

Soil stabilisation with quicklime: influence of lime content and thermal treatment on strength development

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Abstract:

This research addresses the field of sustainable construction materials, with particular emphasis on the manufacture of stabilised adobe intended for low-rise buildings and rural housing. It aims to optimise soil stabilisation by adding quicklime, identifying the optimal conditions of lime dosage and controlled thermal curing in order to enhance the mechanical performance of earthen construction materials. The soil was first sieved to 2 mm and then dried at 65 ± 2 °C for 24 hours to ensure initial homogeneity. Standardized prismatic specimens ($4 \times 4 \times 16$ cm³) were prepared with different lime contents (3%, 5%, 7%, 9%, 11%, 13%, and 15% by dry soil weight) and subjected to curing durations of 3, 7, and 11 days in an oven at 65 °C. The adopted factorial experimental approach enabled evaluation of the interaction between lime dosage and curing duration. The natural soil water content was estimated at 21.35%, based on the liquid and plastic limits. For each formulation, the mixing water content was adjusted according to the percentage of lime incorporated, in order to maintain a consistent water-to-binder ratio and to ensure adequate lime hydration as well as a homogeneous distribution within the soil matrix. Mechanical performance was assessed using uniaxial compression tests.

Keywords:

soil stabilisation, quicklime, experimental optimisation, oven curing, thermal curing

1. Introduction

Soil stabilisation is an essential step in civil engineering construction, which aims to improve the mechanical performance and durability of soils. Among the available techniques, the use of mineral binders, particularly lime, is widely adopted due to its effectiveness in reducing plasticity, increasing strength, and improving volumetric stability. However, the results strongly depend on parameters such as lime dosage and curing conditions. The optimisation of these parameters is crucial to ensure high performance and practical application in construction. For instance, Guettala et al. 2006 [1] emphasised the need to improve the durability of compressed earth blocks when exposed to unfavourable climatic conditions. Likewise, Izemmouren et al. [2] used quicklime and natural pozzolana to stabilise compressed earth blocks by preparing samples with various dosages of quicklime and curing in steam in order to accelerate pozzolanic reactions. Subsequently, the mechanical properties of the samples were tested in the laboratory, and the results showed that the quicklime–pozzolana combination, especially with steam curing, significantly improved the strength and durability of raw earth blocks. Taalaha et al. [3] investigated compressed earth blocks stabilised with quicklime and reinforced with date palm fibres. Despite an alkaline treatment, the fibre/matrix adhesion

remained limited. The blocks exhibited slight mechanical improvement, a reduction in thermal conductivity and density, and an increase in capillary absorption. Alil [4] prepared mortars based on lime and brick dust, which reduce shrinkage, enhance mechanical strength, and ensure good compatibility with ancient substrates. Layachi [5] designed lightweight earth blocks stabilised with lime and incorporating expanded polystyrene (EPS) beads. Lime ensured cohesion and durability of the earthen matrix, while EPS improved thermal insulation. The study highlighted a trade-off between increased thermal performance and reduced mechanical strength, while also lowering energy and environmental impacts. Some researchers also used cement as a hydraulic binder. Dao et al. [6] stabilised adobes with cement (up to 12%), which resulted in high mechanical strength and good durability in humid environments, as a result of the rapid formation of cementitious products (C-S-H, C-A-H). The present research aims to optimise lime stabilisation of soils by adding quicklime, determining the optimal dose under controlled curing conditions [7]. It is hoped that the outcome of this study will provide a basis for the development of sustainable solutions in the field of stabilised construction materials.

2. Methodology

2.1. Materials used

The materials used in this study consisted primarily of natural soil and quicklime. The natural soil served as the base material for analysis, while quicklime was employed as the stabilising binder. Prior to use, the soil was pretreated to ensure homogeneity. Quicklime, owing to its high reactivity and stabilising potential, was selected to improve the engineering characteristics and overall stability of the soil mixture.

2.2. The soil

The material investigated is a natural low-plasticity clayey soil, characterised by a liquid limit (LL) of 25.83% and a plasticity index (PI) of 8.96 (Table 1). It is characterised by its wide availability and abundance. Prior to use, the soil was sieved to 2 mm in order to remove clumps, Fig. 4a. Its physical properties, including particle size distribution and sedimentation analysis, Fig. 1, were determined in accordance with NF P 94–

056 [8] and NF P 94–057 [9], respectively. The bulk density and specific density were measured following NF P 18–554 [10] and NF P 18–555 [11]. The Atterberg limits and the soil plasticity index were obtained according to NF P 94–051 [12]. The methylene blue value was determined in accordance with NF P 94–068 [13] and the pH according to ASTM D6276-99a [14]. These results are summarised in Table 1. The chemical and mineralogical composition of the soil was further investigated using XRF and XRD analyses [15] (Fig. 2). The chemical analysis (Fig. 2a) indicates that the soil is mainly composed of silica ($\text{SiO}_2 \approx 42.6\%$) and alumina ($\text{Al}_2\text{O}_3 \approx 36.6\%$), with a significant amount of calcium oxide ($\text{CaO} \approx 19.2\%$), while the remaining oxides are present in minor proportions. The mineralogical analysis (Fig. 2b) reveals that the dominant clay minerals are illite ($\approx 36.6\%$) and kaolinite ($\approx 12.1\%$), with minor amounts of montmorillonite ($\approx 0.1\%$). Quartz is also present as a significant non-clay mineral phase ($\approx 9.3\%$). The presence of reactive aluminosilicate phases confirms the potential of the soil to interact with lime during stabilization, which is consistent with the mechanical behavior observed after curing.

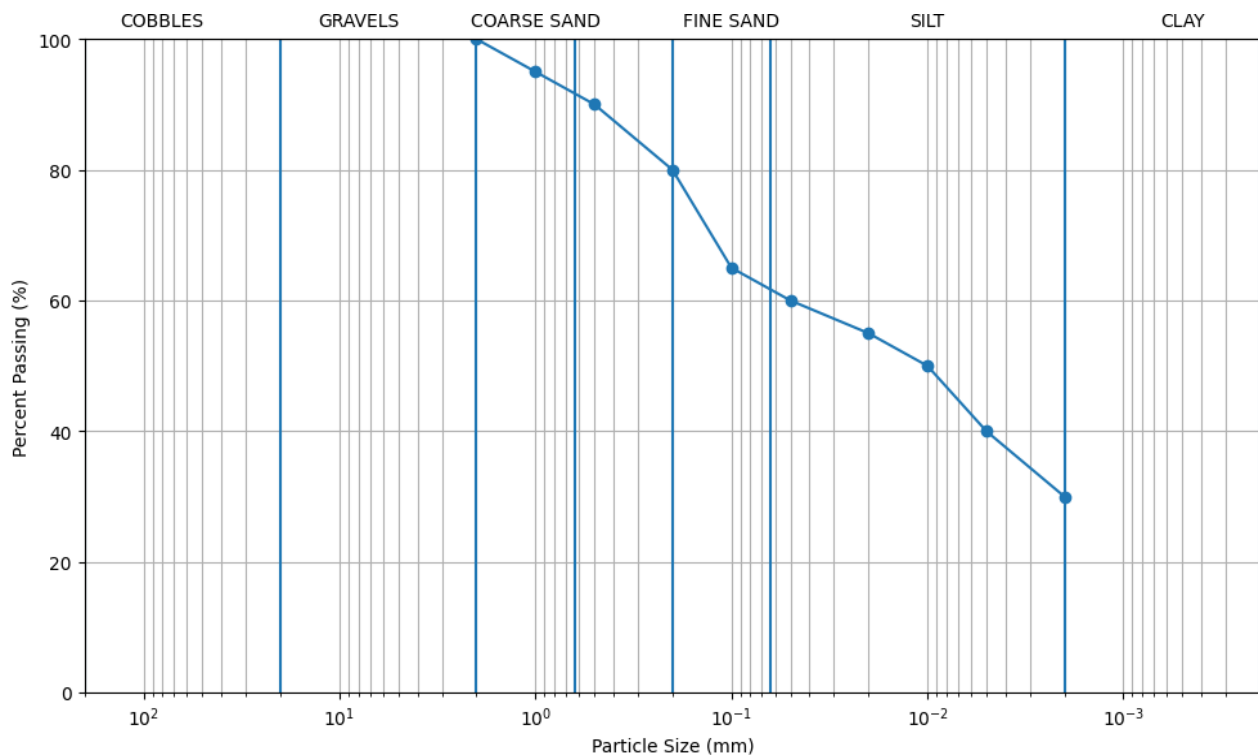


Fig. 1. Grain size distribution curve

Table 1. Soil parameters

Parameters	Value
Liquid Limit (LL)	25.83 %
Plastic Limit (PL)	16.87 %
Plasticity Index (PI)	8.96
Water Content (We)	9.48 %
Bulk Density	1931 kg/m ³
Absolute Density	2668 kg/m ³
Methylene Blue Value (Vs)	5.22
PH	5.80

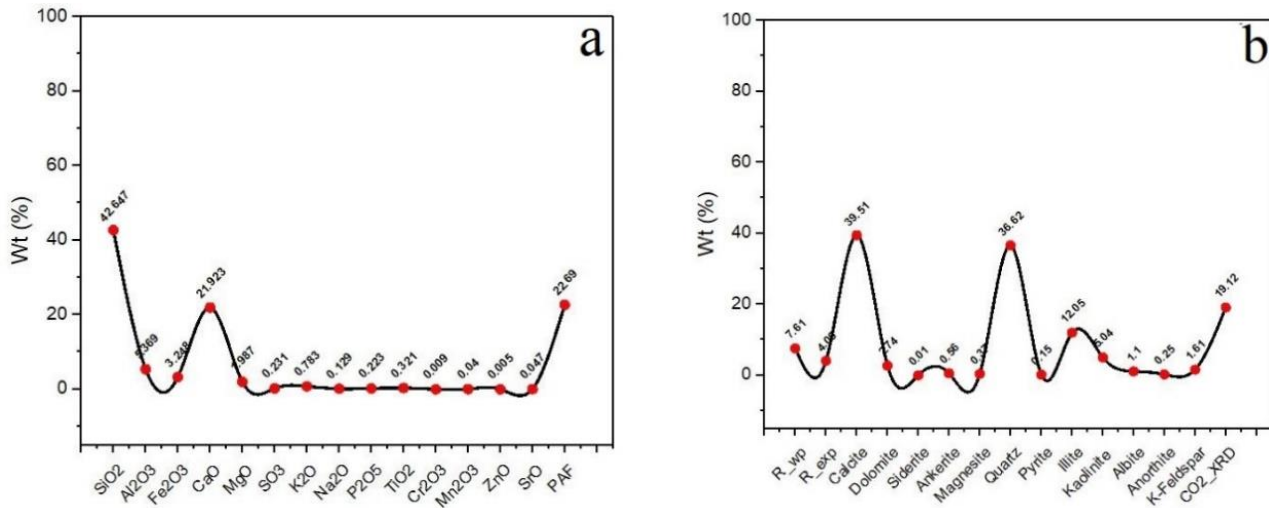


Fig. 2. a) Chemical analysis of soil by XRD, b) mineralogical analysis of soil by XRD

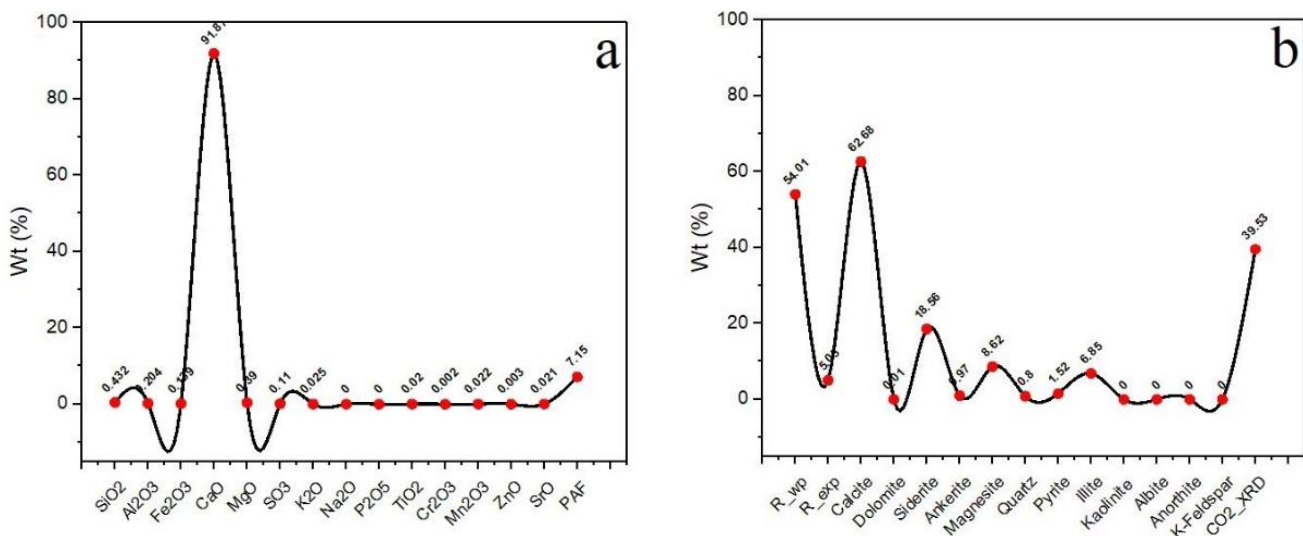


Fig. 3. a) chemical analysis of lime by (XRF), b) mineralogical analysis of lime by (XRD)

2.3. Lime

Lime is a widely used chemical stabilising agent in soil treatment, particularly when the clay fraction is less than 20%. Its action is mainly based on the dissolution of Ca²⁺ and OH⁻ ions [16], which promote the flocculation and stabilisation of fine particles. Used since ancient times as a construction material. Lime improves both the mechanical strength and the moisture resistance of compressed earth blocks. Industrial lime consists mainly of CaO and CaCO₃, but may contain impurities that influence its performance. Two forms are commonly applied: quicklime (CaO), with high reactivity, and hydrated lime [Ca(OH)₂], which is easier to handle. A high-quality lime is characterised by a high proportion of free lime (CaO) and a low content of insoluble compounds, ensuring greater efficiency in stabilisation processes. From a chemical standpoint, its role is particularly explained by the decarbonation reaction CaCO₃ → CaO + CO₂ [17]. The chemical and mineralogical characteristics of the quicklime were further examined by XRF and XRD analyses (Fig. 3). The XRF results (Fig. 3a) confirm that CaO is the dominant component (≈ 91.6%), with minor oxides present in very small amounts, indicating the high purity of the lime. The XRD analysis (Fig. 3b) reveals that the material is primarily composed of calcite (≈ 62.7%) and portlandite (≈ 18.6%), with minor phases such as quartz (≈ 8.6%) and traces of other

minerals. The high CaO content confirms the strong reactivity potential of the lime, which is essential for promoting soil stabilisation through physicochemical interactions.

2.4. Water

The water used for preparing the sample was potable water, maintained at a controlled temperature of approximately 20 °C, with a tolerance of ±2 °C. This parameter is fundamental, as a stable temperature ensures optimal hydration of the components, thereby promoting mixture cohesion and enhancing the mechanical performance of the final material. Compliance with this condition also helps to reduce unforeseen variations that could compromise the durability and strength of the soil samples. Although often overlooked, water thus plays a crucial role in ensuring the proper course of the samples preparation.

2.5. Sample preparation

The soil used in this study was sieved through a 2 mm opening and then dried at 65 ± 2 °C for 24 hours in order to obtain a homogeneous and dry material. From this prepared soil, prismatic specimens with dimensions of (4 × 4 × 16) cm³. Figure 4c was produced following a standard procedure. To determine the optimal quicklime content to be incorporated, the

soil was mixed with different proportions of quicklime, Fig.4b, namely 3%, 5%, 7%, 9%, 11%, 13%, and 15% by dry weight. For each percentage lime content, these samples were prepared for each curing period, these samples were subjected to thermal curing [18], in an oven maintained at 65 °C, for periods of 3, 7, and 11 days. The determination of the compressive strength of the samples, Fig. 5, was adopted as the main criterion in order to identify the optimum percentage of

quicklime that gives the best mechanical performance [19]. Compressive strength testing was performed after each curing period (3, 7, and 11 days) to evaluate the influence of lime content under controlled thermal conditions. The results were subsequently analysed to determine the lime dosage that provides the most suitable mechanical performance.



Fig. 4. Preparation procedure: a) soil, b) lime, c) specimens with dimensions of (4×4×16) cm³



Fig. 5. Compression test

3. Results and discussion

The compressive strength results (Fig.6, Fig. 7, Fig. 8) clearly demonstrate the combined influence of quicklime (CaO) content and curing duration on the mechanical behaviour of the stabilised soil [20]. After 3 days of curing (Fig. 6), the highest strength (2.49 MPa) was achieved with 3% CaO. Beyond this percentage, a gradual decrease was observed, indicating that higher lime contents do not immediately contribute to strength enhancement. At this stage, strength improvement is mainly due to physicochemical interactions, such as cation exchange and particle flocculation, which promote clay particle aggregation and reduce plasticity.

At 7 days of curing (Fig. 7), compressive strength increased and reached 2.61 MPa at 11% CaO. This improvement reflects the progressive development of stabilisation mechanisms associated with the reaction between calcium ions and the reactive silica and alumina present in the clay fraction. These interactions lead to the formation of binding phases that enhance

interparticle bonding and matrix cohesion, resulting in a denser, more structured material.

After 11 days of curing (Fig. 8), compressive strength reached a maximum of 3.81 MPa at 7% CaO, then decreased significantly at higher lime contents. The decline observed beyond the optimum dosage may be attributed to excess unreacted free lime, which can increase internal voids and create weak zones within the matrix. This imbalance negatively affects structural continuity and reduces mechanical performance.

Overall, these findings confirm the role of quicklime in enhancing soil strength through progressive chemical and structural modifications within the clay matrix [20]. The optimal CaO content, therefore, varies with curing duration, evolving from 3% to 11%, and ultimately stabilising at 7%, as summarised in Table 2. This behaviour emphasises the importance of carefully controlling both lime dosage and thermal curing conditions to achieve optimal mechanical performance and long-term stability.

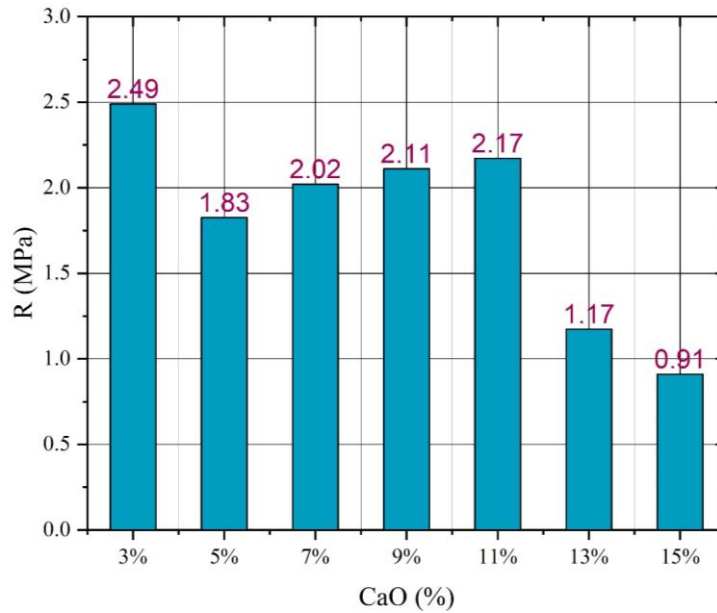


Fig. 6. 03 Days of curing

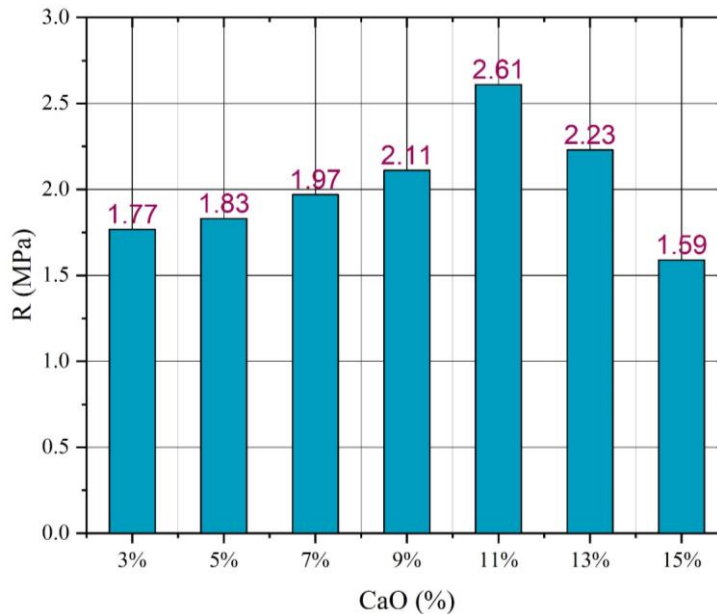


Fig. 7. 07 Days of curing

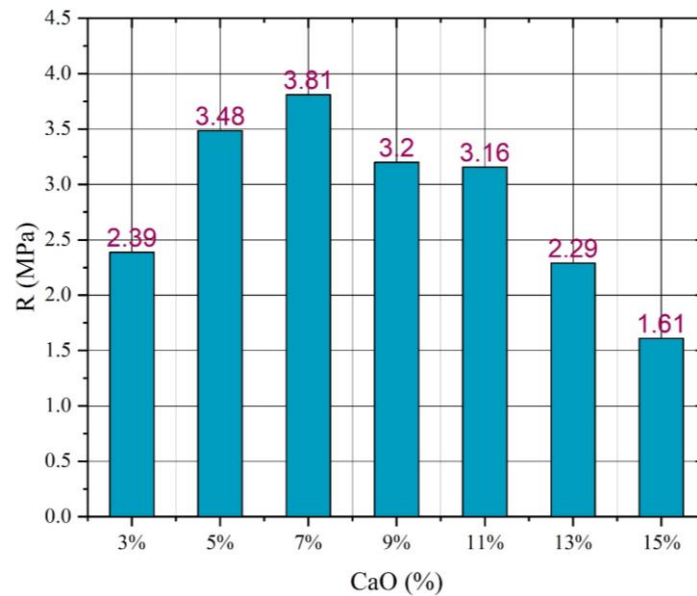


Fig. 8. 11 Days of curing

Table 2. Results

Curing Duration	Maximum Strength (MPa)	Optimal Lime Content
3 Days	2.49	3%
7 Days	2.61	11%
11 Days	3.81	7%

4. Conclusions

This research highlights the influence of quicklime (CaO) content and curing duration on the mechanical behaviour of stabilised soil. The findings reveal an increase in mechanical strength over time, reaching a maximum at 3.81 MPa at 11 days for an optimum lime dosage of 7%. This threshold represents a satisfactory balance between flocculation and cementation reactions, ensuring good matrix cohesion. Conversely, an excess lime content leads to a significant reduction in the strength of the lime-stabilised soil. These results emphasise the need to carefully calibrate the lime dosage based on the required mechanical performance within the studied curing duration, acknowledging that further strength development may occur beyond this period. They also emphasize the essential role of curing conditions, as they govern the kinetics of reactions and the structuring of the material. In conclusion, lime stabilization represents an effective and sustainable solution, provided that the lime dosage–curing duration couple is carefully optimized. This approach guarantees not only enhanced strength but also the durability and reliability of soil-based construction materials.

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