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Research on geotechnical and geochemical properties of lateritic soils of Kaele (Far North Cameroon) for the production of cement-stabilised compressed earth bricks

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Abstract

The need for low-carbon construction materials is driving interest in compressed earth blocks (CEB), especially in semi-arid regions with abundant lateritic soils. This study examines the suitability of Kaélé soils in Far North Cameroon for making cement-stabilized CEB, focusing on how geotechnical and geochemical properties affect mechanical performance and durability.

Four representative lateritic soil samples were collected. Analyzed them for particle size distribution, Atterberg limits, and chemical composition using X-ray fluorescence (XRF). Stabilized blocks were produced with 4%, 6%, and 8% cement contents and tested for compressive strength, water absorption, abrasion resistance, linear shrinkage, and erodability.

The soils have granulometric distributions and low to moderate plasticity, making them suitable for earth construction. They are mainly composed of SiO_2 (61.7-65.2 wt.%) with Al_2O_3 and Fe_2O_3 contents and show signs of moderate weathering. The mechanical performance of the blocks improves significantly with cement content, with strength ranging from 1.36 to 4.08 MPa after 28 days. Durability indicators like water absorption and abrasion loss decrease with increasing stabilization.

The study demonstrates that the combined effects of granulometry, plasticity, and geochemical composition govern the performance of CEB. An optimal cement content of 6-8% is identified, providing a balance between strength and durability. These findings highlight the strong potential of Kaélé lateritic soils for sustainable construction and contribute to the development of locally adapted, low-carbon building materials for Sahelian environments.

Keywords:

Earth blocks; Lateritic soils; Cement stabilization; Geochemistry; Durability; Cameroon.

1. Introduction

The construction sector uses a lot of resources and contributes to greenhouse gas emissions mainly due to cement-based materials [1,2]. To address economic challenges, compressed earth blocks have become popular as sustainable alternatives, especially in developing countries [3-8]. CEB provides low embodied energy, reduced construction costs, and the potential for environmentally friendly housing solutions [9,10].

Lateritic soils, resulting from intense tropical weathering, are widely distributed in intertropical regions [11,12]. These soils constitute a major raw material for earth-based construction in Cameroon [6,8,13,14]. When used without stabilization, these soils generally exhibit low mechanical strength and high sensitivity to water, limiting their application in load-bearing structures [6,15]. The utilization of chemical stabilizers, such as cement, has been successfully adopted to improve the mechanical properties and durability of CEB by enhancing interparticle bonding and reducing porosity [8,16,17]. Many studies have shown that cement contents between 4% and 10% usually yield blocks that meet compressive strength requirements for masonry, although performance is strongly influenced by soil characteristics such as particle size distribution, plasticity, and mineralogical composition [6,16-18].

In Cameroon, several investigations have demonstrated the potential of stabilized earth construction for low-cost housing. Lateritic soils from Adamaoua, Garoua, Maroua, and other regions have been shown to achieve satisfactory compressive strengths when stabilized with cement, with performance depending on intrinsic soil properties [6]. Furthermore, natural fibers, such as rattan or agricultural residues, can enhance the mechanical performance and durability of stabilized CEB, creating eco-composites suitable for construction in diverse climatic conditions [19-21].

Semi-arid Sahelian climates, such as those of northern Cameroon and the Kaélé area, are characterized by high temperatures and episodic rainfall, which exacerbate moisture-related degradation and influence the long-term durability of earth-based masonry. In these contexts, properties such as dimensional stability, water resistance, and resistance to wet-dry cycles are critical for the longevity of masonry structures. Despite previous studies in northern Cameroon, limited research has explicitly examined

the combined influence of geotechnical and geochemical parameters on the performance of stabilized CEB. Therefore, this study aims to evaluate the performance of cement-stabilized CEB produced from Kaélé lateritic soils by integrating geotechnical, geochemical, and mechanical analyses to establish relationships controlling strength and durability.

2. Materials and methods

2.1. Geographical and geological setting

The study was conducted in Kaélé, Far North Region, Cameroon (Figure 1). The area has a Sudano- climate with a long dry season and a short rainy season [22]. High temperatures, strong solar radiation, and seasonal influence of the Harmattan and monsoon air masses strongly control weathering processes and soil formation in the area [23].

Geologically (Figure 2), the area belongs to the Precambrian basement, which is mainly composed of granites, gneisses, and migmatitic formations formed during the Pan-African orogenic cycle [22, 23]. These crystalline rocks are locally covered by ancient sand and alluvial lateritic weathering profiles developed under tropical climatic conditions, resulting from intense chemical alteration processes involving hydrolysis, leaching, and iron enrichment [24, 25]. The progressive weathering of these granitic formations produces soils dominated by quartz, kaolinitic clay minerals, and iron oxides, which largely control the geotechnical and mineralogical properties of lateritic materials used for earth construction.

The pedological map of Kaélé (Figure 1) indicates a heterogeneous soil cover dominated by vertisols, locally associated with hydromorphic clayey or sandy-clay vertisols in poorly drained depressions [25]. Ferruginous tropical soils occur mainly on slightly elevated surfaces and pediments, while colluvial and alluvial deposits are present along drainage axes [25]. These soils originate from the weathering of basement rocks and commonly produce lateritic materials rich in clay minerals and iron oxides, which largely control the plasticity, cohesion, and compaction behaviour of earthen construction materials. From a geotechnical standpoint, ferruginous lateritic soils generally provide suitable granulometric distribution and bonding properties for compressed earth blocks,

whereas vertisols, due to their high clay content and shrink-swell behaviour, may require stabilization to improve their durability. Consequently, the pedological variability of the Kaélé area constitutes an important factor influencing the engineering performance of cement-stabilized compressed earth blocks produced from local soils.

2.2. Sample Strategy and Preparation

To meet the objectives of this study, several field surveys were conducted in the Kaélé area to identify representative lateritic soil deposits suitable for earth-based construction materials. Preliminary site investigations were carried out to obtain practical information on the thickness of soil horizons and the spatial homogeneity of the deposits. Based on these preliminary assessments, four representative lateritic soil samples were collected from different localities around Kaélé: Mazang (MA1), Lara (LA1), Gaban (GA1), and Moumour (MO1). Sampling was performed at depths ranging from 0.5 to 1.2 m in order to avoid organic-rich surface layers and to obtain subsoil materials representative of horizons commonly exploited for geotechnical applications and compressed earth block production [26]. After collection, the soil samples were carefully packaged in plastic bags, labeled with indelible markers, and transported to the laboratory. The samples were then air-dried, gently disaggregated, and sieved before physicochemical and geotechnical analyses aimed at evaluating their suitability for the production of cement-stabilized compressed earth blocks.

2.3. Laboratory Work

2.3.1. Determination of geotechnical properties

The collected soil samples were air- and oven-dried at 105 °C for 24 h, then crushed to obtain homogeneous material for physico-chemical and geotechnical analyses (particle size distribution and Atterberg limits), conducted at the MIPROMALO geotechnical laboratory (Cameroon). Particle size distribution was determined using two complementary methods. Dry sieving [27] was applied to the coarse fraction (≥ 80 µm), and the cumulative retained (CR) and passing (CP) percentages were calculated as:

$$CR = \frac{R}{H} \times 100 \quad (1)$$

$$CP = 100 - (CR) \quad (2)$$

where W is the total sample mass and R the retained mass. The fine fraction (≤ 80 µm) was analyzed by gravity sedimentation according to NF P 94-057 [28].

The plasticity characteristics were determined using Atterberg limits tests following NF P 94-051 [29], including the measurement of the liquid limit (LL) and plastic limit (PL), from which the plasticity index (PI) was calculated. The Plasticity data were analyzed using Casagrande's plasticity chart. This chart helps classify granular soils based on liquid limit and plasticity index [30]. The obtained plasticity values were compared with recommended plasticity domains for earthen construction materials, compressed earth blocks [31]. This comparison provides a framework for evaluating the suitability of the studied soils for earthen construction.

2.3.2. Geochemical analyses

The geochemical composition determined by X-Ray fluorescence (XRF) and were performed at the geochemistry unit of CIMENCAM Company (Cameroon). A Bruker S8 TIGER 4 kW spectrometer was used following ASTM C114-15 [32] procedures. To minimize matrix effects and improve accuracy, fused glass beads were prepared from the material. Major element concentrations were expressed as oxide weight percentages. Loss on ignition was determined after heating samples at 1000 °C for 2 hours. The Chemical Index of Alteration was calculated from oxides (Equation 3), with CaO* corrected for possible carbonate and apatite contributions following the method proposed by Ozaytekin and Uzum [33].

$$CIA=Al_2O_3/(Al_2O_3+CaO^*+Na_2O+K_2O)\times 100 \quad (3)$$

2.4. Compressed earth blocks preparation and testing

Compressed earth blocks were produced using the previously characterized soils stabilized with ordinary Portland cement. The cement supplied by the CIMENCAM Company, located in Figuil in Northern Cameroon, was a Multi X type Portland cement CEM II with a 32.5 MPa resistance class and with slow setting properties. Cement was incorporated at 4%, 6%, and 8% by dry weight of soil, proportions commonly reported as effective stabilization ranges for tropical lateritic soils used in earth construction [25]. The dry soil and cement were first thoroughly mixed to ensure uniform distribution of the

binder. Water was then progressively added until a workable consistency suitable for compaction was obtained.

The mixtures were compacted using a hydraulic press to produce rectangular blocks with nominal dimensions of 29.5 × 14 × 8 cm³. Compaction pressure was maintained between 4 MPa, in accordance with commonly used procedures for compressed earth block production described in ASTM C55-07 [34] and in technical guidelines for earthen construction [4]. Immediately after molding, the blocks were carefully demolded and stored under ambient laboratory conditions for curing. Mechanical and durability tests were performed after 7, 14, and 28 days of curing, allowing the evaluation of the progressive development of material properties.

Several physical and mechanical tests were carried out to assess the performance of the stabilized blocks. Linear shrinkage (LS) was measured to evaluate the dimensional stability of the specimens during drying. The initial length of each specimen was recorded immediately after molding (L_1), while the final length (L_2) was measured after complete drying. Linear shrinkage was calculated as the relative reduction in specimen length according to Eq. (4):

$$LS\ \frac{L1-L2}{L2} \times 100 \qquad (4)$$

Water absorption tests were conducted to determine the capacity of the stabilized blocks to absorb water. The test consisted of immersing dried specimens in water and measuring the mass increase due to water uptake. Water absorption was calculated from the difference between the saturated mass (m_2) and the dry mass (m_1) according to NF EN 14617-1 [35], using Eq. (5):

$$ABS = \frac{m2-m1}{m1} \times 100 \qquad (5)$$

where m_1 is the dry mass (g), and m_2 is the mass after water immersion (g).

The compressive strength of the stabilized blocks was determined using a hydraulic testing machine equipped with a 200 kN load cell (Figure 3a). The tests were performed under uniaxial compression at a displacement rate of 0.5 mm min^{-1}, following the procedure described in NF P 15-451 (1963). The compressive strength (Rc) was calculated from the maximum load at failure (Fc) divided by the loaded surface area (S) using Eq. (6):

$$F = \frac{Fc}{S} \times 100 \quad (6)$$

where Rc is the compressive strength (N mm⁻²), Fc is the maximum applied force (N), and S is the loaded surface area (mm²).

To evaluate the resistance of the stabilized blocks to rainfall erosion, a drip erosion test based on the procedure proposed by Mbumbia et al. [36] was conducted. Four specimens were tested for each formulation. The test simulates the erosive effect of rainfall by exposing the specimen surface to a continuous water jet (Figure 3b). During the experiment, samples were positioned at an inclination of approximately 63° relative to the horizontal and subjected to a water flow applied from a height of about 1.5 m above the specimen surface. Each specimen was exposed to the water jet for 15 and 30 minutes, enabling the assessment of the surface degradation behaviour of the stabilized blocks under simulated rainfall conditions.

3. Results and discussion

3.1. Properties of lateritic soils

The main physical and geotechnical characteristics of the studied soils are presented in Table 1, while their particle-size distribution curves are shown in Figure 4. The four investigated soils (MA1, LA1, GA1, and MO1) display typical macroscopic features of lateritic materials developed under tropical weathering conditions on granitic parent rocks. All samples exhibit a reddish-brown color (2.5YR5/4) and a massive structure, associated with the presence of angular quartz grains and ferruginous concretions, which are characteristic of intense chemical weathering and iron enrichment processes commonly observed in tropical lateritic profiles [37, 7]. From a granulometric point of view, the soils correspond mainly to sandy silt to sandy clay materials, indicating a relatively balanced distribution between coarse and fine particles. The clay fraction varies from 13.49% to 25.33%, while the silt fraction ranges between 22.99% and 37.92%. Sand contents range from 14.68% to 36.08%, whereas the gravel fraction locally reaches 57.64%, reflecting the contribution of partially weathered granitic fragments and quartz grains derived from the parent rock [37,38].

The particle-size distribution curves (Figure 4) show that most samples fall within or near the recommended grading envelope for soils used in compressed earth block

production, as defined by the NC 102 standard [39]. Such a distribution ensures a favorable balance between coarse particles, which provide a granular skeleton improving compaction and dimensional stability, and fine fractions, which act as natural binders enhancing cohesion and plasticity during molding. Similar granulometric characteristics have been reported for lateritic soils used for compressed earth block production in several tropical regions [4-6]. However, slight deviations from the recommended granulometric ranges can be observed among the samples. The MA1 soil exhibits the highest clay content (≈25%), which may enhance cohesion but could also increase drying shrinkage and cracking risks. Conversely, GA1 contains a relatively high proportion of coarse particles, particularly gravel, which may reduce plasticity but improve packing density and mechanical stability after compaction. Similar variations in granulometric composition have been widely reported for Garoua and Maroua lateritic soils, reflecting the natural heterogeneity of weathering profiles and the influence of local geological conditions [6].

The Atterberg limits provide insight into the plastic behavior of the studied soils. The liquid limit (LL) ranges from 23.79% to 46.79%, while the plasticity index (PI) varies between 8.87 and 27.09, indicating low to moderate plasticity of the materials. According to the Casagrande plasticity chart (Figure 5), the samples plot mainly in the inorganic clay domain of low to medium plasticity, confirming the presence of sufficient clay minerals to ensure cohesion and workability during molding. Furthermore, comparison with the recommended plasticity spindle for earthen construction materials (Figure 6) shows that most samples fall within or close to the recommended plasticity range for compressed earth blocks according to NF-XP-P13-901 [40]. These results indicate that the studied lateritic soils possess adequate plasticity for compressed earth block production, ensuring good workability during compaction while limiting excessive shrinkage during drying, which is consistent with previous studies on lateritic soils used for earth construction materials [1,5].

The organic matter content, which ranges between approximately 5.9% and 6.7%, remains relatively moderate for tropical soils. Although organic matter can influence the stabilization reactions between soil particles and cement, several studies indicate that

moderate organic contents do not necessarily prevent the successful production of stabilized earth blocks when appropriate binder contents are used [41].

Overall, the combined analysis of granulometric composition, plasticity characteristics, and field observations indicates that the lateritic soils from the Kaélé area possess generally favorable geotechnical properties for compressed earth block production. Their particle-size distributions and plasticity indices fall within ranges commonly reported in previous studies on lateritic soils used for earthen construction materials. These results therefore confirm the technical potential of these local lateritic materials for the production of cement-stabilized compressed earth blocks, although stabilization remains necessary to optimize their mechanical performance and durability under the semi-arid climatic conditions of northern Cameroon.

3.2. Geochemical Composition

The chemical composition of the Kaélé lateritic soils reflects typical features of tropical soils subjected to moderate chemical weathering. Silica (SiO_2) dominates the composition, ranging from 61.7 to 65.2 wt.%, indicative of quartz enrichment and the persistence of primary silicate minerals. Aluminum oxide (Al_2O_3) contents are moderate (11.6-12.2 wt.%), corresponding to the presence of kaolinitic clay minerals, while ferric oxides (Fe_2O_3: 5.7–8.3 wt.%) highlight the ferruginous nature of these soils formed under oxidizing tropical conditions. The SiO_2/Al_2O_3 ratios (5.05–5.62) and Chemical Index of Alteration (CIA: 42.2-49.6) indicate low to moderate degrees of chemical weathering, consistent with incomplete alteration of feldspars and limited leaching of mobile cations (Ca^{2+}, Na^{+}, K^{+}).

Loss on Ignition (LOI) values, measured at 5.91 % (GA1), 5.98 % (MA1), 4.69 % (LA1), and 5.97 % (MO1), show how much organic matter and water are present in the soil. These low LOI values are typical of weathered lateritic soils and suggest minimal organic content. This is consistent with the observed chemical weathering and ferruginous enrichment [42]

The A-K ternary diagram (Figure 7) confirms this weathering stage [43]. The samples are positioned near the CN-K join. This suggests that pedogenesis has not yet produced aluminous phases like gibbsite [13]. These geochemical trends are consistent

with soils reported in other regions of Cameroon. They display high silica content, moderate alumina, ferric oxide enrichment, and CIA values indicative of weathering stages [7, 8, 13-15].

Such chemical characteristics are important for making cement-stabilized earth blocks. The quartz fraction provides support. Clay minerals, iron oxides, and minor organic components contribute to particle cohesion and mechanical strength upon stabilization. Understanding the chemical composition, including LOI, informs both the reactivity during cement stabilization and the long-term durability of CEB [6,7].

3.3. Mechanical and durability performance of cement-stabilized CEB

The physico- properties of compressed earth blocks made from Kaélé lateritic soils depend on the intrinsic characteristics of the raw materials and the cement stabilization rate (Figure 8-11). The overall improvement observed with increasing binder content reflects enhanced interparticle bonding. It also shows reduced connectivity and matrix densification. This behavior is linked to the distribution. Graded soils promote better packing and lower porosity. Poorly graded materials with insufficient fines exhibit cohesion at low stabilization [1,11].

Erosion resistance improves with increasing stabilization. Values approach the threshold of 10 mm/h at 8 % (Figure 8). This behavior is controlled by optimization and plasticity. These factors favor the development of a cohesive matrix resistant to water-induced degradation. [44,45].

Water absorption values (7.48-14.08 %) are within the limit of 15 % defined by Cameroonian standards (Figure 9). These values are controlled by stabilization and geochemical composition. The high silica content ensures a granular framework. Moderate alumina content is associated with minerals responsible for plasticity. At stabilization (4 %), instability in some samples (GA1) is due to low plasticity indices and insufficient clay fraction [36,46,47]. Increasing cement content (6-8 %) enhances compactness. It forms C-S-H phases, reducing porosity and water uptake. Abrasion resistance improves significantly with stabilization (Figure 10). This is due to cementation particle interlocking and the presence of iron oxides. Soils with plasticity further enhance surface cohesion. They limit particle detachment under stress [48,49].

Figure 11 shows that compressive strength (1.36-4.08 MPa) increases with cement content. It also reflects the influence of granulometry, plasticity, and geochemistry. Lower values at 4 % are associated with clay content and low plasticity. Higher strengths at 6–8 % result from cement hydration and the presence of reactive aluminosilicates. Moderate CIA values (42-50) indicate weathering. They show the persistence of minerals to stabilization reactions [15,50].

Overall results indicate that a stabilization rate of 6-8 % provides a balance between strength, durability, and water resistance. The observed variability highlights the coupled role of granulometry, geochemical composition, and Atterberg limits in controlling CEB performance. This confirms the suitability of Kaélé soils for sustainable construction.

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5. Conclusions

This study assessed the suitability of soils from Kaélé for making cement-stabilized compressed earth blocks. It integrated geochemical and mechanical analyses. The results show that the investigated soils generally exhibit particle size distribution and low-to-moderate plasticity. These are favorable for CEB production.

However, some variability related to clay content and grading highlights the importance of soil selection and possible formulation adjustments. Geochemical analyses reveal silica compositions with moderate alumina and iron contents. CIA values indicate weathering. This confirms the presence of mineral phases conducive to cement stabilization.

Mechanical and durability performances are strongly influenced by cement content. Increasing stabilization from 4% to 8% significantly enhances strength. It reduces water absorption. Improves resistance to abrasion and erosion. These improvements are attributed to matrix densification and the formation of compounds.

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Table 1 Summary of main physical characteristics of the soil used in this research

Sampling code	**MA1**	**LA1**	**GA1**	**MO1**
Soil provenance	Mazang	Lara	Gabane	Moumour
Coordinates	14°28' E 10°05 N	14°30 E 10°9 N	14°25 E 10°10 N	14°20 E 10°05 N
Color (dry)	Reddish brown (2.5YR5/4)	Reddish brown (2.5YR5/4)	Reddish brown (2.5YR5/4)	Reddish brown (2.5YR5/4)
Textural class	Sandy clay	Sandy silt	Sandy silt	Sandy silt
Structure	Massive	Massive	Massive	Massive
Rock fragment /nodule(Φ>5 mm)	10%	10%	5%	10%
Lithology	Granite	Granite	Granite	Granite
Special feature	Ferruginous concretion Angular quartz grains	Relict bedrock Angular quartz grains	Ferruginous concretion Angular quartz grains	Ferruginous concretion

Table 2 Geotechnical properties and geochemical Composition of studied lateritic soil

	GA1	MA1	LA1	MO1	Recommended proportion for CEB [39]
Particle size distribution (%)					
Clay (< 0.002 mm)	25.33	15.06	13.49	20.44	10 - 15 %
Silt (0.02≥Φ≥0.002	37.92	24.90	22.99	29.89	10 -25 %
Sand : (2≥Φ≥0.02)	22	30.56	14.68	36.08	55 - 75 %
Gravel: (Φ≥2mm)	36.8	40.64	57.64	30.44	0 -25 %
Atterberg Limits					
Liquid limit (%)	46.79	41.02	30.69	23.79	25 - 50
Plastic limit (%)	19.7	23.01	14.89	14.92	20 - 35
Plastic index	27.09	18.01	15.79	8.87	2 - 30
Geochemical composition (%)					
SiO_2	61.69	61.74	65.19	62.35	
Al_2O_3	12.04	12.23	11.59	12.06	
Fe_2O_3	8.02	5.7	7.55	8.3	
CaO	11.35	14.35	13.33	12.85	
MgO	0.39	0.33	0.17	0.25	
Na_2O	0.23	0.23	0.63	0.56	
K_2O	0.65	0.88	1.95	0.95	
P_2O_5	0.1	0.05	0.03	0.05	
LOI	5.91	5.98	4.69	5.97	
SiO_2/Al_2O_3	5.12	5.05	5.62	5.17	
CIA : Chemical alteration index	49.61	44.17	42.15	45.65	

SiO_2/ Al_2O_3: Ruxton ratio: CIA: Chemical alteration index; LOI: Loss on ignition

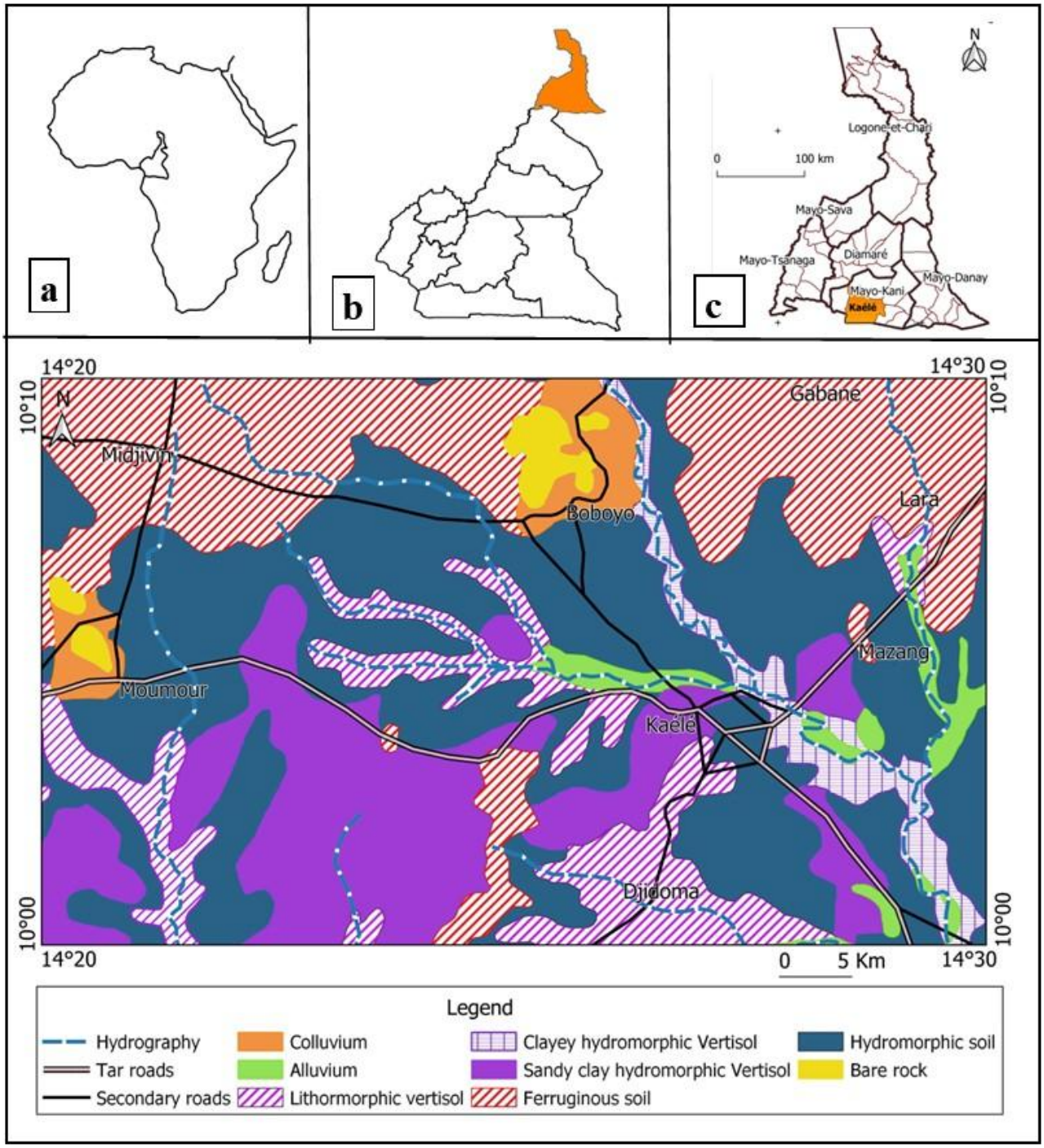


Figure 1 (**a**) Location of Cameroon in Africa, (**b**) Location of Far North Region in Cameroon, (**c**) Location of Mayo Kani Department on the map of the Far North Region, (d) Location of the study area illustrated in an excerpt from the Kaélé soil map, IRCAM 4, 1963 1:100000

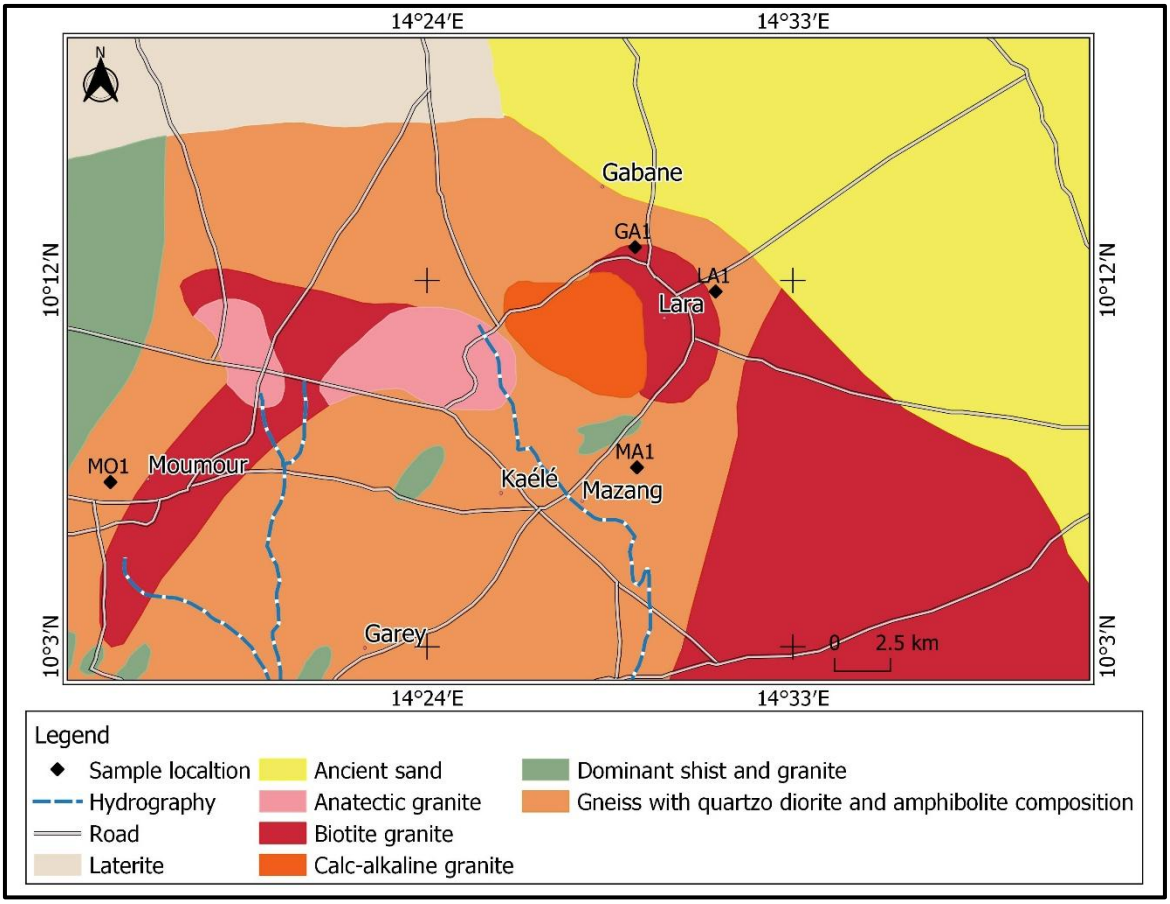


Figure 2 Geologic Map of the Study Area extracted from Geological reconnaissance map of theFederal Republic of Cameroon: sheet NC 33 Number E62.

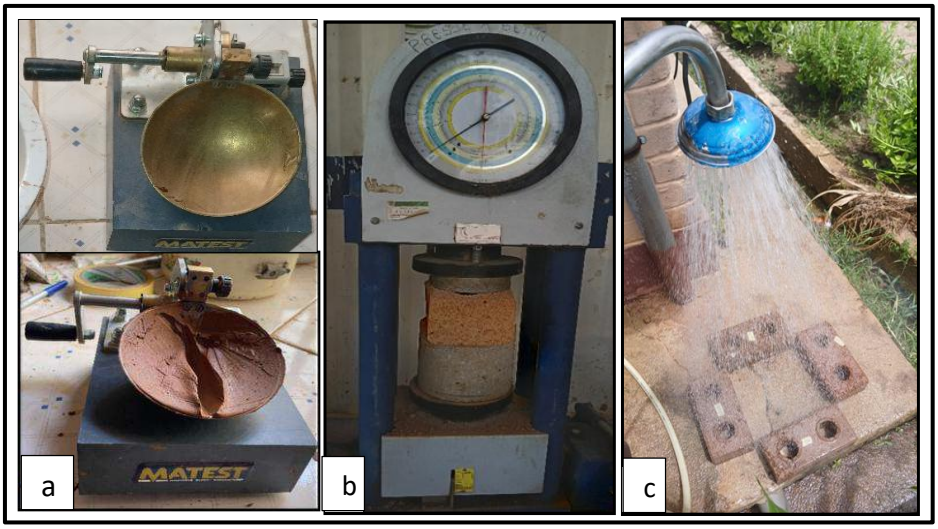


Figure 3 Photograph of lateritic soil using Casagrande apparatus, (b) Compression test on a CEB (c) Erodibility test setup

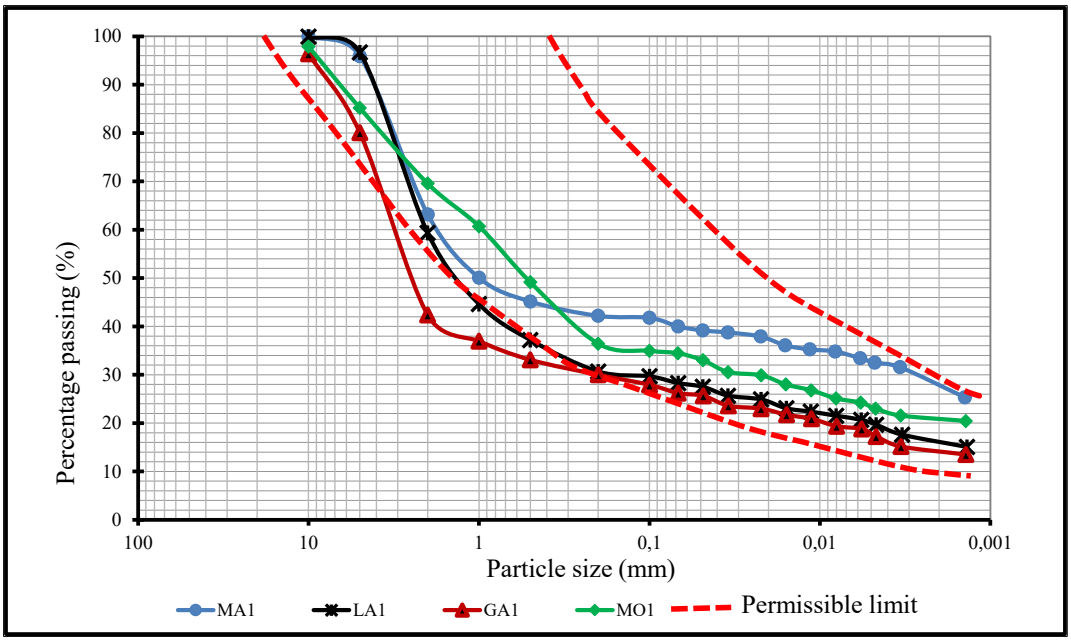


Figure 4 Particles size distribution projected into the grading envelope of soils materials used for the production of compressed earth bricks according to the NC 102-114 [38] standard.

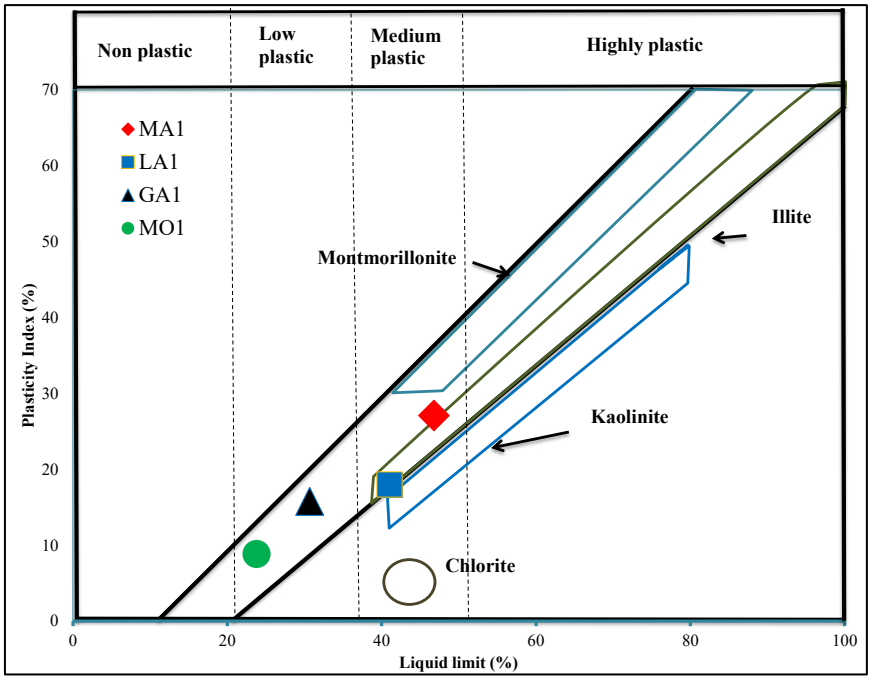


Figure 5 Casagrand's plasticity chart [29] showing representative clay material samples.

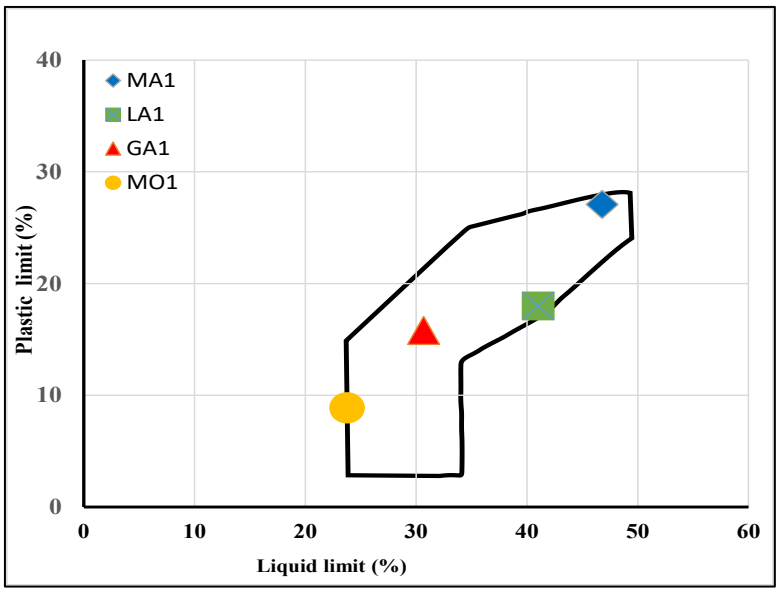


Figure 6 Recommended plasticity spindles for building with BTC and Adobe according to French standards [38].

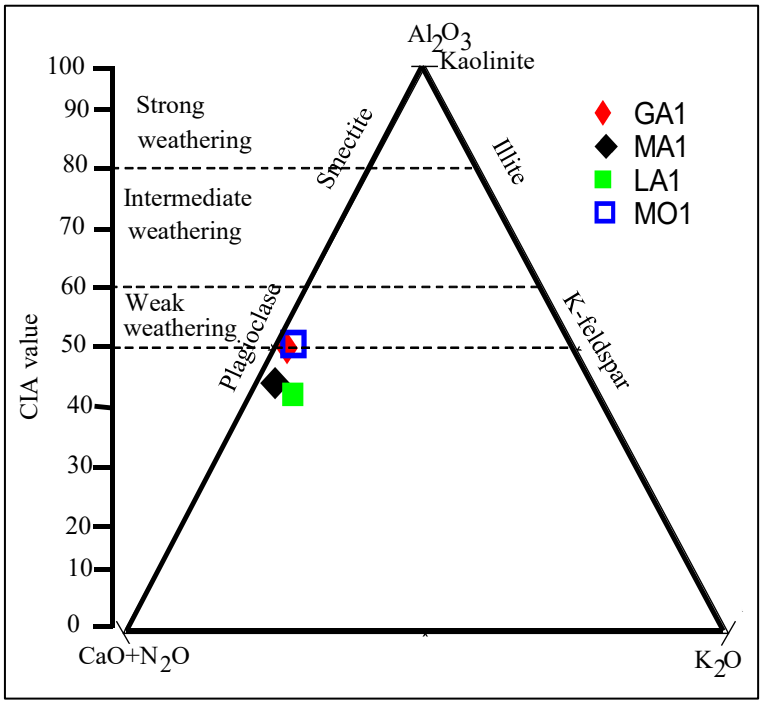


Figure 7 Position of the studied clayey materials in the ternary diagram of Nesbitt and Young [42]

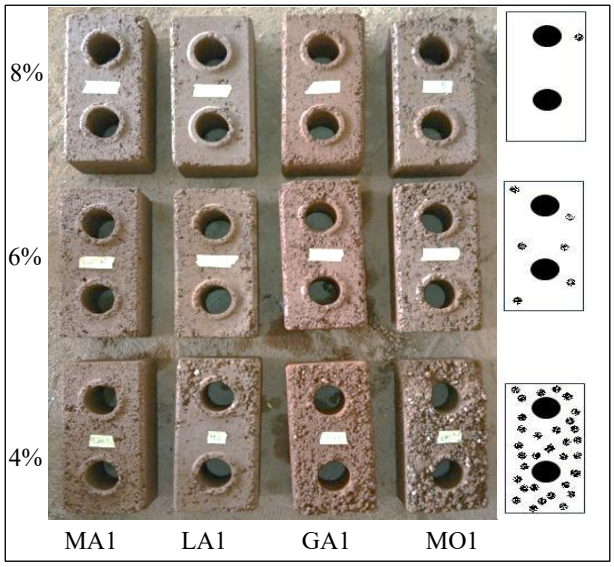


Figure 8 Aspect of CEBs after the erosion test.

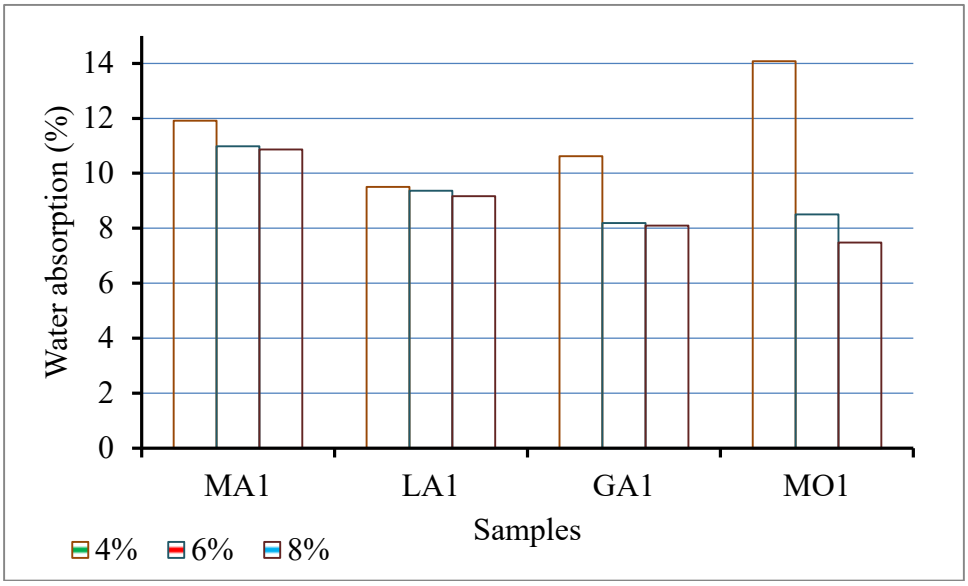


Figure 9 Water absorption coefficients of CEB at different percentage.

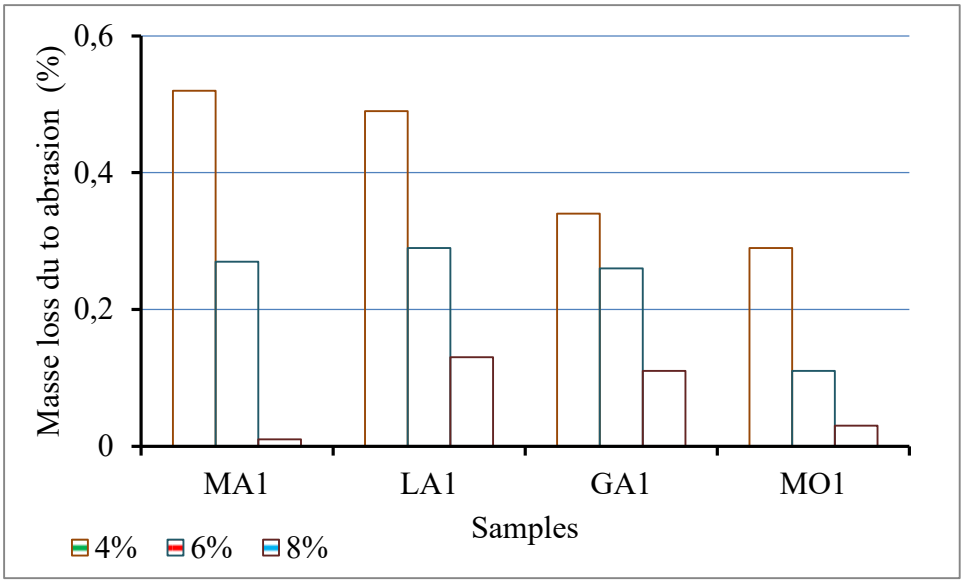


Figure 10 Mass loss due to abrasion of CEB at different percentage

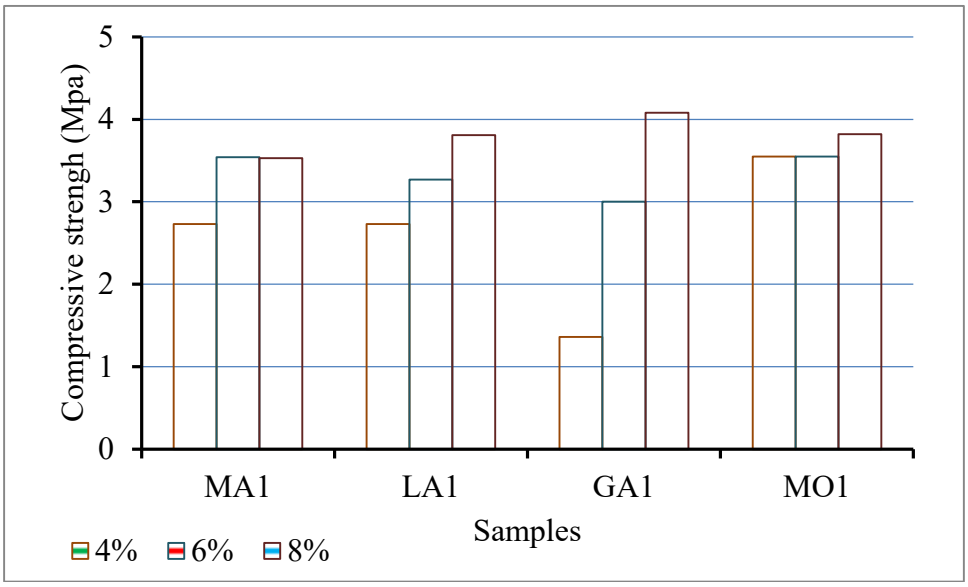


Figure 11 Compressive strength of CEB at different percentage.