured in accordance to NZS 4298, 1998).

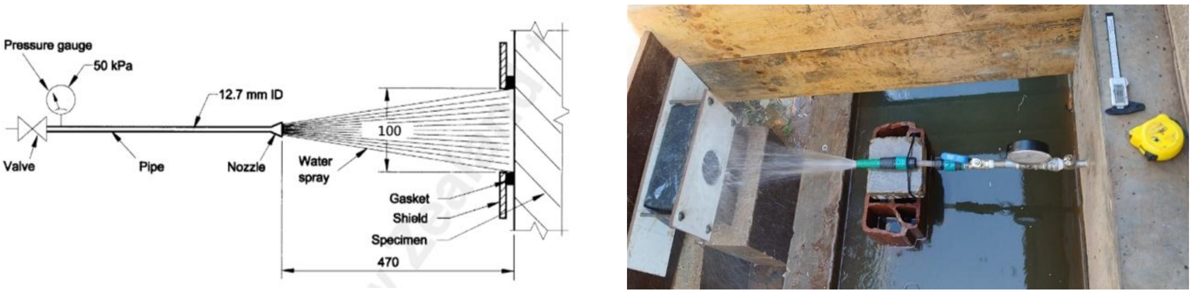


(a) Drip test setup (NZS 4298, 1998) (b) Drip test experimental setup

Fig 5: Erosion resistance, drip test setup (NZS 4298, 1998)

(iv) Erosion Resistance, the spray test (NZS 4298, 1998)

This test replicated heavy rainfall. Over an exposure area of 10cm in diameter, blocks were subjected to a pressurized water jet of 50 kPa, 47cm away from the blocks, and for 1h (Figure 8). The erosion depth (DE) was recorded every 15min and moisture depth penetration (DP) was measured at the end, after sawing the block. The blocks were classified by the erodibility index (EI) according to (NZS 4298, 1998) standard.



(a) Spray test setup (NZS 4298, 1998) (b) Spray test experimental setup

Fig. 6: Erosion resistance, spray test setup (NZS 4298, 1998)

3. Results and Discussion

3.1 Material Characterization

The XRD spectrum for laterite soil and Metakaolin are a shown in Figure 9. The presence of quartz in both samples indicated significant silicate content. The laterite soil contained Kaolinite minerals which confirmed the clayey nature of the soil. The detection of goethite indicates the presence of iron oxides, which are typical in lateritic soils.

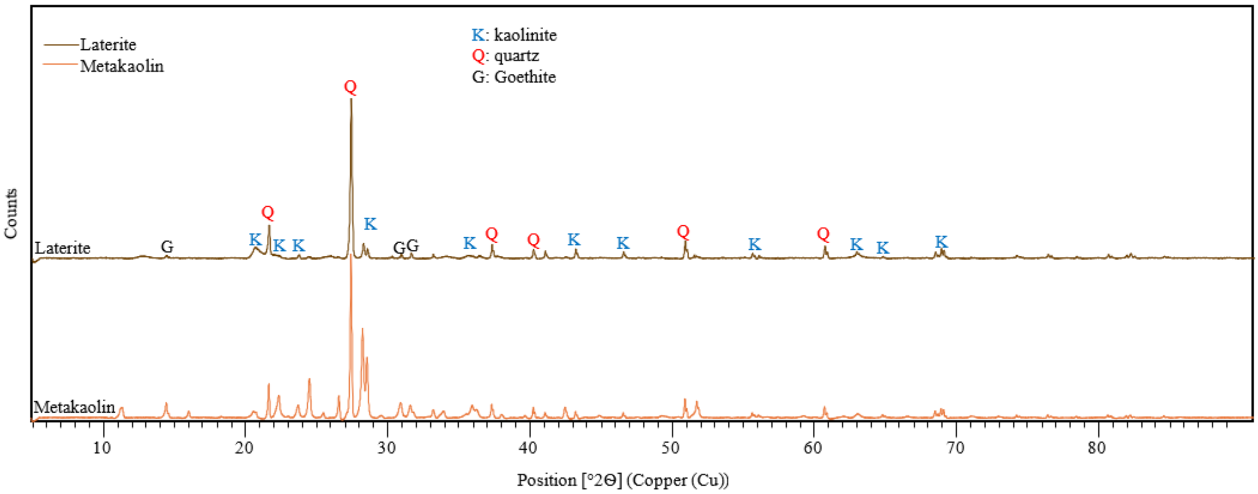
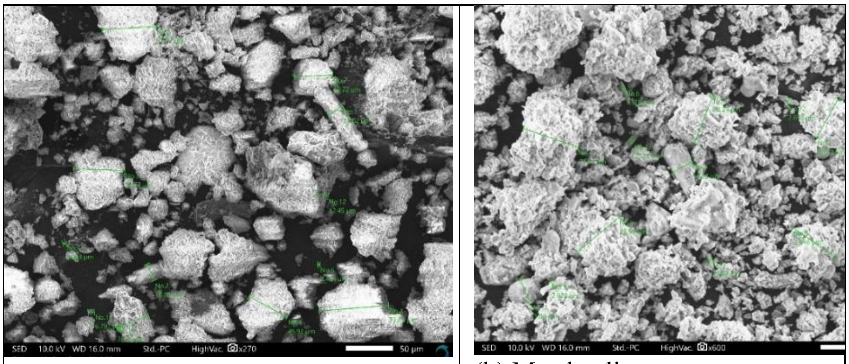


Fig. 7: XRD peaks for laterite soil and Metakaolin

On the other hand, metakaolin presents a broad amorphous hump between 20° - 30° 2θ Cu, signifying the dehydroxylation of kaolinite into an amorphous aluminosilicate structure. The absence of kaolinite peaks in metakaolin confirms successful thermal activation, making it a suitable precursor for geopolymerization or pozzolanic applications.

These findings suggest that laterite soil retains a crystalline structure, while metakaolin becomes highly reactive due to its amorphous nature, thereby enhancing its potential as a stabilizer in compressed earth blocks.

Fig. (a) illustrates the SEM image of laterite, revealing a heterogeneous structure composed of irregular, angular, and coarse particles. The presence of voids and pores is evident to the contribution of the material’s water absorption characteristics and influence in its binding efficiency with stabilizers. Additionally, the angular particles suggest that laterite may exhibit good mechanical interlocking when compacted in CEBs.



(a) Laterite soil

(b) Metakaolin

Fig. 8: Scanning electron microscopy images

In contrast, Fig. (b) presents the microstructure of metakaolin, which exhibits a rough surface and more compact particle distribution. The particles appear rough on the surface as compared to laterite. This indicates a higher surface area and reactivity. This rough texture enhances pozzolanic activity of metakaolin, making it an effective additive for improving the strength and durability of CEBs through geopolymerization.

The distinct morphological differences between laterite and metakaolin play a critical role in determining the mechanical and durability properties of stabilized earth blocks. The angular nature of laterite contributes to structural integrity, while the rough metakaolin particles enhance chemical bonding and densification. These microstructural observations validate the suitability of these materials in optimizing the performance of CEBs.

Error! Reference source not found. shows that the primary chemical constituents of the laterite soil, Metakaolin and Ordinary Portland Cement used in the study. The silica-sesquioxide ratio (SiO_2/(Al_2O_3 +Fe_2O_3)) in laterite soil was 1.44 falling in the range 1.33 to 2 as suggested by (Diop et al., 2025; Kamtchueng et al., 2015). Consequently, the chemical composition verified that the soil utilized in this work for the production of the CEBs was lateritic soil.

The total amount of (SiO_2 + Al_2O_3 +Fe_2O_3) in Metakaolin is 92.72%. Hence, the metakaolin was classified as class N pozzolan according to the requirements of the (ASTM C618, 2022) standard.

Table 21. Chemical composition by percentage (%) weight of raw materials.

Oxides	**Laterite**	**Metakaolin**	**Cement (CEM I)**
Silicon oxide (SiO_2)	55.137	76.259	20.84
Aluminum oxide (Al_2O_3)	16.834	10.630	5.10
Iron oxide (Fe_2O_3)	21.328	5.831	3.24
SiO_2 + Al_2O_3 +Fe_2O_3	93.299	92.72	29.18
Calcium oxide (CaO)	1.996	0.824	63.23
Potassium oxide (K_2O)	0.686	4.891	0.49
Magnesium oxide (MgO)	0.000	0.000	0.84
Phosphorus pentoxide (P_2O_5)	0.000	0.095	-
Loss of Ignition (LOI)	-	2.52	-

The laterite soil spectrum (Figure) exhibited characteristic hydroxyl (-OH) stretching vibrations at 3669 cm^{-1} and 3626 cm^{-1}. This confirmed the presence of kaolinite as argued by (Qtaitat & Al-Trawneh, 2005). A peak at 1742 cm^{-1} corresponds to carbonyl (C=O) stretching, while the strong absorption at 1001 cm^{-1} is associated with Si-O stretching in aluminosilicates (Kakali et al., 2001). The band at 523 cm^{-1} indicates Al-O vibrations, reinforcing the presence of clay minerals.

The metakaolin spectrum (Figure) shows a significant reduction in hydroxyl (-OH) absorption bands, indicating the dehydroxylation of kaolinite during calcination (Ozer & Soyer-Uzun, 2015). The Si-O stretching vibration was prominent at 1001 cm^{-1}, with additional bands at 1211 cm^{-1} and 783 cm^{-1} suggesting structural reorganization in the aluminosilicate framework (Daniel et al., 1995). The transformation from crystalline kaolinite to amorphous metakaolin is confirmed by the disappearance of hydroxyl-related peaks.

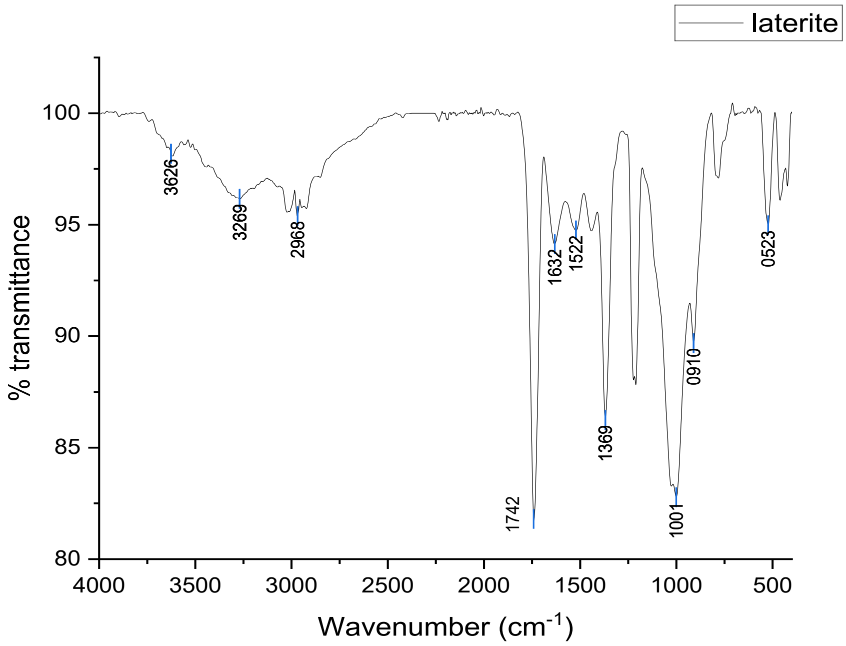


Figure 9: Fourier Transform Infrared spectrum of laterite soil

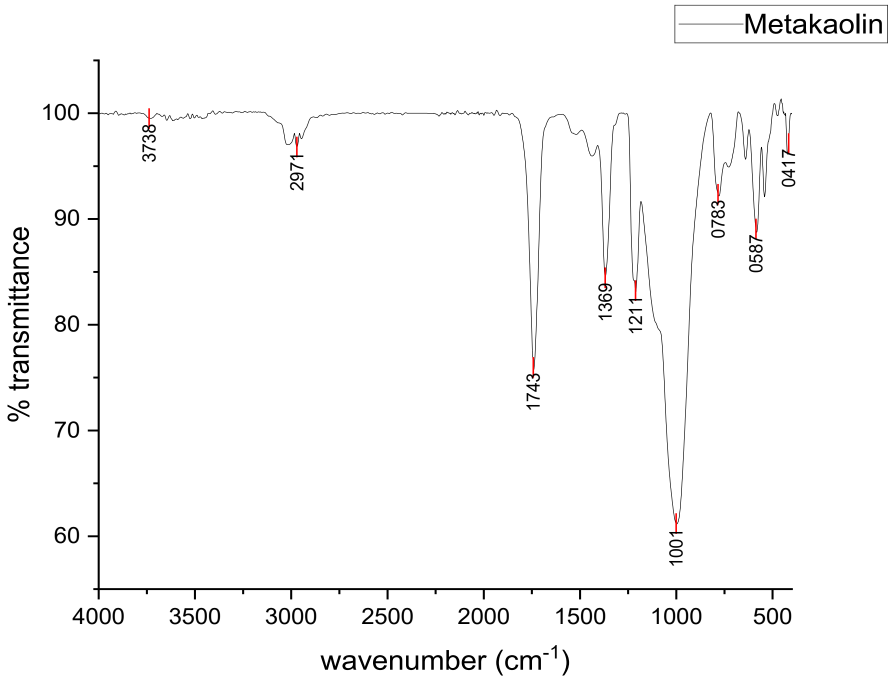
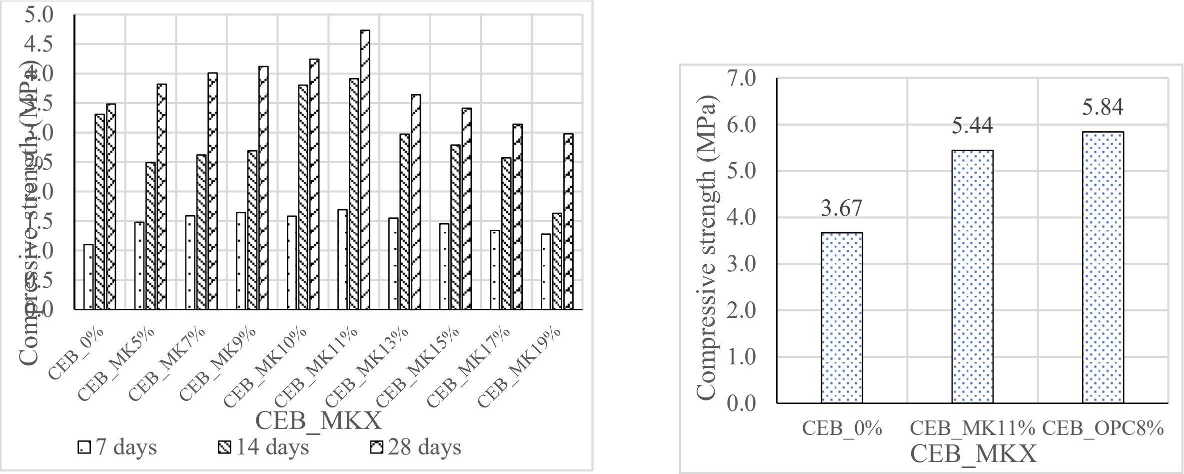


Figure 10: Fourier Transform Infrared spectrum of metakaolin

3.2 Engineering Properties of the Metakaolin-Stabilized Compressed Earth Blocks at 180 days

(i) Compressive strength

At 28 days, the metakaolin-stabilized CEB (CEB_MK11%) exhibited the highest strength (4.73 MPa). This met the minimum requirements of 2.5 MPa as set by the KS 1070 (1993). This value represents a 35.9% increase compared to the control mix (CEB_0%) which achieved a compressive strength of 3.48 MPa (Figure 13a).



(a) Day 7-28 compressive strength

(b) Day 180 compressive strength

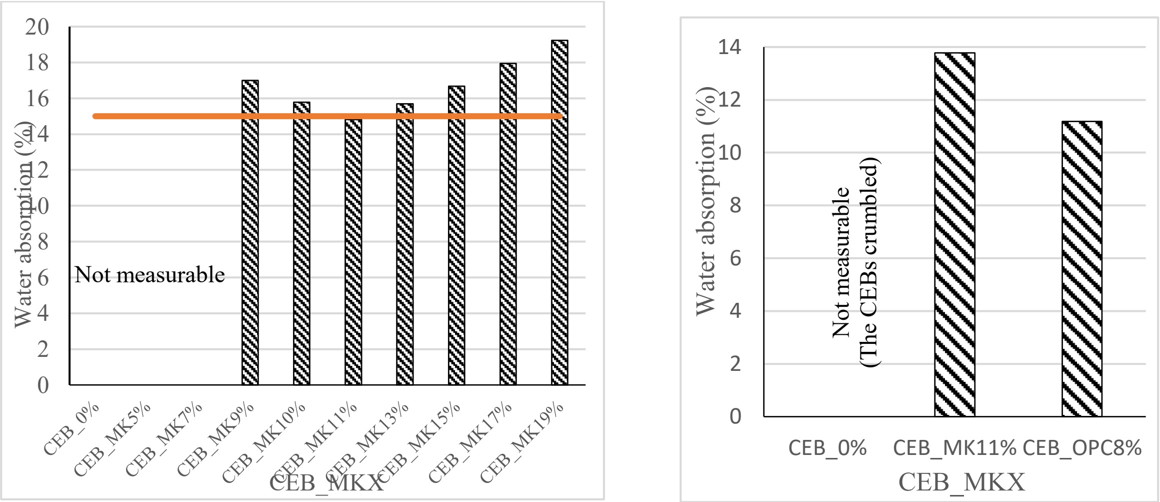
Fig. 11: Compressive strength of CEBs at 180 days

The CEB exhibited continuous increase in compressive strength up to 180 days (Figure 13b). The CEB_0% compressive strength increased to 3.67 MPa, while Compressed Earth Blocks stabilized with 11% Metakaolin further improved to 5.44 MPa, showing a 15.0% gain from its 28-day strength. In comparison, the cement-stabilized mix (CEB_OPC8%) achieved 5.84 MPa, which is 7.4% higher than Compressed Earth Blocks stabilized with 11% Metakaolin at the same age. The 5.44 MPa achieved by Compressed Earth Blocks stabilized with 11% Metakaolin demonstrates that metakaolin stabilization can produce comparable long-term performance while reducing cement use.

As observed in the compressive strength gain trend, metakaolin stabilization significantly enhances both early and long-term strength development. The continued strength gain of Compressed Earth Blocks stabilized with 11% Metakaolin suggests that pozzolanic reactions between metakaolin-laterite soil matrix contribute to long-term strength improvement unlike in un-stabilized CEB.

(ii) Water absorption by immersion

The Water absorption by immersion results at 28 days and 180 days are presented in **Fig** .



(a) 28day water absorption

(b) 180day water absorption

Fig 12: Water absorption of CEBs

The water absorption test results reveal that CEB_0% was highly susceptible to moisture ingress, as the samples crumbled upon exposure to water, making their absorption levels unmeasurable. The water absorption reduced on adding metakaolin up to 11%. The Compressed Earth Blocks stabilized with 11% Metakaolin exhibited an improvement on water absorption from 14.81% on 28-day to 13.77% on

180-day. The CEB_OPC8% blocks recorded an absorption rate of 11.18% on 180-day. These results indicate that metakaolin stabilization of CEBs enhances water resistance over time but remain slightly more permeable than cement-stabilized CEBs. The reduction in water absorption for Compressed Earth Blocks stabilized with 11% Metakaolin can be argued that metakaolin promotes the formation of additional cementitious compounds, leading to a denser and more cohesive microstructure, as evidenced in SEM images shown in Fig. . This helps in mitigating moisture ingress. However, its relatively higher water absorption compared to CEB_OPC8% may be attributed to differences in density and hydration mechanisms. These findings highlight metakaolin's potential as a sustainable stabilizer, improving water resistance while maintaining the structural integrity of CEBs over time.

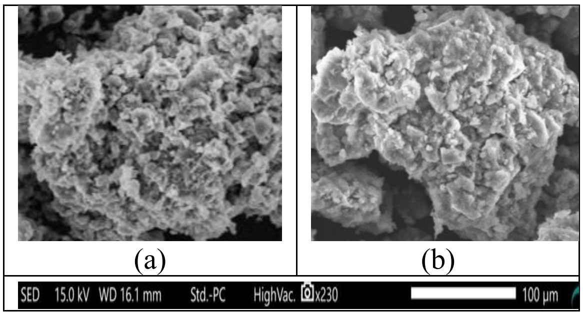

(a)
(b)

***Fig. 13**: SEM images of CEB_MK11% at (a) 28 days and (b) 180 days*

(iii) Water absorption by capillarity

On testing the CEB_0% blocks by capillarity absorption, the particles detached from the bottom and disintegrated quickly upon water exposure. The blocks demonstrated lack of cohesion and high vulnerability to moisture ingress. Due to the rapid degradation of the un-stabilized blocks, the absorption values for CEB_0% were not recordable as the material's structural integrity was compromised before reaching equilibrium.

The initial absorption rate (first 20 minutes) for Compressed Earth Blocks stabilized with 11% Metakaolin and Compressed Earth Blocks stabilized with 8% Cement exhibited a steady but controlled increase in absorption as shown in Figure 16. This indicating the presence of a refined pore structure that slows down water penetration compared to un-stabilized earth blocks. The slightly higher initial absorption rate in Compressed Earth Blocks stabilized with 11% Metakaolin suggests that metakaolin contributes to pore refinement but does not reduce permeability as effectively as cement stabilization.

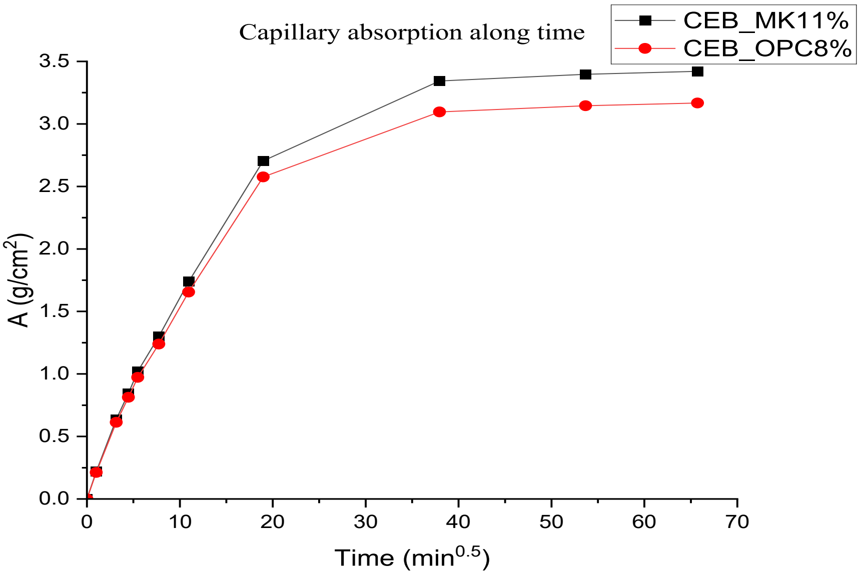


Fig. 14: Capillary absorption along time (72 hours)

The final absorption for CEB_OPC8% blocks depicted a lower absorption value, confirming its superior resistance to moisture ingress due to cement's ability to form a dense, impermeable matrix as observed by (Cruz & Bogas, 2024). Compressed Earth Blocks stabilized with 11% Metakaolin showed slightly higher water absorption than CEB_OPC8% (Figure 16), indicating that while metakaolin stabilization improves moisture resistance compared to un-stabilized blocks, it does not match the impermeability provided by cement.

The findings suggest a trade-off between sustainability and performance. Cement-based stabilization (CEB_OPC8%) provides better pore refinement and moisture resistance, reducing long-term water absorption. On the other hand, metakaolin stabilization (CEB_MK11%) offers environmental benefits while maintaining reasonable durability, though its absorption performance remains slightly higher than cement-stabilized alternatives.

(iv) Abrasion resistance

The abrasion resistance test results indicate that CEB_0% exhibited the lowest abrasion coefficient of 0.35 cm²/g, signifying a high susceptibility to surface wear and material loss. In contrast, Compressed Earth Blocks stabilized with 11% Metakaolin demonstrated a significantly improved abrasion resistance with a coefficient of 2.73 cm²/g, whereas CEB_OPC8% exhibited the highest resistance, with a coefficient of 3.87 cm²/g (Figure 17).

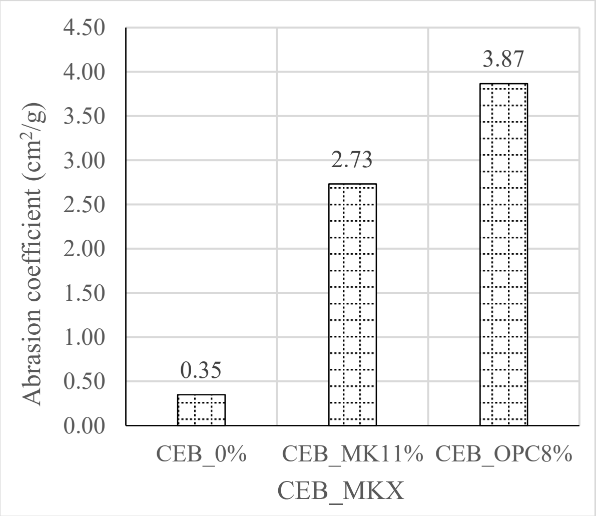


Fig. 15: Abrasion resistance of CEBs at 180 days

The enhanced abrasion resistance of Compressed Earth Blocks stabilized with 11% Metakaolin compared to CEB_0% suggests that metakaolin stabilization improves surface hardness and cohesion by promoting the formation of additional cementitious compounds. However, the slightly lower resistance compared to CEB_OPC8% may be attributed to differences in hydration reactions and the lower density of metakaolin-stabilized CEBs. These findings highlight that while metakaolin contributes to improved durability against surface erosion, cement stabilization remains superior in abrasion resistance. Nonetheless, metakaolin-stabilized CEBs present a viable and sustainable alternative with enhanced wear resistance over un-stabilized blocks.

(v) Erosion resistance (The drip test)

Un-stabilized CEB suffered considerable damage with an erosion depth of 3.8mm, (Fig (a)). On the other hand, both the cement stabilized and metakaolin stabilized CEB did not suffer visible erosion (DE = 0 mm), as shown in Fig (b) and (c). According to Table, extracted from (NZS 4298, 1998) standard, the stabilized CEB fell into the category EI1, while CEB_0% fell in EI2. Therefore, Metakaolin proved to be as effective as OPC under light water erosion. Similar results were reported for un-stabilized and Portland cement stabilized CEBs by (Bogas et al., 2019; Cruz & Bogas, 2024).

(a) CEB_0%   (b) CEB_MK11%   (c) CEB_OPC8%

Fig 16: Surface condition of the block after the drip test

Table 3: Classification of CEB regarding erodibility index (NZS 4298, 1998)

Drip Test	Spray Test	Erodibility index (EI)
DE (mm)	DE/hour (mm/hour)	
0	0 < DE / hour < 15	1
0 < DE < 5	15 < DE / hour < 37.5	2
5 < DE < 10	37.5 < DE / hour < 67.5	3
10 < DE < 15	67.5 < DE / hour < 90	4
15 <= DE	90 <= DE / hour	5 (Not acceptable)

Although no visible erosion was observed in both metakaolin and OPC stabilized CEBs, the moisture depth penetration (DP) varied significantly with the type of SCEB. The depth penetration was 29.5% higher in Compressed Earth Blocks stabilized with 11% Metakaolin (21.1) than in CEB_OPC8% (16.3). This indicated the block's absorptivity under low-pressure conditions, suggesting that its behavior is similar to that identified in capillary absorption. Nevertheless, the DP was less than 90 mm, including that of CEB_0% (23.3), revealing good durability against dripping action, according to NZS 4298 (NZS 4298, 1998).

(vi) Erosion Resistance (The spray test)

When the blocks were tested under a water spray of 0.5 bar pressure to simulate heavy rainfall, the un-stabilized CEBs suffered significant erosion as depicted in Figure 18. CEB_0% were completely eroded (Fig. a) in less than 30 minutes, for an erosion rate of over 200 mm/h (Figure 18a). This indicated that the un-stabilized blocks are not suitable for utilization in outdoor environment. On the other hand, the erosion rate in the metakaolin-stabilized CEBs, Compressed Earth Blocks stabilized with 11% Metakaolin was 38.5 mm/h, falling under erodibility index EI3 as per Table 3. The cement stabilized blocks CEB_OPC8% had an erosion rate of 3.9 mm/h falling under erodibility index EI1. These findings are in line with the study carried out by (Bogas et al., 2019; Cruz & Bogas, 2024). A summary of the properties of the stabilized blocks is as shown in Table 4.

(a) CEB_0% (b) CEB_MK11% (c) CEB_OPC8%

Fig. 17: Erosion pattern of the block after the spray test

Table 4: Average values of some engineering and durability properties of the CEBs at 180 days

Properties	**CEB_0%**	**CEB_MK11%**	**CEB_OPC8%**
Compressive strength, MPa	3.67	5.44	5.84
Dry density (kg / m^3)	1798	1908	1926
Water Absorption by immersion (%)	//	13.77	11.18
Abrasion Resistance (cm^2/g)	0.35	2.73	3.87
DE / DP, for spray test	Fully eroded	38.5 / 92.0	3.9 / 50.5
DE / DP, for drip test	3.8 / 23.3	0 / 21.1	0 / 16.3

DE = Erosion depth, in mm; DP = Moisture depth penetration, in mm;

Overall Conclusion

This study demonstrated that metakaolin-based geopolymer stabilization significantly improves the engineering properties and durability of compressed earth blocks, with 11% metakaolin identified as the optimal content. While not surpassing cement in all aspects, metakaolin provided a sustainable and effective alternative binder, enhancing strength, density, and durability performance of lateritic soil blocks for sustainable construction applications.

Key Findings:

i) The results found that the optimum metakaolin content for stabilising the laterite soil was 11% (CEB_MK11%), as it consistently exhibited enhanced mechanical and durability performance.

ii) At 28 days, Compressed Earth Blocks stabilized with 11% Metakaolin achieved a compressive strength of 4.73 MPa, marking a 35.9% increase compared to non-stabilized CEBs, and surpassing the Kenyan standard requirement of 2.5 MPa. Long-term strength development was evident, with Compressed Earth Blocks stabilized with 11% Metakaolin reaching 5.44 MPa at 180 days, demonstrating the sustained pozzolanic activity of metakaolin. Although slightly lower than the cement-stabilized variant (5.84 MPa), this result affirms metakaolin's potential as a viable alternative to ordinary Portland cement (OPC) in earth block stabilization.

iii) Dry density results indicated a progressive increase with metakaolin incorporation up to 11%, reaching 1908 kg/m^3 at 180 days, signifying enhanced particle packing and microstructural densification. However, excessive metakaolin beyond the optimal level resulted in increased porosity, thereby reducing dry density.

iv) Water absorption tests showed a steady improvement in water resistance over time, with Compressed Earth Blocks stabilized with 11% Metakaolin recording 14.81% at 28 days and reducing to 13.77% at 180 days.

v) The durability assessment further demonstrated metakaolin's beneficial effects. The abrasion resistance of Compressed Earth Blocks stabilized with 11% Metakaolin (2.73 cm^2/g) was significantly superior to non-stabilized CEBs (0.35 cm²/g), indicating improved surface wear resistance.

vi) Compressed Earth Blocks stabilized with 11% Metakaolin stabilised blocks showed progressive mass loss during wetting-drying cycles, exceeding the 15% limit after 5 cycles and reaching 17.18% after 12 cycles, indicating moderate durability loss due to weakened bonding.

vii) In the capillary absorption test, Compressed Earth Blocks stabilized with 11% Metakaolin blocks reached a maximum absorption of 3.42 g/cm², which was slightly higher than CEB_OPC8% of 3.12 g/cm² after 72 hours. Compressed Earth Blocks stabilized with 11% Metakaolin absorbed water faster at early stages, indicating higher capillarity, but both stabilized blocks showed similar trends in water uptake over time.

viii) Erosion drip tests revealed no visible surface erosion for both stabilized CEBs, though moisture depth penetration was 29.5% higher in Compressed Earth Blocks stabilized with 11% Metakaolin (21.1 mm) than in CEB_OPC8% (16.3 mm), suggesting slightly lower water ingress resistance. However, all DP values remained below 90 mm, according to the NZS 4298 (1998) durability standard. Under heavy water spray (0.5 bar), Compressed Earth Blocks stabilized with 11% Metakaolin had an erosion rate of 38.5 mm/h (class EI2), which was higher than that of CEB_OPC8% (3.9 mm/h, class EI1), but far superior to unstabilized CEBs, which eroded completely (>120 mm/h, class EI5)

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