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Research Article

Eco-friendly production of compressed earth blocks with Moroccan pozzolana as a cement alternative

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Abstract

This study explores the potential use of naturally and locally available pozzolana as an eco-friendly alternative to cement in the manufacture of compressed earth blocks (CEBs). Wet granulometric tests were carried out on samples taken from a construction site in Casablanca to determine their appropriateness for CEB production. CEBs were made with different percentages of pozzolana, both used individually and in combination with cement. Soil was treated uniformly through mixing, compaction, and curing, followed by compressive strength tests to determine mechanical characteristics, and X-ray diffraction (XRD) analysis to examine the mineral composition of the samples. The results were encouraging, as the CEBs stabilized with 4% pozzolana achieved higher compressive strength than those stabilized with 4% cement. The XRD results showed that in the soil-pozzolana mixture, significant mineralogical transformations occurred, such as the formation of calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH), which strengthen the soil matrix and improve the compressive strength. Such a finding demonstrates the potential of pozzolana to act as a greener stabilizer in low-load structural applications, partially replacing cement with lowering environmental impact. This work highlights the feasibility of using pozzolana as a sustainable, locally adapted solution for construction.

1. Introduction

As the push for sustainability grows in the field of construction, materials like compressed earth blocks are gaining traction as more sustainable alternatives to conventional building materials [1]. CEBs are made from locally sourced soils and, as such, offer additional advantages by reducing carbon emissions, particularly in resource-scarce regions [2]. While there are environmental and economic advantages in most applications, stabilization processes must be carried out to meet structural requirements. Cement has traditionally played this role; however, its production is energy intensive and emits large quantities of CO_2, which contributes to ongoing ecological issues [3]. Therefore, this calls for ecologically friendly alternatives to cement to mitigate its environmental impacts.

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Consequently, in response to these challenges, several studies have been conducted to reduce the consumption of cement in the manufacture of CEBs. For example, Abdeljebar et al. [4] studied cement replacement with industrial and artisanal lime. In this context, a mixture with 12.5% lime achieved optimal strength. Similarly, the study by Barbaro-Barrera et al. [5] shows that natural hydraulic lime (NHL) with a percentage fluctuating between 3% and 12% significantly improves the compressive strength of CEBs. Other than lime-based stabilizers, the work of Lahbabi et al. [6] , adding bentonite clay from 0% to 20%, identified 10% as the optimum value; this optimum was more pronounced after oven drying the CEBs compared to air drying. Izemmouren et al. [7] examined a combination of natural pozzolana, quick lime, and crushed sand, reporting a notable improvement in mechanical properties with an optimal mixture of 10% lime and 3% pozzolana.

The work of Khadija Annaba et al. [8] also offers insight into pozzolana's role as a cement replacement. She investigated its use in concrete showing that substitution of aggregate with pozzolana led to a loss in compressive strength, whereas substitution of cement with pozzolana produced significant gains in strength. While these results are in accord with the expected behavior of natural pozzolana, its action in CEB stabilization is less clearly understood.

Based on these results, natural pozzolana from Morocco has been confirmed as a sustainable replacement for cement, mainly in regions such as the Middle Atlas and Sefrou, where it is abundantly available (Fig. 1), [9], [10]. The chemical composition of pozzolana, which contains 50–60% silica and 15–20% alumina, along with traces of iron, calcium, and magnesium oxides, makes it particularly suitable for construction applications [11]. Moreover, the study conducted by Danso et al. [12] showed that pozzolana enhances compressive strength, thermal resistance, and durability in construction materials, positioning it as a viable cement replacement. However, its standalone use in compressed earth block stabilization under field-representative conditions has not been extensively studied.

Fig. 1. Habri Middle Atlas mountain in Morocco deposit of Pozzolana [9]

Unlike cement, pozzolana is not considered a binding agent. Nevertheless, it reacts with calcium hydroxide ($Ca(OH)_2$) under aqueous conditions initiating a pozzolanic reaction that produces calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH), which improve the matrix integrity and strength of the material [13]. The use of natural Moroccan pozzolana aligns with global sustainability goals by lowering the carbon footprint of construction materials and offering a cost-effective alternative for eco-friendly projects [14].

This study adopts a simple and practical methodology, unlike many recent approaches that rely on additives or thermal treatments. It uses only natural Moroccan pozzolana without any additive or soil treatment. The pozzolana was crushed and sieved to particle sizes of less than 0.08 mm, then blended with soil and compacted at 2 MPa pressure, which reflects the capacity of portable field presses usually used on site. This lower compaction pressure, compared to the 5 MPa and 8 MPa usually developed in laboratories, ensures that the findings reflect realistic field conditions. The findings presented here offer new insights into the potential of pozzolana as a sustainable, standalone stabilizer for compressed earth blocks, bridging laboratory investigations and practical field applications.

For further investigation into its application, some soil samples were collected from a construction site in Casablanca and analyzed through wet granulometric tests to highlight their suitability and composition. CEBs with different pozzolana ratios, either as a single binder or combined with cement, were produced through mixing, compaction, and curing in accordance with standards. Subsequently, their mechanical performance was characterized through compressive strength tests, and their mineralogical composition was assessed using XRD. Despite these promising findings, the use of pozzolana as a standalone stabilizer in CEBs remains underexplored. While several studies have explored pozzolana as a partial cement substitute in concrete or in combination with other binders for CEBs, limited research has assessed its standalone effectiveness at low dosages (≤6%) under realistic field compaction conditions. Most literature reports focus on high-pressure compaction (≥5 MPa) or high binder content (≥10%), which are not representative of low-resource settings where manual presses are typically used.

This study addresses this gap by evaluating the performance of CEBs stabilized with Moroccan natural pozzolana alone (2% to 6%), using a compaction pressure of 2 MPa and without additives or thermal treatment, reflecting realistic in-situ production practices. It also provides a direct comparison between pozzolana and cement-stabilized blocks under identical conditions. This work contributes new evidence on the viability of low-dose pozzolana stabilization for sustainable construction, offering reduced environmental impact and material cost. Importantly, the simplicity of the method, based on untreated soil, low binder content, and manual compaction, makes it highly scalable and replicable in other regions with similar pozzolanic resources and traditional construction techniques. This enhances its potential as a transferable low-carbon solution for building in resource-constrained contexts worldwide.

2. Materials and Methods

2.1 Materials

The main material used in this study is a soil, sourced from a construction site in Casablanca, Morocco, at coordinates (33.567183, -7.639711), (Fig. 2a). This soil was previously analyzed in depth [15] to understand its properties and suitability for use in compressed earth blocks (CEBs). Classified as a sandy clay loam, the soil has a balanced mix of sand, silt, and clay, which is critical for its performance as a building material. In addition to the soil, this study uses natural pozzolana sourced from Morocco's High Atlas region (Fig. 2b). This volcanic material, rich in minerals, serves as a stabilizer that improves the soil's binding properties. The cement used in this study is a Portland cement (CEM I 42.5 N), conforming to the EN 197-1 standard.

(a) (b)

Fig. 2. (a) Soil from Casablanca; (b) Natural pozzolana

The X-ray fluorescence analysis was performed with a Bruker S2 Ranger spectrometer, providing the chemical composition of the soil and natural pozzolana. The samples were first dried, ground into fine powders, and then pressed into pellets for quantitative analysis. This analysis provided information about the oxide composition of the materials, which is essential for evaluating them as stabilizers in CEBs and for understanding their pozzolanic potential, as summarized in Table 1.

Table 1. Chemical composition of cement, pozzolana and soil.

Oxide	Cement (%)	Pozzolana (%)	Soil (%)
CaO	62.0–67.0	12.13	29.81
SiO_2	19.0–23.0	38.05	36.16
Al_2O_3	4.0–8.0	16.53	16.77
Fe_2O_3	2.0–6.0	15.61	9.51
MgO	0.5–4.0	6.9	2.3
SO_3	2.0–4.0	0.07	0.18
K_2O	0.2–1.3	1.49	2.38
Na_2O	0.2–1.0	2.5	1.2
P_2O_5		0.97	
CI		0.3	0.11
TiO_2		3.85	1.17
CuO		0.49	
ZnO		0.23	
SrO		0.18	
ZrO_2		0.08	0.09
BaO		0.13	
MnO			0.12

2.1.1 Particle Size Analysis

The soil sample was analyzed for particle size following the NF EN ISO 17892-4 standard for wet particle size analysis. The analysis revealed that the soil contains a significant amount of sand (47%), along with 25% silt and 26% clay. As shown in Fig. 3, the soil is suitable for CEB production, as it lies within the lower and upper limits set by CRAterre's guidelines. The gravel content was minimal, at approximately 2%, highlighting that this soil is predominantly a sandy clay loam.

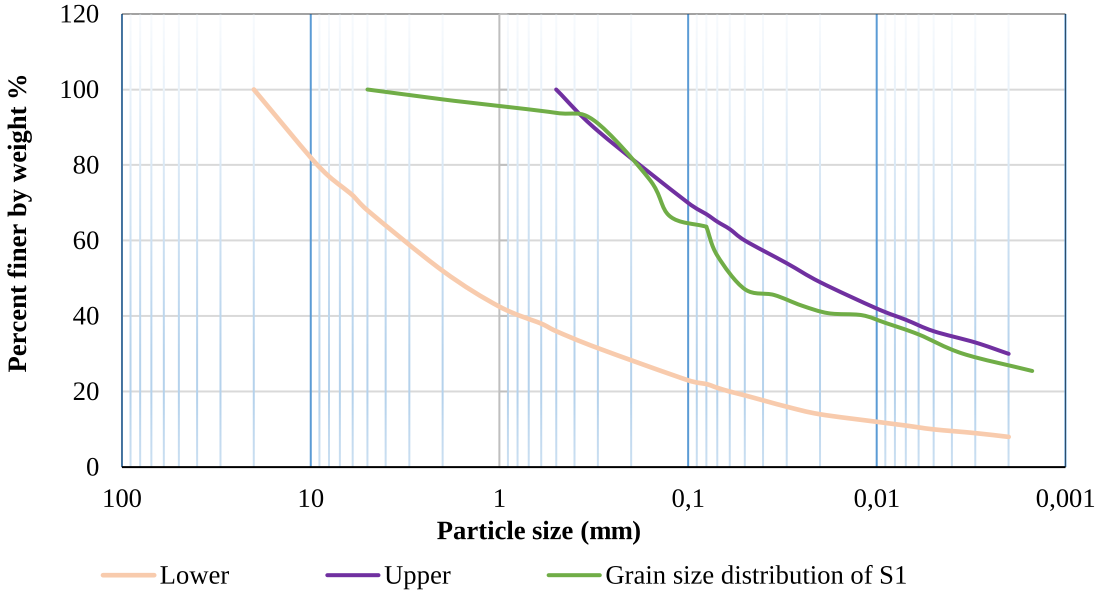

Fig. 3. Sieve analysis of the soil

2.1.2 Atterberg Limits

The Atterberg limits of the soil were measured to assess its plasticity characteristics, in accordance with the guidelines of CRAterre. As shown in Table 2, the soil has a liquid limit (W_l) of 18.2% and a plastic limit (W_p) of 14.8%, yielding a plasticity index (PI) of 3.6, which indicates low plasticity. These properties make the soil well-suited for CEB production, as they suggest a suitable balance of cohesiveness and workability.

Table 2. Results of the Atterberg limits of the soil

	W_l (%)	W_p (%)	Ip = Wl- Wp
Soil	18.2	14.8	3.6

2.1.3 Optimum Moisture Content

A series of compaction tests were conducted on the soil at 2 MPa, as shown in Fig. 4, to determine its optimum moisture content (OMC), which would allow the soil to reach its maximum dry density, following CRAterre's guidelines. By testing different moisture levels, the dry density was found to peak at 12%, establishing this value as the ideal moisture content for the soil, as shown in Fig. 5. Maintaining the moisture level around 12% during CEB production helps achieve the best compaction. To ensure consistency across all mixtures, this same OMC was applied to the pozzolana-stabilized, cement-stabilized, and hybrid mixtures.

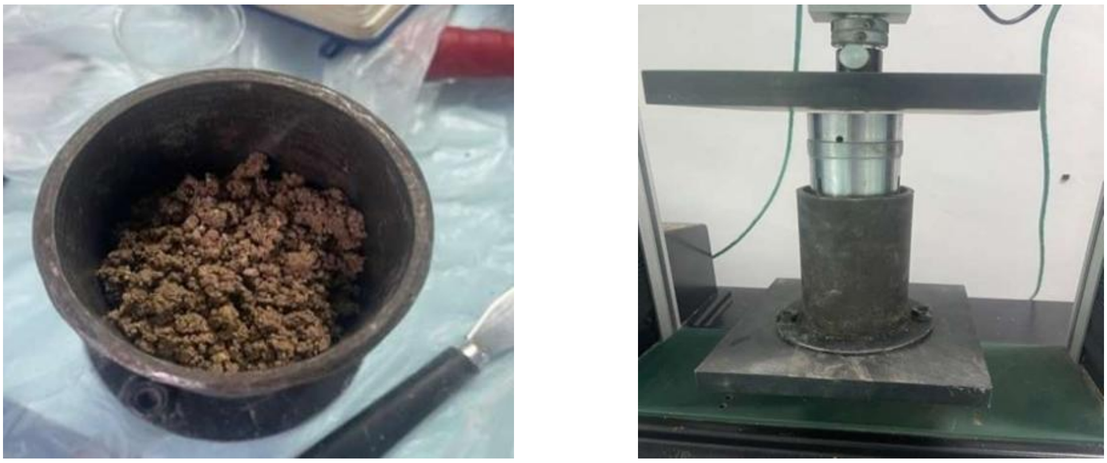

Fig. 4. Experimental set-up of the compaction tests

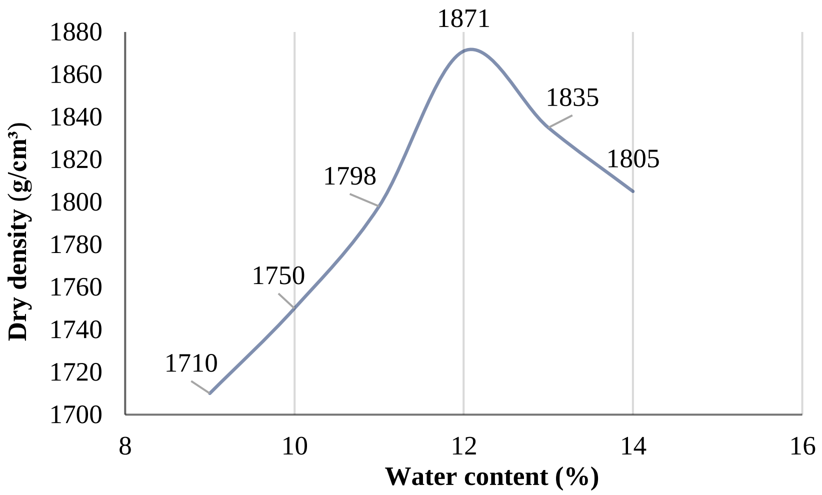

Fig. 5. Changes in dry density as a function of soil water content of the soil.

2.2 Sample Preparation and CEB Production

In this study, we investigate how various stabilization methods affect the compressive strength of compressed earth blocks. We produced three types of samples: CEBs stabilized solely with cement, CEBs with a combination of cement and pozzolana, and CEBs stabilized only with pozzolana. In the following sections, we outline the rationale for each sample type and describe the consistent steps followed for mixing, pressing, and curing.

To enhance pozzolana's reactivity, we finely ground it to ensure it passed through a 0.08 mm sieve, following the work of Khadija Annaba et al. [8]. This fine particle size increases the surface area, which promotes a more complete pozzolanic reaction. This reaction, in turn, strengthens the blocks by forming stable compounds within the soil structure, reinforcing their overall structural integrity [16].

For each sample, we carefully mixed the soil, stabilizers (cement and/or pozzolana), and water to achieve a uniform distribution of stabilizers throughout the mixture. The blended material was then compacted with a compression force of 2 MPa using a standardized mold (Fig. 6a) and a manual hydraulic press (Fig. 6b). After compaction, all samples were subjected to a two-phase curing process to ensure consistent compressive strength results across the different stabilizer combinations. Figure 7 illustrates the different stages of sample preparation and CEB production.

(a)

(b)

Fig. 6. (a) Standardized mold; (b) Manual hydraulic press

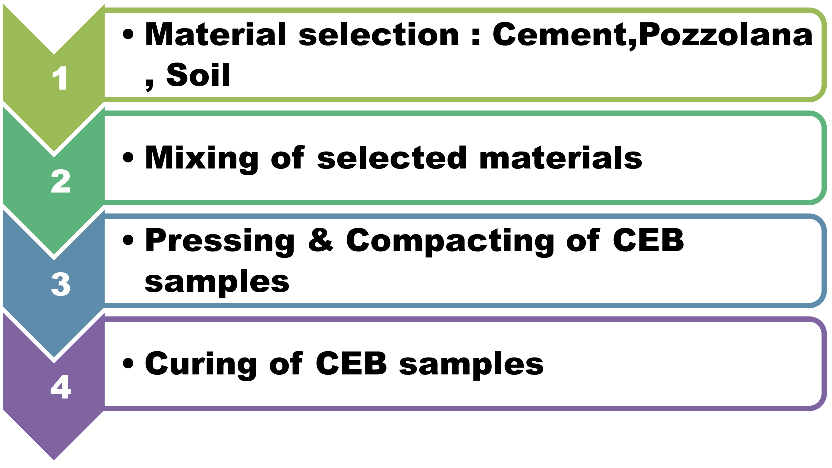

Fig. 7. Process of sample preparation and production of stabilized CEBs

2.2.1 Purpose of Sample Variations

Three types of samples were designed to evaluate how well cement and pozzolana perform as stabilizers, both on their own and in combination:

- Cement-only CEBs: stabilized exclusively with 4%, 6%, and 8% cement by weight, these samples provide a baseline to measure the effectiveness of cement as a commonly used stabilizer.
- Cement and pozzolana stabilized CEBs: pozzolana was added in increments of 1%, 2%, 3%, and 4% to CEBs already containing 4% cement. The approach explores the possibility of small additions of pozzolana to reduce cement usage, while maintaining acceptable strength levels, thereby supporting efforts to minimize the environmental impact of CEBs.
- Pozzolana-only CEBs: stabilized solely with pozzolana in proportions of 2%, 4%, 5%, and 6% by weight. This set was created to assess whether pozzolana alone can provide sufficient stabilization to produce durable, load bearing CEBs.

The composition of the three types of samples was designed to reflect typical application practices, acknowledging the different stabilization mechanisms of cement and pozzolana. Rather than using identical percentage ranges, realistic proportions for each material were selected to gather data about each material and their combined effects on CEB performance.

2.2.2 Mixing Process

The mixing process was standardized across all samples:

- Materials and Mixing Ratios: Cement-only samples used 4%, 6%, and 8% cement by weight (Table 3).

Table 3. Composition of cement-only samples

Specimen	0% cement	4% cement	6% cement	8% cement
Cement mass (g)	0	50	75	100
Soil mass (g)	1250	1200	1175	1150
Water mass (g)	150	150	150	150
Total mass (g)	1400	1400	1400	1400

- For cement-pozzolana samples, the cement content was fixed at 4%, with pozzolana added in increments of 1%, 2%, 3%, and 4% (Table 4).

Table 4. Composition of cement-pozzolana samples

Specimen	4% cement + 1% Pozzolana	4% cement + 2% Pozzolana	4% cement + 3% Pozzolana	4% cement + 4% Pozzolana
Pozzolan Mass (g)	12.5	25	37.5	50
Cement Mass (g)	50	50	50	50
Soil mass (g)	1187.5	1175	1162.5	1150
Water mass (g)	150	150	150	150
Total mass (g)	1400	1400	1400	1400

- Pozzolana-only samples included 2%, 4%, 5%, and 6% pozzolana by weight (Table 5).

Table 5. Composition of pozzolana-only samples

Specimen	2% Pozzolana	4% Pozzolana	5% Pozzolana	6% Pozzolana
Pozzolan Mass (g)	25	50	62.5	75
Soil mass (g)	1225	1200	1187.5	1175
Water mass (g)	150	150	150	150
Total mass (g)	1400	1400	1400	1400

2.2.3 Pressing and Compaction

All CEB samples were prepared using a standardized pressing process:

- Compression force: A compression press set at 2 MPa was used for all samples to ensure consistent block density and mechanical properties.
- Surface preparation: After compaction, each block was surfaced to ensure flat, uniform faces, providing consistent conditions for subsequent compressive strength testing.
- Number of samples and variability: Each sample type was produced in quadruplicate, with the mean value reported and standard deviation tracked for accuracy. The average standard deviation across all results was 0.18, with pozzolana-based samples ranging from 0.06 to 0.15, cement and pozzolana-based samples from 0.06 to 0.18, and cement-based samples from 0.15 to 0.57. This higher standard deviation in cement-stabilized samples may be attributed to increased sensitivity to mixing uniformity, moisture distribution, and curing conditions. As cement content increases, the material's reactivity and density introduce more variability, leading to higher standard deviation values.

2.2.4 Curing Process and Conditions

Curing plays a vital role in strengthening and enhancing the durability of stabilized CEBs, allowing enough time for essential reactions to fortify their structure. Building on previous studies [17], a 28-day, two-phase curing process has proven effective:

- Moisture retention phase (first 14 Days): During this initial phase, the samples were wrapped in plastic to keep them moist, an important step to trigger binding reactions. The retained moisture encourages the formation of calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH), both of which contribute to the blocks' compressive strength [13].
- Air curing phase (second 14 Days): After the moisture retention phase, the blocks were exposed to open air for 14 days under ambient conditions of 19°C and 60% relative humidity. This gradual release of moisture supports continued strength development within the block. Studies show that this phase is beneficial for all types of stabilized CEBs [18].
- This curing strategy aligns with best practices, as it provides ample time for pozzolanic reactions and other bonding processes to complete [19].

2.2.5 Compressive Strength Testing Procedure

After the curing process, compressive strength tests were performed on the prepared CEB samples (Fig. 8) using a Tinius Olsen ST model press (Fig. 9a), specifically designed for composite material testing in compliance with NF P EN 772-1. The press features a double-column frame and optimized platen sizes to accommodate a range of sample geometries. During testing, the press speed was set to 0.5 mm/s (Fig. 9b), as recommended by the standard, to ensure precise and reliable results.

Fig. 8. CEB samples tested during compressive strength tests

The Tinius Olsen press setup included real-time strength monitoring, with load measurements recorded through a connected system to ensure accurate data collection. Each sample was carefully aligned within the press to ensure uniform load distribution and minimize the effects of surface irregularities. This method, consistent with international standards, provided a controlled environment for consistently assessing the compressive strength of the CEB samples.

(a) (b)

Fig. 9. (a) Compression press and strength monitoring; (b) Compression test on a compressed earth block specimen

2.2.6 X-ray Diffraction Analysis

X-ray diffraction (XRD) was used to determine the mineralogical composition of the samples. Following established protocols, the samples were powdered, pressed into flat pellets, and analyzed under standard XRD settings to ensure accurate and reproducible phase identification [11], [20].

3. Results and discussion

This section presents the compressive strength and XRD analysis results for compressed earth blocks (CEBs) stabilized with either cement alone, a pozzolana-cement combination, or pozzolana alone. By comparing these results with cement-only samples used as the baseline, we assess the effectiveness of pozzolana as an alternative stabilizer. The aim is to determine the optimal stabilizer mix that delivers both structural strength and environmental benefits. This analysis provides insights into how different stabilizer combinations influence the compressive strength and overall performance of CEBs. A one-way ANOVA and Welch's t-test were conducted to verify the statistical significance of the observed trends. Additionally, a cradle-to-gate life cycle assessment (LCA) was carried out to compare the embodied carbon of pozzolana- and cement-stabilized blocks.

3.1 Compressive Strength Results

3.1.1 Compressive Strength of Cement Only

The compressive strength of CEBs stabilized only with cement was tested with four different cement contents: 0%, 4%, 6%, and 8%. These tests were conducted until the sample failed (Fig. 10). The stress-displacement curves recorded during the tests are presented in Fig. 11. The shape of these curves offers insight into the evolving failure behavior. Specimens with lower cement content (0% and 4%) exhibit more gradual post-peak decline, indicating a ductile failure mechanism with progressive deformation. In contrast, specimens with higher cement content (6% and 8%) show a sharper peak followed by a steeper drop, characteristic of brittle failure. This transition from ductile to brittle behavior reflects the increase in stiffness and internal cohesion imparted by the cement, which enhances strength but reduces deformability.

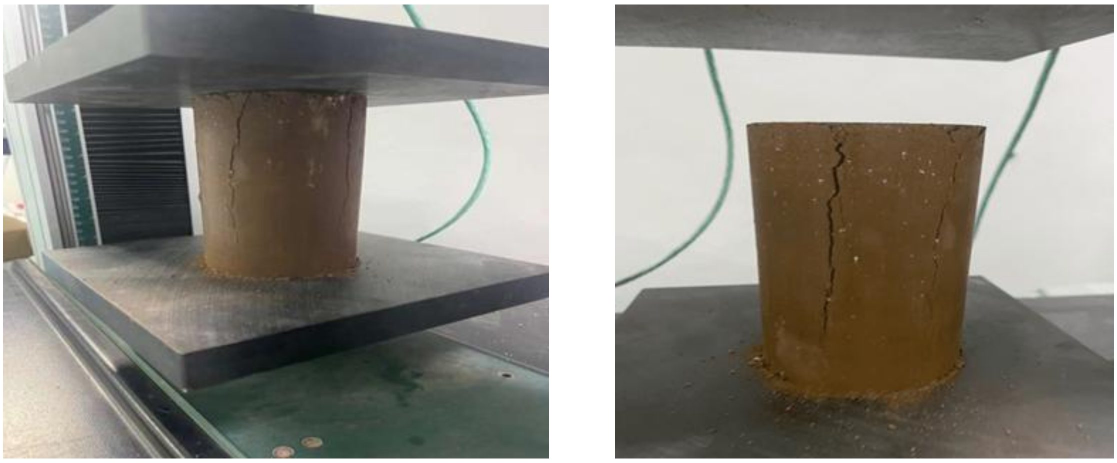

Fig. 10. Images of CEBs stabilized after compressive strength tests

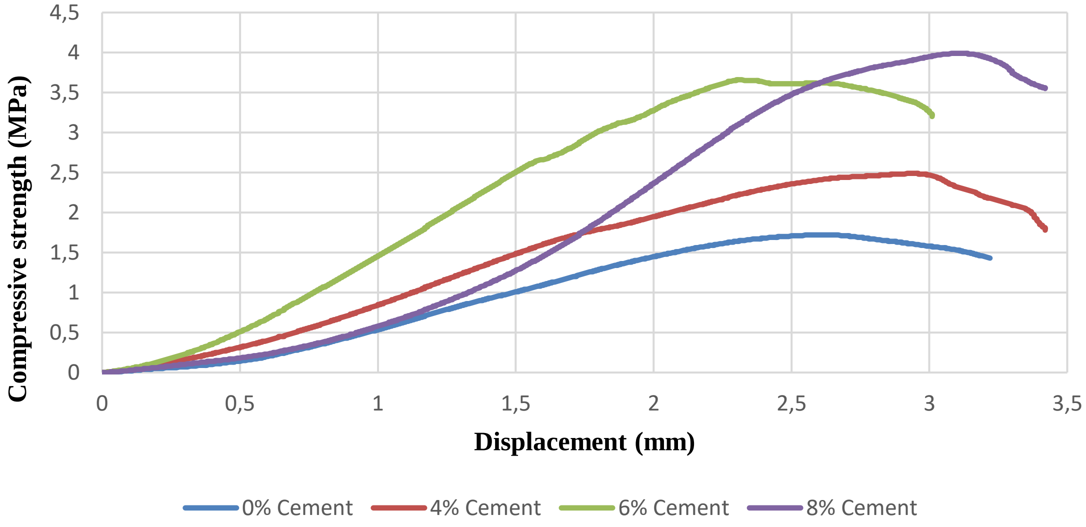

Fig. 11. Typical recorded stress-displacement curves during compressive strength of CEB with cement

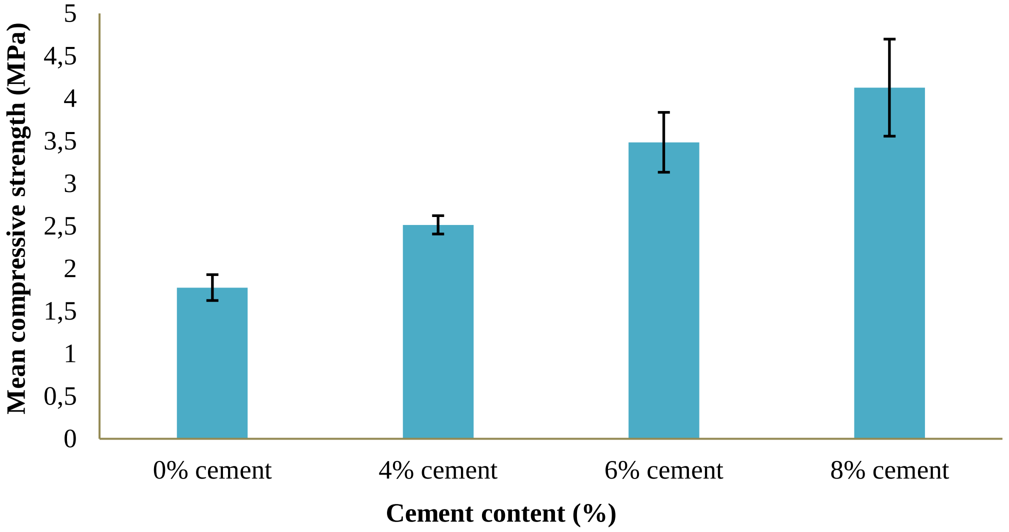

Fig. 12. Mean compressive strength of CEBs at different cement percentages. Error bars represent the standard deviation based on n = 4 specimens per mixture

The results in Fig. 12 below clearly show that the strength increases with the increase in cement content. The strength at 4% cement is 2.52 MPa, an increase of 42% from 0% cement. The strength goes up to 3.49 MPa with 6% cement, showing a 96% increase. When the cement content reaches 8%, the strength peaked at 4.13 MPa, a 132% increase compared to the blocks without cement, which had a strength of 1.78 MPa. To provide a comprehensive overview of the compressive strength performance across different stabilizer compositions, the results of the cement-only mixtures will be used as a baseline.

3.1.2 Compressive Strength of CEB with Cement and Pozzolana Combination

The compressive strength of CEBs stabilized with a combination of 4% cement and varying percentages of pozzolana (1%, 2%, 3%, and 4%) was measured to assess the impact of mixed stabilizers on mechanical performance. The stress-displacement curves recorded during testing are shown in Fig. 13.

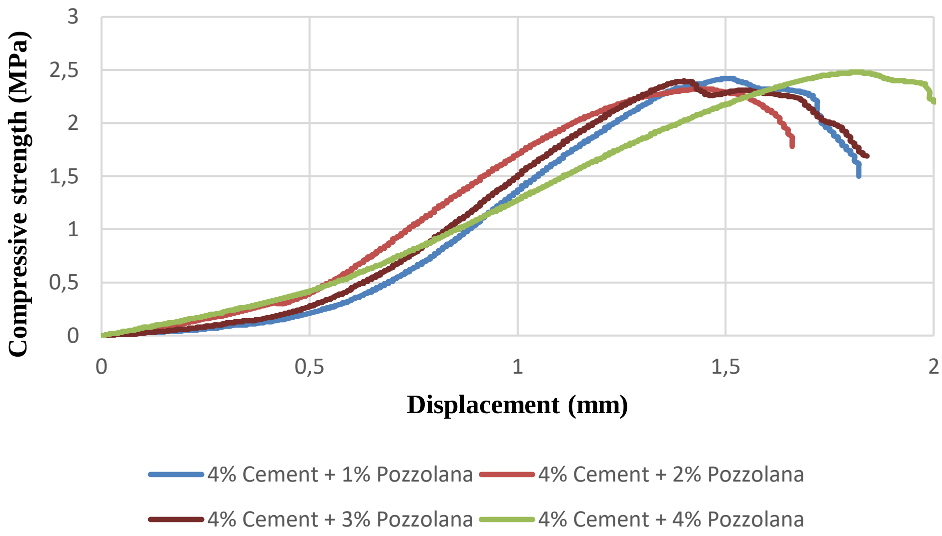

Fig. 13. Typical recorded stress-displacement curves during compressive strength testing of CEB with cement and pozzolana

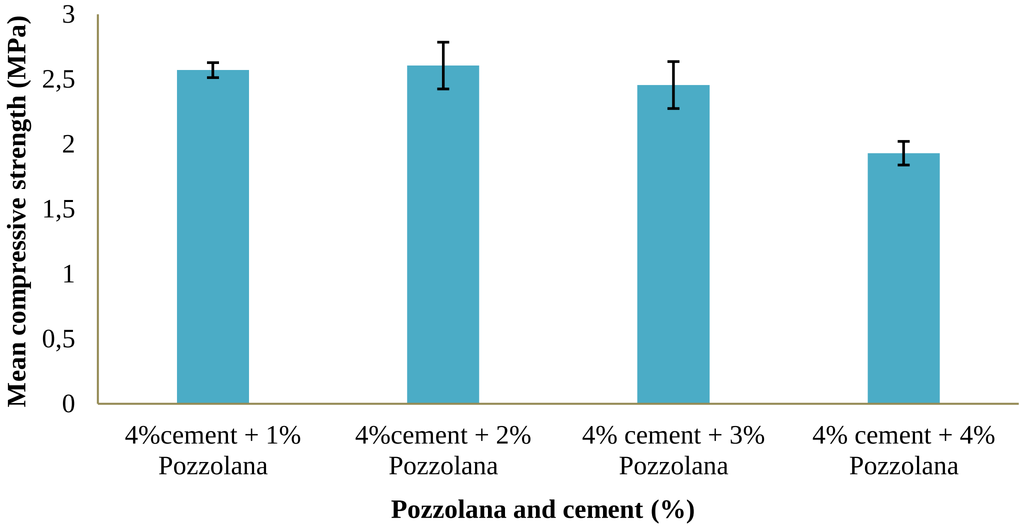

Fig. 14. Mean compressive strength of CEBs at different cement pozzolana compositions, error bars represent the standard deviation based on n = 4 specimens per mixture

Figure 14 presents the mean compressive strength along with the standard deviation for each cement and pozzolana combination. The results show that different ratios impact block strength, with the highest compressive strength achieved at the 4% cement + 2% pozzolana mix. A noticeable decline in strength is observed as the pozzolana content increases beyond this point.

The results suggest that adding small amounts of pozzolana (1% and 2%) to a 4% cement base slightly improves compressive strength. The highest average value of 2.61 MPa was obtained with the 4% cement + 2% pozzolana mix, representing a modest gain over the 4% cement-only sample. As pozzolana content increased to 3% and 4%, compressive strength declined to 2.46 MPa and 1.93 MPa, respectively. When compared to the cement-only baseline (Fig. 15), these findings indicate that low pozzolana additions can enhance performance, while higher proportions reduce it. This confirms the potential of pozzolana to partially replace cement when used in appropriate amounts. The initial strength gain may be explained by complementary chemical reactions: cement hydration releases calcium ions (from C_3S and C_2S), while pozzolana supplies reactive silica and alumina, enabling the formation of additional calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) gels. However, the decline in strength at higher dosages is likely due to pozzolana saturation effects, as discussed later and supported by similar trends in natural pozzolana systems [21].

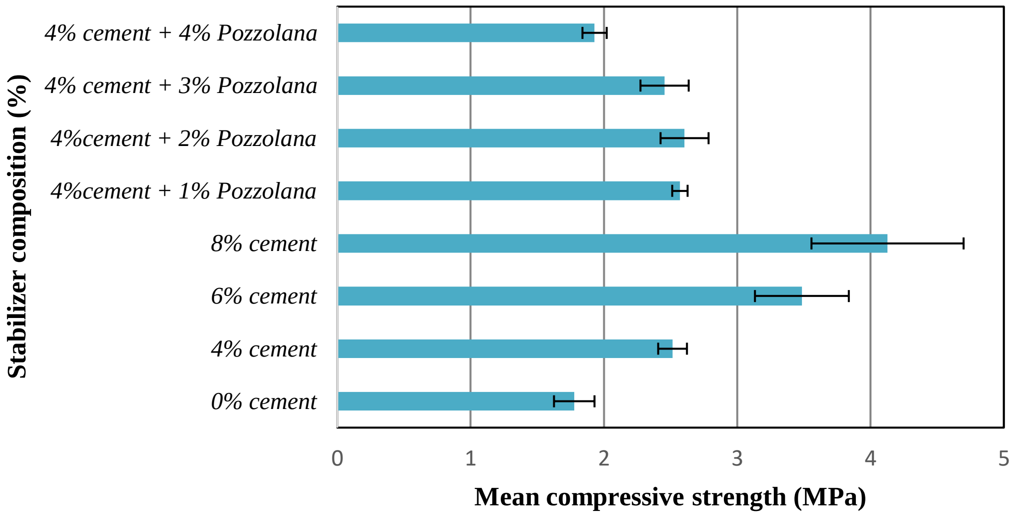

Fig. 15. Comparison of the mean compressive strength of CEBs stabilized with different pozzolana percentages, pozzolana–cement blends, and cement only. Error bars represent the standard deviation based on n = 4 specimens per mixture

3.1.3 Compressive Strength of CEB with Pozzolana Only

The compressive strength of CEBs stabilized solely with pozzolana was assessed for different pozzolana percentages: 2%, 4%, 5%, and 6%. The stress-displacement curves recorded during the tests are shown in Fig. 16.

Figure 17 presents the mean compressive strength and the standard deviation for each pozzolana percentage. It highlights how different levels of pozzolana affect the strength of the blocks, with a peak strength observed at 4% pozzolana and a decline at higher percentages.

These mechanical trends are visually supported by the failure modes shown in Fig. 18. At 2% pozzolana, cracks are moderate and localized, reflecting limited binder interaction. At 4%, the specimen maintains better cohesion with narrower, more controlled cracking, consistent with peak compressive strength. At 6%, extensive and dispersed cracking is evident, aligning with the observed reduction in strength and indicating a loss of internal bonding due to excess pozzolana.

At 4%, pozzolana achieved its highest compressive strength (2.7 MPa), slightly exceeding that of 4% cement (2.52 MPa) and outperforming unstabilized blocks by 52%. However, pozzolana strength declined beyond 4%, while cement performance continued to improve, reaching 3.49 MPa at 6% and 4.13 MPa at 8% (Fig. 19). This contrast highlights pozzolana's efficiency at low contents, but also reveals its saturation limit, unlike cement which benefits from higher dosages.

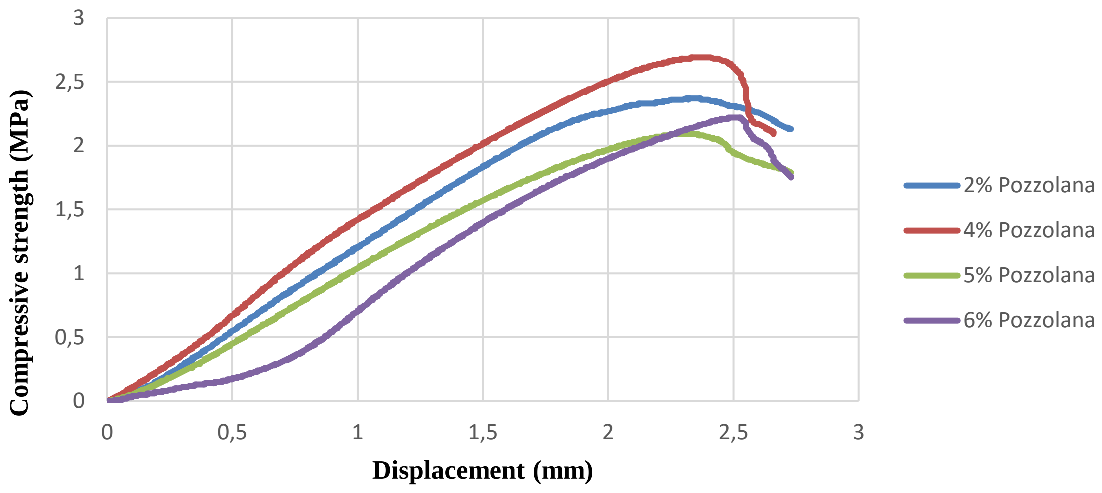

Fig. 16. Typical recorded stress-displacement curves during compressive strength testing of CEB with pozzolana only

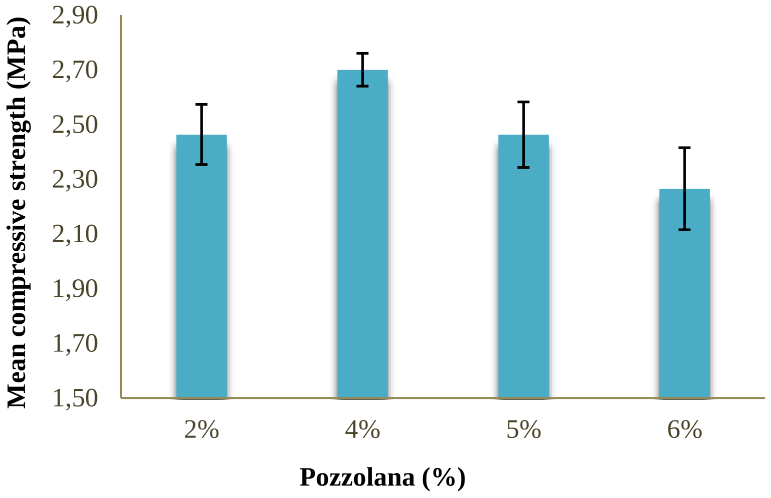

Fig. 17. Mean compressive strength of CEBs at different pozzolana percentages. Error bars represent the standard deviation based on n = 4 specimens per mixture

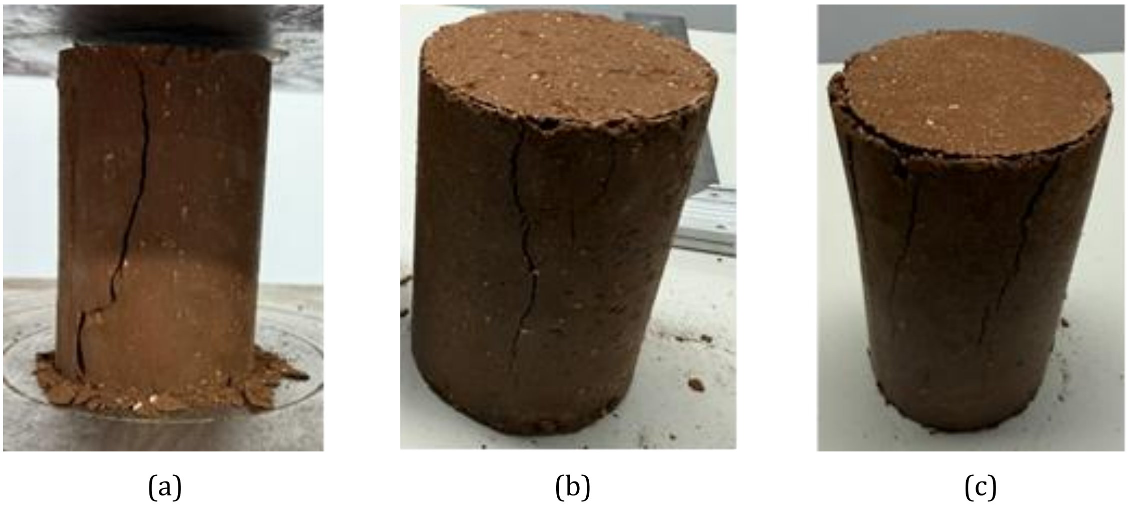

Fig. 18. Failure modes of pozzolana-stabilized CEBs. (a) 2% pozzolana; (b) 4% pozzolana; (c) 6% pozzolana

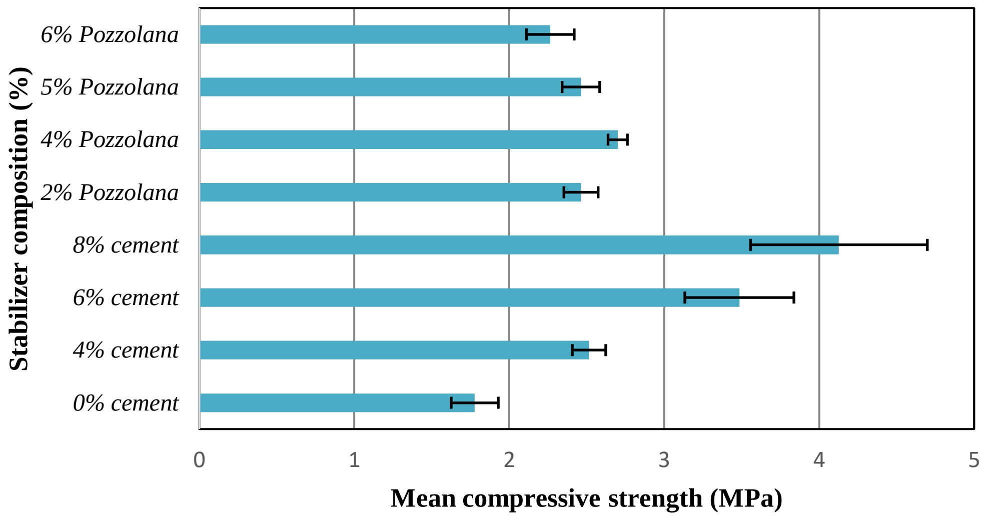

Fig. 19. Comparison of the mean compressive strength of CEBs at different pozzolana percentages and cement-only samples. Error bars represent the standard deviation based on n = 4 specimens per mixture

This diminishing performance beyond 4% pozzolana aligns with findings from Bahadori et al. [21] and Nshimiyimana et al. [22], who also attributed strength loss at higher pozzolana dosages to incomplete reactions and matrix dilution due to an excess of reactive material. The findings of this study align with previous research on natural pozzolana; however, comparable results were attained using significantly reduced stabilizer contents and lower compaction pressures. For instance, Danso et al. [23] reached 3 MPa using 20% clay pozzolana at 5 MPa, whereas this study achieved 2.7 MPa with only 4% pozzolana and 2 MPa pressure. Similarly, Lechheb et al. [24] and Turco et al. [25] reported strengths below 2.6 MPa using 5% cement, lime, or other binders, demonstrating that natural pozzolana can match or surpass traditional stabilizers under milder conditions. Bouassria et al. [26] also reported that cement contents exceeding 7% were needed to achieve comparable strengths for various Moroccan soils. These comparisons highlight pozzolana's efficiency, lower environmental footprint, and potential to reduce cement use in sustainable construction.

The pozzolanic activation process in raw soil environments is generally slow due to low alkalinity and benefits from extended curing. As observed by Bahadori et al. [21], increased volcanic ash content and longer curing durations significantly improve strength development through gradual formation of CSH and CAH. While the current results at 28 days are already promising, extended curing is expected to further enhance mechanical performance. This trend was also confirmed by Harichane et al. [27], who reported that the strength of clayey soils stabilized with natural pozzolana and lime increased significantly between 28 and 90 days, underscoring the importance of longer-term pozzolanic reactions. Overall, these findings confirm that natural pozzolana competes well with conventional stabilizers and offers a viable, lower-impact solution for sustainable construction.

3.1.4 Statistical Analysis of Compressive Strength Results

To determine whether the differences in compressive strength across the various stabilizer types and dosages were statistically significant, a one-way ANOVA was conducted. The analysis included twelve groups: four cement-only mixtures (0%, 4%, 6%, and 8%), four pozzolana-only mixtures (2%, 4%, 5%, and 6%), and four hybrid mixtures combining 4% cement with 1% to 4% pozzolana. Each group consisted of four replicate specimens.

The ANOVA yielded a highly significant result: $F(11, 36) = 31.68$, $p < 0.0001$, indicating that the observed differences in mean compressive strength are unlikely to be due to random variation and are attributable to the type and dosage of stabilizer.

To assess whether the slight difference in compressive strength between the 4% pozzolana and 4% cement mixtures was statistically meaningful, an independent Welch's t-test was performed. Although both mixtures exhibited comparable mean strengths, the test confirmed that the 4% pozzolana formulation performed significantly better than the 4% cement one: $t(4.73) = 3.56$, $p = 0.015$. The non-integer degrees of freedom reflect Welch's adjustment for unequal variances. This result reinforces the conclusion that pozzolana, even at low dosages, can outperform cement as a stabilizer, not only in average strength but also in statistical reliability, highlighting its potential as a sustainable alternative.

These statistical findings reinforce the experimental trends and provide quantitative evidence that pozzolana, even at low dosages, is a viable and effective stabilizer. They also strengthen the case for the environmental benefits of replacing cement with locally sourced pozzolana in compressed earth blocks.

3.2 X-Ray Diffraction Results

3.2.1 XRD analysis of the Soil

The XRD analysis of the soil sample (Fig. 20) shows that the mineral composition is primarily quartz (Q) which helps maintain its structural integrity and supports its classification as a sandy clay loam. The presence of chlorite (Ch) reflects a clay-rich fraction that improves the plasticity and moisture retention of the soil. Dolomite (D) and calcite (C) indicate the presence of carbonate-bound calcium which may influence the soil's alkalinity and reactivity. Moreover, the broad background signal suggests the presence of some amorphous component, likely consisting of poorly crystalline clays or organic matter, which may enhance the pozzolanic activity potential.

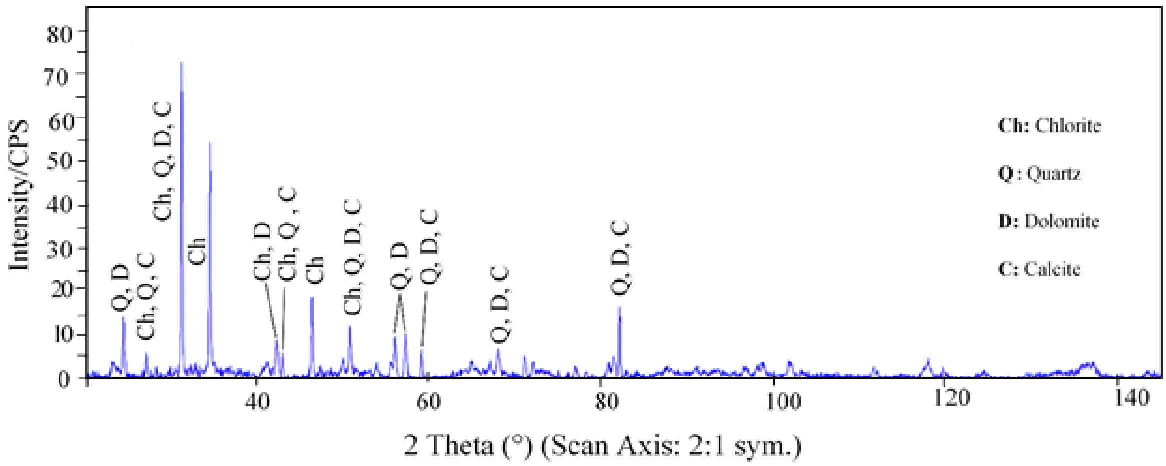

Fig. 20. Diffractogram of the soil only

3.2.2 XRD analysis of the Pozzolana

The X-Ray diffraction analysis of the pozzolana sample (Fig. 21) highlights its volcanic origin and high mineralogical activity. Key findings include the presence of crystalline silica (eg. quartz) and feldspar, typical of volcanic materials; alumina-rich minerals such as zeolites or pumice, which indicate pozzolana's reactivity potential, and a complex diffraction pattern that reflects a mix of reactive and inert phases.

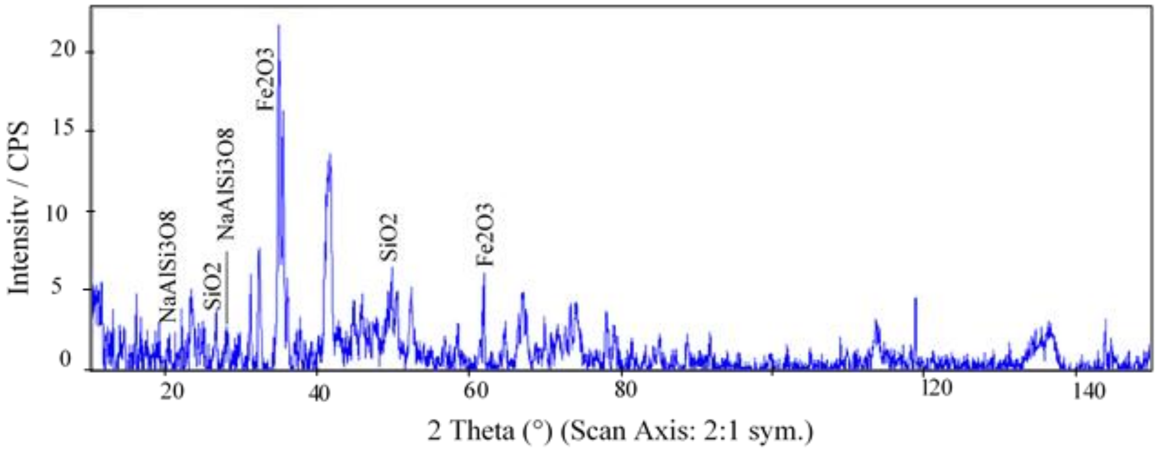

Fig. 21. Diffractogram of the natural pozzolana

3.2.3 XRD analysis of the Soil and Pozzolana Mixture

The XRD analysis of the soil and pozzolana mixture (Fig. 22) reveals combined features of both components along with indications of new reaction products, such as the formation of new peaks beyond 80° 2θ. Key observations include the presence of quartz peaks, consistent with earlier soil findings. The possible formation of calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH) is also noted, as these compounds contribute to improved compressive strength. Moreover, the pozzolana-related peaks are visibly reduced, suggesting that reactive silica and alumina were consumed during pozzolanic reactions. Based on the chemical composition shown in Table 1, the pozzolana provides a significant amount of reactive silica (SiO_2) and alumina (Al_2O_3), while the soil contains calcium (CaO) and dolomite ($CaMg(CO_3)_2$) as a mineral source. Under moist curing conditions, dolomite can slowly dissolve and release Ca^{2+} ions into the system. These ions contribute to the formation of cementitious gels (CSH, CAH, and possibly C-A-S-H), which enhance interparticle bonding and contribute to a denser microstructure. This interpretation aligns with findings from Bahadori et al. [21], who observed similar phase formation and performance enhancement in pozzolana-stabilized marl soils. It is important to note that this XRD analysis remains qualitative; no phase quantification was performed. Future work will incorporate quantitative XRD (QXRD) or Rietveld refinement to better assess the extent of pozzolanic reactions.

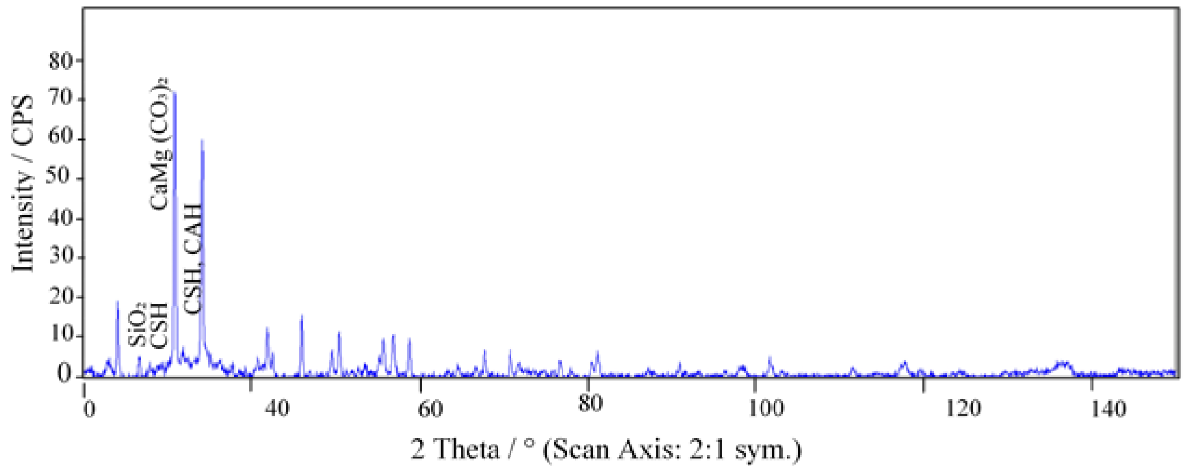

Fig. 22. Diffractogram of the soil stabilized with natural pozzolana

A broad comparison of the mechanical and mineralogical results reveals significant differences among various mixtures. CEBs with cement demonstrated a consistent rise in compressive strength as the cement content increased, underscoring its effectiveness as a stabilizer. Conversely, CEBs made exclusively with pozzolana achieved peak strength at 4%, with reduced performance at higher contents, likely due to limited availability of calcium ions and dilution of the binding matrix. Mixtures combining 4% cement with 1% and 2% pozzolana showed modest synergistic strength gains. These patterns underscore the critical role of stabilizer selection and dosage in governing both the mechanical behavior and mineralogical development of CEBs.

To facilitate mineralogical comparison, key phases identified in each sample type are summarized in Table 6. The appearance of CSH and CAH in the pozzolana-stabilized mixture confirms active pozzolanic reactivity, supported by the consumption of amorphous silica and alumina from pozzolana in the presence of calcium-rich soil components.

Table 6. Summary of key mineral phases identified by XRD in soil, pozzolana, and stabilized soil

Sample	Major Mineral Phases Identified	Notes / Implications
Soil only	Quartz (SiO_2), Chlorite, Dolomite, Calcite	Silica-rich, moderate clay content, carbonate-bound Ca source
Pozzolana only	Quartz (SiO_2), Feldspar ($NaAlSi_3O_8$), Fe_2O_3	Volcanic origin; reactive silica and alumina present
Soil + Pozzolana mix	Quartz (SiO_2), CSH, CAH, $CaMg(CO_3)_2$ (Dolomite)	New phases (CSH/CAH) confirm pozzolanic reaction in matrix

3.2.4 Embodied Carbon Comparison of Pozzolana and Cement only Stabilized CEBs

Embodied carbon refers to the total CO_2 emissions associated with the process of material extraction, processing, and transport [28]. A cradle-to-gate life cycle assessment (LCA) was conducted to compare CEBs stabilized with 4% pozzolana and 4% cement, as these formulations exhibited comparable compressive strength. The LCA follows ISO 14040:2006 standards and includes emissions from raw material sourcing and transport, specifically 80 km for cement and 200 km for pozzolana. These transport distances were selected to reflect typical local supply chains but may vary in other geographic or infrastructural contexts, potentially affecting total emissions.

Cement production emits approximately 507 kg CO_2 per ton, primarily due to energy-intensive processes such as limestone calcination and clinkerization [29]. Pozzolana, which does not undergo calcination, has a much lower footprint: 4.5 kg CO_2/t from extraction and transport, 1.8 kg CO_2/t from drying, and 1.84 kg CO_2/t from grinding [30], [31]. As shown in Table 7, this results in a total of 20.3 kg CO_2/t for 4% cement-stabilized CEBs versus only 0.33 kg CO_2/t for pozzolana-stabilized ones, representing a reduction of approximately 98% in embodied emissions while maintaining equivalent structural performance.

Table 7. Comparison of CO_2 Emissions Between Cement- and Pozzolana-Stabilized CEBs.

Parameter	4% Cement only CEBs	4% Pozzolana only CEBs	% Reduction
Stabilizer (kg/ton of CEBs)	40	40	
CO_2 Emissions (kg CO_2/t)	507 [29]	8.14 [30], [31]	-
CO_2 Emissions (kg CO_2/t)	20.3 kg	0.33 kg	98 %

This cradle-to-gate analysis excludes operational use and end-of-life stages. To fully evaluate the environmental impact, future studies should adopt a cradle-to-grave scope, which would further explore pozzolana's role in circular construction [32]. Although the environmental benefits are clear, this study does not provide a detailed cost analysis or an availability assessment of pozzolana's regional availability. These aspects are crucial to confirm its viability as a truly affordable and accessible alternative and should be integrated into subsequent investigations.

4. Conclusion

The current study shows that natural pozzolana, a readily available regional resource, is a sustainable and effective alternative to cement for the stabilization of compressed earth blocks (CEBs). Used in suitable proportions, pozzolana significantly increases the compressive strength of CEBs, as a 4% mix using only pozzolana reached strength higher than the blocks stabilized with 4% cement. This implies that pozzolana has strong potential to serve as an applicable environmental alternative in low-load applications, helping to reduce the environmental impact of traditional cement use.

XRD analysis confirmed mineralogical transformations in the soil-pozzolana mixture, including the formation of calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH), which contribute to improved matrix integrity and strength. However, this study focused solely on compressive strength. Additional durability-related properties, such as bulk density, water absorption, porosity, and erosion resistance, were not evaluated. These are essential to fully assess the long-term performance and resilience of pozzolana-stabilized CEBs. Future studies will investigate these parameters in detail, with particular attention to moisture uptake rates and their long-term effects on structural integrity.

Moreover, our future research scope will include extended curing periods beyond 28 days, environmental exposure testing under field conditions, and a comprehensive economic analysis of pozzolana availability and processing costs. This broader approach will help validate pozzolana's viability across technical, environmental, and financial dimensions.

Furthermore, the mix containing 4% cement and 2% pozzolana achieved marginally higher strength than the 4% cement-only mixture, suggesting potential for partial cement replacement without compromising mechanical performance.

Overall, the findings support the increased use of pozzolana as a partial or total substitute for cement in contexts where reducing carbon emissions is a priority. Studies like this contribute to advancing our understanding of pozzolana as a key material in the development of durable, climate-resilient, and low-carbon construction practices.

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