

# Evaluation of Suitable Soils for Compressed Earth Block Manufacturing

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**ABSTRACT:** This study aims to establish soil suitability criteria for compressed earth block (CEB) production, addressing the limitations of existing granulometry and plasticity nomograms in evaluating soil for unstabilized CEBs. Soils were sourced from five deposits, and their fine particles were analyzed using X-ray diffraction (XRD), methylene blue value (MBV), and granulometric analysis. Large portions of the soils were dried and sieved into various grain size classes, which were then mixed in specific proportions to produce 50 soil samples with known granulometric characteristics. Compressed earth blocks (CEBs) were made from each sample, and their compressive strengths were evaluated. Additionally, some blocks were characterized for shrinkage, and empirical models linking the compressive strength and shrinkage values of CEBs to specific soil characteristics were developed. This helped to establish a more objective soil suitability criterion based on minimum compressive strength and maximum shrinkage values. This research paves the way for a more reliable and systematic approach to soil assessment for earth-based construction, while emphasizing the necessity of considering a broader range of soil and production parameters to expand the current soil selection criteria.

**Keywords:** Compressed earth block; Earth construction; Suitable soil for construction; Compressive strength; Soil shrinkage.

## I. INTRODUCTION

Sub-Saharan Africa is experiencing a significant demographic surge, with a population of 800 million projected to reach 2 billion by 2050 (Zuberi and Thomas, 2012). The construction industry, a sector with immense potential for environmental, social, and economic impacts (Fei et al., 2021), must effectively respond to the growing demand for housing. Currently, housing remains a significant challenge even at the local level. According to estimates by the United Nations-Habitat Program, around 60 percent of the population in Yaoundé, the capital of Cameroon, lives in slum settlements (UN-Habitat, 2020). Due to the relatively high construction cost, about 87.6% of Cameroonian families cannot afford to own a home without direct aid from the state (INS, 2020). On the other hand, in 2017, building construction and operations accounted for approximately 36% of global energy consumption and 39% of energy-related carbon dioxide (CO<sub>2</sub>) emissions. Of this, 11% resulted from the manufacturing of building materials and products like steel, cement, and glass, while 28% came from operational emissions related to heating, cooling, and powering buildings (Global Status, 2018). This suggests that efforts to address housing challenges and accommodate demographic growth will likely result in heightened energy demands and increased

emissions. In this context, eco-construction emerges as a vital solution, offering a pathway to reduce the industry's environmental impact while promoting sustainable development. Various sustainable housing concepts are currently being explored, and building with earth has shown considerable promise and has garnered significant research interest in recent years (Shantanu et al., 2022; Turco et al., 2021). Among various earth construction methods, compressed earth blocks (CEBs) stand out, as they represent a modern evolution of adobe. They offer modular advantages that facilitate easier construction and design flexibility, and are distinguished by a compaction process that uses mechanical stabilization to create denser and stronger blocks (Turco et al., 2021). CEBs also require less water during production, minimizing excessive shrinkage and enhancing durability. The controlled compaction process lowers porosity, improving dimensional stability and reducing the risk of structural failure (Brahim et al., 2025). Additionally, CEBs allow for efficient space utilization, as they can be stacked immediately after production (Houben and Guillard, 1989). Despite the extensive research published on earth constructions, the effective implementation of this building technique still encounters several challenges. These include ambiguity in soil selection criteria for earth constructions, a lack of universally accepted standards for production and testing, insufficient models to describe the durability and longevity of constructed buildings, etc. (Islam et al., 2020).

Soil selection recommendations based on granulometry and plasticity are available in various literature (AFNOR, 2021; Houben and Guillard, 1989; Rigassi, 1995). However, the recommendations often vary among authors and can be broad or vague, complicating the soil assessment process (Ciancio and Jaquin, 2011). Furthermore, the literature presents numerous cases where soils not meeting established recommendations can still produce quality earth blocks. In contrast, some soils that comply with these guidelines may result in poor-quality blocks. These inconsistencies have led many researchers (Ciancio and Jaquin, 2011; Hamard et al., 2018; Nshimiyimana et al., 2022; Rojat et al., 2020) to question the adequacy of the current standards and methods used for soil assessment. To address this gap, this work proposes an objective method of soil selection for earth construction, based on empirical relationships established between soil properties and structural characteristics of CEBs: compressive strength and shrinkage. The goal is to generate evidence-based insights that can inform the development of improved soil evaluation procedures, potentially enhancing the sustainable use of local earth materials for affordable, high-performance building solutions. In this study, soil samples were collected from five deposits in different parts of Cameroon. These locations were selected to ensure that the samples exhibited distinct characteristics. The soil from each deposit was sieved to obtain different grain size classes, which were then mixed in defined proportions to create soil samples with specific granulometries, resulting in a total of 50 soil samples. XRD analyses were conducted, followed by the determination of MBV for the fine particles that passed through a 0.2 mm sieve from each deposit. Next, the static optimum moisture content (OMC) for each sample was also determined, compressed earth blocks (CEBs) were produced, and their compressive strengths and shrinkage were measured. The effects of soil properties on the compressive strength and shrinkage of CEBs were analyzed using an empirical model. This relationship served as a base in developing a clear methodology for selecting suitable soil for CEB production.

## II. MATERIAL AND METHOD

### A. Soil collection and characterization

Soil was collected from earth block-making sites in five towns in Cameroon: Maroua (Ma), Garoua (Ga), Bamenda (Ba), Bertoua (Be), and Douala (Do), using the diagonal sampling method as described by Mathieu and Pieltain (2003).

Soil from each deposit was sun-dried, crushed, and sieved through a 0.2 mm sieve. The coarse fraction (particles > 0.2 mm) was washed and sieved through various sieve sizes: 20 mm, 6.3 mm, 2 mm, 1 mm, 0.63 mm, and 0.4 mm. The particles on each sieve were then dried and mixed in specific ratios to create samples with granulometric structures labeled "C1" to "C10" (Figure 1). From the five deposits and ten granulometric structures, a total of 50 soil samples were obtained. Each sample is named to reflect its soil deposit and the curve that defines the granulometry of its coarse fraction. For example, "MaC1" indicates the soil sample from the Ma deposit, with the coarse fraction represented by curve C1. The fine fraction of each sample (particles < 0.2 mm) retained the original granulometry of the deposit from which the soil was collected. This fine fraction was characterized through the methylene blue value test (MBV), which correlates with the soil's plasticity properties (Suhendra Nugraha et al., 2020), in accordance with NF P94-068 (AFNOR, 1996). This was followed by X-ray diffractometry (XRD) conducted with a Seifert Calypso goniometer (40 kV, 40 mA, copper anode, wavelength 1.5418 Å). Their particle size distribution (PSD) of the fine fraction was determined by wet sieving and the hydrometer method described in NF ISO 11277 (AFNOR, 2020).

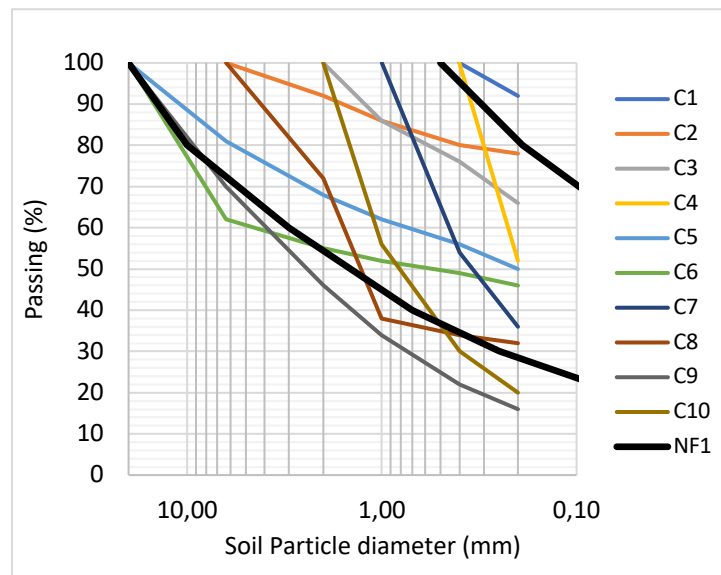


FIGURE 1. Granulometric curves of coarse-grained soil samples.

Curves: NF1, NF2 (XP\_P13\_901 2001) (AFNOR, 2021); C1, C2, C4, C9 (Rojat et al., 2020); C3 (Goutsaya et al., 2021); C6 (Wouatong, 2015); C8 (Pagna Kagonbe et al., 2020); and C10, C7, C5 (Tchamba et al., 2012).

### B. Production of CEBs

Firstly, the static OMCs of each sample were determined to identify the moisture levels at which each sample achieves its optimal compaction. The procedure described in Boubekeur et al. (2000)

was adopted, given that the method better reflects CEB production when compared to the Proctor test (Nshimiyimana et al., 2022). The procedure involved preparing soil samples with varying moisture contents by mixing them with distilled water. Each mixture was placed in a compaction mold, where a compacting pressure of 6 MPa was applied using a static compaction machine, simulating conditions for earth brick production. The resulting dry densities were measured and plotted against their moisture contents to create a moisture-density curve, identifying OMC at the peak of the curve. This method ensures that the OMCs are theoretically valid and relevant to production, enhancing the reliability of the evaluated material properties. Furthermore, each soil sample was mixed with distilled water to achieve its OMC, ensuring uniform texture. Five CEBs were produced from each mixture at a forming pressure of 6 MPa, a value between medium and high compression as defined by Rigassi (1995). After production, the compressed earth blocks (CEBs) were allowed to dry in a room where the temperature and humidity varied slightly around 25°C and 76%, respectively, until they reached a constant mass. They were then tested for compressive strength after a curing period of 14 days.

#### *C. Compressive strength and shrinkage test on CEBs*

The compressive strength test was conducted following the equipment description, material preparation, and operational procedures outlined in XP P13-901 (AFNOR, 2021). A slight deviation from this standard was implemented by performing a direct unit test on cubes measuring 4x4x4 cm (Hussain et al., 2023) instead of a stacking of two half blocks separated by mortar. This adjustment aimed to avoid yielding an unconfined masonry strength rather than the actual strength of the blocks, and also to eliminate variations that may arise from mortar performance and the quality of workmanship in preparing the prism (Morel et al., 2007).

The shrinkage analysis was conducted on selected soil samples to evaluate the effect of soil properties on the shrinkage of CEBs. The study was done on samples with 92%, 66%, and 32% fines content (C1, C3, and C8 soils) from various deposits, with brick sizes measuring approximately 10cm×10cm×10cm. This targeted selection reduced the number of evaluations while allowing for a general view of the entire experimentation domain. Four CEBs of each size were produced from the stated samples, and their dimensions were measured before being allowed to dry in a room at 25°C until they reached a constant mass and dimensions over 14 days. Afterward, they were dried again in an oven for 48 hours at 105°C. Their final dimensions were taken, and the shrinkage value was calculated as a percentage of the initial dimensions of the soil blocks.

#### *D. Empirical Models*

The empirical analysis involved studying data from 50 soil characteristics to establish separate relationships between soil properties and compressive strength, as well as between soil properties and shrinkage. These relationships guided the formulation of empirical models that define soil suitability for compressed earth block (CEB) production. The models focus on identifying suitable soil types based on minimum compressive strength values and maximum shrinkage values. This approach enables the development of a range of soil materials that meet the necessary criteria for effective earth construction, enhancing the reliability and applicability of soil assessments in this context.

## II. RESULTS AND DISCUSSION

### A. Characterization of soil samples

Figure 2a presents the granulometric curves obtained for all 50 soil samples. The clay content of the soil from each deposit is summarized in Table 2, along with its respective MBV. The MBV values range from 4.79 g/100g to 0.62 g/100g, in decreasing order: Ma, Ga, Be, Ba, Do. The XRD analysis (Figure 2b) revealed a diverse range of mineral compositions in the soil samples. Importantly, the Do sample was predominantly composed of quartz and kaolinite, which are also present in all deposits. In addition to quartz and kaolinite, the soil from Ma contained montmorillonite and illite, while the soils from Ga and Be exhibited traces of illite. Furthermore, both the Ba and Be soils, classified as lateritic, featured hematite and maghemite.

The Ma sample, with a clay content of 49.7% and the presence of montmorillonite, exhibits the highest MBV of 4.785 g/100g. This high value indicates a strong capacity for dye adsorption, largely due to montmorillonite's extensive surface area, along with illite and kaolinite (Hang and Brindley, 1970). In contrast, the Ga sample, despite having the highest clay content of 57.1%, presents a significantly lower MBV of 1.644 g/100g. This discrepancy can be attributed to the presence of kaolinite and traces of illite in Ga, which generally have lower adsorption capacities compared to montmorillonite (Hang and Brindley, 1970).

Meanwhile, the Ba sample, with a clay percentage of 29.2%, has an even lower MBV of 0.661 g/100g, reflecting its mineral composition that limits dye adsorption. On the other hand, the Be sample, featuring 35.3% clay, achieves a moderate MBV of 1.112 g/100g, thanks to the presence of illite, which enhances its adsorption potential (Hang and Brindley, 1970). Lastly, the Do sample, despite having a clay content of 54.4%, exhibits the lowest MBV of 0.624 g/100g, underscoring how even its high kaolinite content results in relatively lower dye adsorption capabilities.

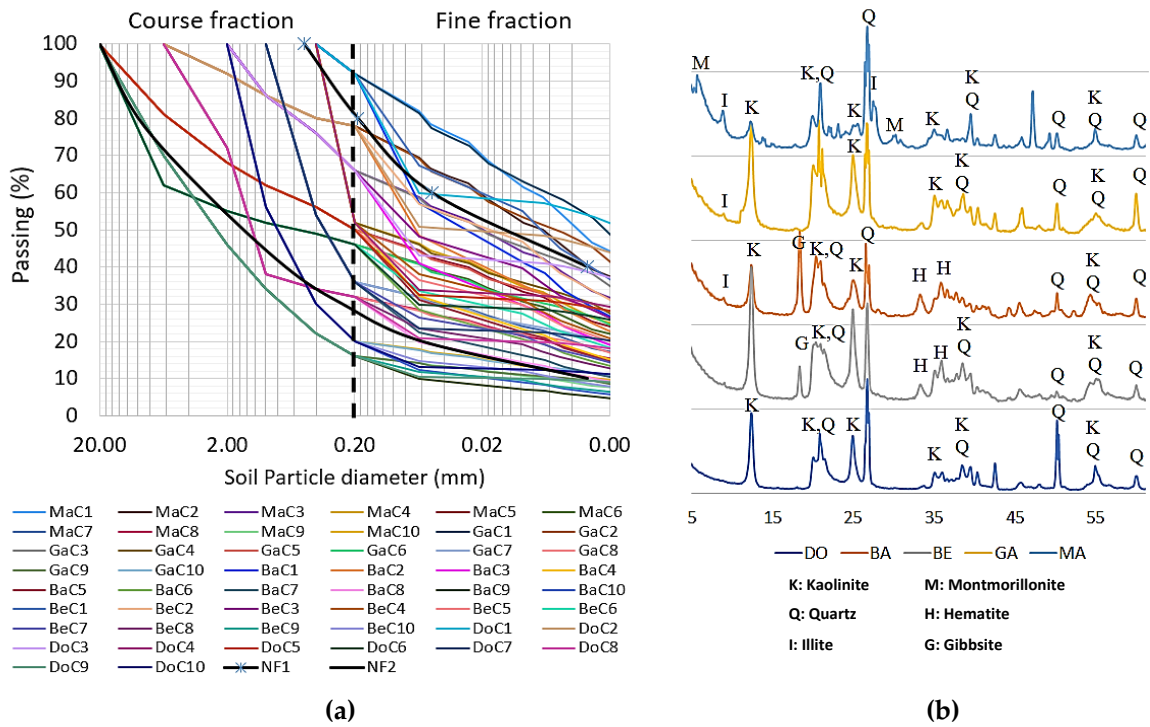


FIGURE 2. (a) Granulometric curves and (b) XRD data of soil samples

TABLE 2. Soil sample nomenclature

	Clay (%)	MBV (g /100g)	Minerals
Ma	49.7±2.8	4.785 ±0.18	M, I, K, Q
Ga	57.1±1.9	1.644 ±0.01	K, Q, I
Ba	29.2±1.8	0.661 ±0.06	K, Q, H, G
Be	35.3±3.9	1.112 ±0.11	I, K, Q, H, G
Do	54.4±3.3	0.624 ±0.05	K,Q

B. Empirical Models for Predicting Compressive Strength and Shrinkage

Compression test results (Figure 3a) reveal notable differences in CEB strength, with a trend from C1 to C10 indicating that finer particles enhance strength. For instance, MaC1 achieves 10 MPa, whereas DoC10's 0.36 MPa underscores the challenges of attaining high strengths from soils with significant percentages of coarse particles (Minke, 2005). Strength increases linearly with the fine fraction percentage (Figure 3a), with R<sup>2</sup> values ranging from 97.0% to 98.5%, ranked as Ma > Be > Ga > Ba > Do. The Ma samples, rich in montmorillonite, exhibit the highest compressive strengths due to their superior plasticity. However, this also increases shrinkage, aligning with findings in the literature (Mango-Itulamy and Fagel, 2022 Panda et al., 2023). Ga's substantial clay enhances plasticity but falls short of the strength seen in Be with presence sesquioxides which improves cohesion and structural integrity (Oyelami and Van Rooy, 2018; Townsend et al., 1971). The relatively low amount of clay in Ba slightly limits its performance when compared to Be and Ga.

Composed mainly of quartz and kaolinite, Do shows the weakest strength and lowest shrinkage values, aligning with previous research indicating that low of kaolinites limits their strength and also reduces shrink-swell potential (Miranda-Trevino and Coles, 2003).

It was observed that compressive strength exhibits a cubic relationship with MBV across soil samples with the same percentage of fine particles. Consequently, the graph of compressive strength against the cube root of MBV is a straight line (Figure 3b).

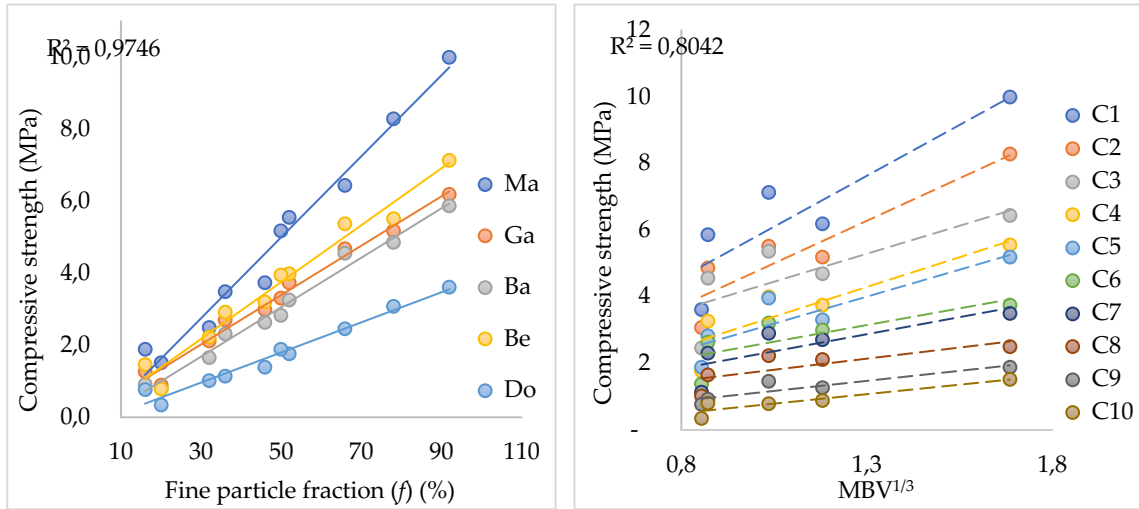


FIGURE 3. Compressive strength CEBs versus (a) fine fraction of soil and (b) cube root of MBV

Both compressive strength and shrinkage values evolve linearly with the property:  $f \times MBV^{1/3}$ , with  $R^2$  values of 91% and 92%, respectively, with RMSE of 0.62MPa and .31% (Figure 4).

The resulting empirical equation for compressive ( $Y_T$ ) strength and shrinkage ( $Y_s$ ) is given in equation (2).

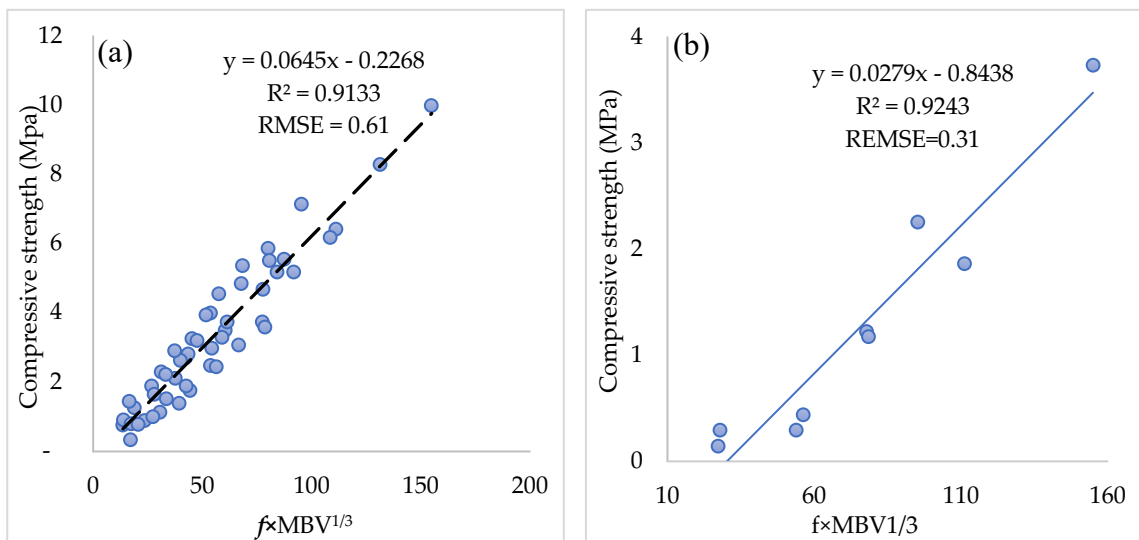


FIGURE 4. (a) Compressive strength and (b) Soil shrinkage versus properties of fine particles.

$$Y_T = 0.0645f \times MBV^{\frac{1}{3}} - 0.2268 \quad (1)$$

$$Y_S = 0.0279f \times MBV^{\frac{1}{3}} - 0.8438 \quad (2)$$

C. *Determination of suitable soil for earth construction.*

For soil to be suitable for earth construction, the compressive strength of the soil must meet a minimum value ( $T_{min}$ ), defined by various standards. At the same time, the shrinkage value must not remain below a maximum value  $S_{max}$  defined by the standard. Therefore, a suitable soil for earth construction is such that equations (3) must hold.

$$T_{min} + \epsilon < 0.0645f \times MBV^{\frac{1}{3}} - 0.2268$$

$$S_{max} - \epsilon > 0.0279f \times MBV^{\frac{1}{3}} - 0.8438$$

$$\frac{T_{min} + \epsilon + 0.2268}{0.0645} < f \times MBV^{\frac{1}{3}} < \frac{T_{min} - \epsilon + 0.8428}{0.0279} \quad (3)$$

Where  $\epsilon$  and  $\epsilon$  represent the RMSE for the models of tensile strength and shrinkage, respectively.

For example, any arbitrary standards that define a minimum compressive strength of 2 MPa (NMAC, 2009) and a maximum shrinkage value of 2% (WD-ARS 1333 (ARSO, 2018)), and considering RMSE values of 0.61 MPa for compressive strength and 0.31% for shrinkage, the suitability of soils for earth construction will be determined by the expression in equation 4:

$$44 < f \times MBV^{\frac{1}{3}} < 90 \quad (4)$$

Note: this is for a forming pressure of 6 MPa. At higher forming pressures, OMC may value decreases, resulting in a lower amount of water needed to form the blocks. This may lead to reduced shrinkage values for the same soil sample. At the same time, increased forming pressures contribute to higher compressive strengths of CEB. Consequently, soil samples that were previously excluded due to poor strength or high shrinkage may become suitable. Therefore, it is essential to study how forming pressure affects compressive strengths and shrinkage values to develop a generalized soil suitability chart for earth construction.

D. *Analysis of the proposed model under the French standard XP\_P13\_901 (AFNOR, 2021)*

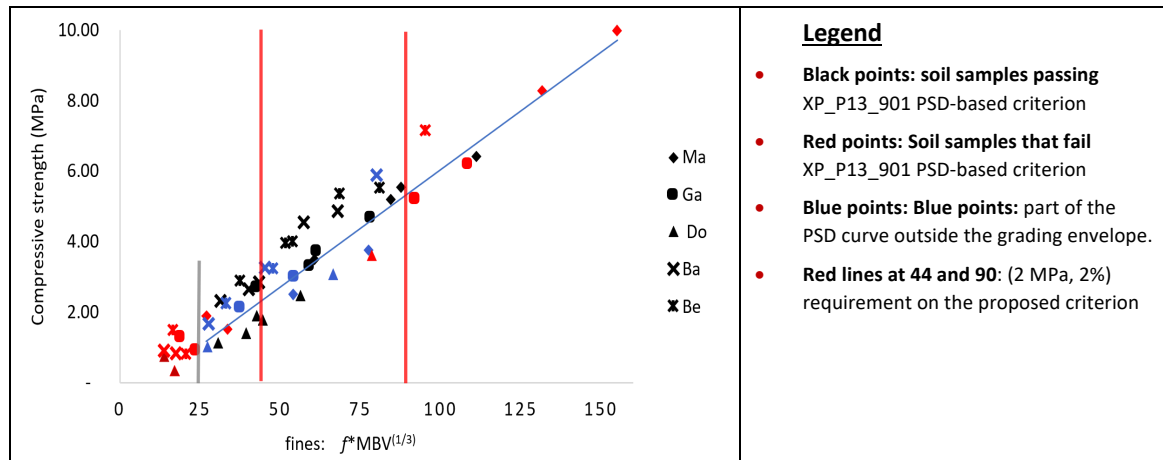


FIGURE 5. Analysis of the model

In analyzing the proposed suitability criterion under the PSD-based criterion of the French standard: XP\_P13\_901 (AFNOR, 2021), three important considerations can be drawn from Figure 5.

- It is observed that most soils passing the PSD-based criterion are found between 25 (1.13 MPa) (indicated by short gray line) and 90 on the horizontal axis. In contrast, XP\_P13\_901 (AFNOR, 2021) and other commonly used PSD-based recommendations like Boubekour et al. (1998) suggest similar PSD, yet request a minimum compressive strength of 2MPa for CEBs. This discrepancy may explain why many authors report several instances in the literature where soils passing the PSD-criterion still produce substandard CEBs (Ciancio and Jaquin, 2011; Danso, 2018; Jiménez Delgado and Guerrero, 2007).
- The graph also indicates that, based on the PSD criterion, MaC3 is suitable for earth construction, while DoC1 is not, due to its higher fine particle content. However, the evaluation based on shrinkage values favors DoC1 over MaC3, raising further concerns similar to those highlighted in the literature (Ciancio and Jaquin, 2011; Danso, 2018).
- Additionally, soils represented in blue indicate ambiguous cases (e.g., C6 and C8 soils) where a small part of the granulometric curve goes outside the grading envelope of the PSD-based criterion. In such instances, the decision regarding suitability may be very subjective.

In essence, correlating fine particle properties with compressive strength and shrinkage marks a significant advancement in identifying suitable soils for earth construction, aiding in soil stabilization techniques by allowing for targeted modifications of fine content to improve soil stabilization. The proposed criterion offers objectivity by defining precise parameters (compressive strength and shrinkage) to assess soil suitability, and enhances flexibility, allowing for adjustable requirements of compressive strength and shrinkage based on specific requirements. Finally, it simplifies assessment, saving time by requiring only a dry mass of the fine fraction of the soil sample and a quick MBV analysis, thereby avoiding painstaking methods like sedimentation.

## Conclusion

This study introduces a novel soil suitability criterion for compressed earth block (CEB) production, overcoming limitations in conventional granulometry-based assessments. By analyzing 50 soil samples from five distinct deposits, empirical models that correlate specific soil properties with the compressive strength and shrinkage of resulting CEBs were developed. These models provide a comprehensive framework for assessing soil suitability in earth construction.

Our findings demonstrate significant improvements over existing PSD-based criteria (e.g., XP\_P13\_901), revealing cases where soils meeting traditional standards still produced inadequate blocks. The proposed criterion eliminates such ambiguities, offering a more reliable, objective, and flexible assessment method. Beyond refining soil selection, this research advances the understanding of CEB performance and opens new avenues for soil stabilization techniques. By establishing clear relationships between fine particle properties and mechanical behavior, this research opens avenues for further exploration in soil stabilization techniques wherein one can objectively modify the fine fraction of soil to obtain specific mechanical characteristics of CEBs. In perspective, the influence of forming pressure on shrinkage and compressive strength can be further explored to create a versatile selection guide applicable to all CEB production conditions.

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