Influence of metal oxides and particle size on earthen mortar built with tropical soils

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ABSTRACT French Guiana heavily relies on high-cost imported materials to sustain its strong population growth and construction demand. Local alternatives such as earth concrete are needed to reduce the use of conventional concrete. It is currently unknown if tropical soils are suitable for non-cement stabilized earth construction and especially what are the characteristics of these soils. In this study, 14 soils were characterized (particle size, EDS-SEM, FTIR, color) and evaluated as building materials on earth mortar prismatic specimens. For each soil, physical and mechanical mortar properties were evaluated based on two formulations of equivalent plastic consistency, with or without dispersant (0.5% of dry mass). The results show that hardened mortar properties were driven by water content at fresh state, particle size, and Fe and Al-oxide content. Water content directly correlated with fine-grains content and negatively impacted all mortar properties. The use of dispersant reduced water content and considerably improved compressive strengths, reaching up to 4 MPa. Compressive strength positively correlated with Fe and Al content and could be predicted by soil color. Overall, the characterized soils demonstrated good mechanical aptitude when mixed with a low level of dispersant, indicating a high potential for construction, particularly for metal oxide-rich soils.

Keywords Earth mortar, Tropical soil, dispersant, compressive strength, metal oxides

I. INTRODUCTION

The population of French Guiana in northeastern South America is expected to double in the next ten years, developing a high demand for new infrastructure. Currently, construction's economic and environmental cost is exceptionally high, owing primarily to the importation of most raw construction materials, such as clinker, the main constituent of cement. Alternatives to conventional, high-cost cement materials are desperately needed.

Earth construction is a building material made of soil and water with or without additives or binders. It is a local alternative recognized for its low environmental impact and high recyclability. French Guiana has no earth construction tradition. As an alternative, a local company provides a stabilized (cement) compressed earth brick (SCEB), but even a low percentage of cement incurs a high environmental cost for a moderate mechanical improvement (Van Damme and Houben, 2018). A local alternative without a hydraulic binder stabilization is critically needed. The objective of this study was to evaluate whether tropical soils present in French Guiana could represent a suitable earth construction material.

Soil evaluation for earth construction is considered crucial as not all soils are suitable for construction (Jiménez Delgado and Guerrero, 2007). Studies based on French soils or Greek soils (Lagouin et al., 2021; Meimaroglou and Mouzakis, 2019) have shown a strong association between soil properties, such as cation exchange capacity and particle size on earth mortar mechanical properties. It is currently unknown whether tropical soil could represent a suitable earthen construction material without any hydraulic binder addition.

Physical properties of tropical soil, such as mineralogy or particle size, are determined by the parent rock (Oyelami and Van Rooy, 2016). Tropical soils generally have a high proportion of fine-grains particles (Rashid et al., 2017). Tropical soil is mainly composed of kaolinite (1:1 clay), Fe-oxides (hematite, goethite), and Al-oxide (gibbsite). Aluminum and iron oxide were found to strengthen soil structure, but their exact role is still not clearly understood (Goldberg, 1989; Zhang et al., 2016). Iron oxides and their hydrates contribute to cement clay particles together, forming strong aggregate (Goldberg, 1989). The stabilizing effect of iron and aluminum oxides on soil physical properties (aggregate stability, friability, porosity) is well acknowledged (Goldberg, 1989). However, the influence of these metallic oxides on reworked soils, i.e., soil samples whose natural soil structure has been destroyed, such as those of earthen construction, is not yet established.

Different additives can be added to earth formulation to optimize its properties. A trend in earth construction science is the use of dispersants to deflocculates the clay fraction, acting as a superplasticizer (water reducer) of earth mortar. Sodium hexametaphosphate (HMP) is one of the most studied dispersants for earth construction (Van Damme and Houben, 2018). Using HMP can reduce water content, decrease porosity, and increase density and compressive strength (Guihéneuf et al., 2021). It's unclear if these findings extend to tropical soils with high levels of iron and aluminum.

This study aims to characterize some of the diversity of soils encountered in French Guiana to determine their suitability as an earth construction material. The correlation between specific quickly measurable soil properties (grain size, chemical composition, mineralogy by FTIR, color) and physical (density, loss of mass, shrinkage) and mechanical (flexural and compressive strength) of soil earth mortar is then investigated in this study. The results of this study will likely contribute to the evaluation of tropical soils for earthen construction by identifying some quick-to-measure soil parameters that can be used to select suitable soil for unstabilized earth construction.

II. MATERIALS AND METHODS

A. Raw materials

The raw materials used in this study were soil, Sodium hexametaphosphate (HMP, 99% pure), and distilled water. Fourteen soil samples from 7 different quarries were collected on the French Guiana coast. Soil samples were selected to represent the different soils present the quarries of French Guiana, with different textures, colors, and geological origins. Names of the soil samples are given according to the first letter of the closest city (A: Awala, C: Cayenne, M: Mana, K: Kourou, S: Sinamary, SLM: Saint-Laurent-du-Maroni, and T: Tonate) and numbers are added when different samples are taken in a single quarry. All samples were taken from laterite quarries except the T sample that was from a granite quarry. Geological characterization is a key factor to consider for soil selection. The source rock of the 14 soil samples was defined according to the different detailed geological maps produced and established under the direction of Boris Choubert from 1956 to 1962. For the soil collected, three types of formation are described in geological maps. Soil samples A, C, and T came from altering an igneous rock corresponding to different kinds of granite. Soil samples K and S came from altering an ancient metamorphic rock described respectively as amphibolite and Schist and staurolite mica-schist, garnet. M and SLM come from recent marine and fluviomarine deposition described respectively as red and white clay, clay sand and gravel, soft yellow sandstone, and clastic rock (white sand). The seven selected quarries showed different geological origins.

B. Soil characterization

Four physico-chemical properties (particle size, color, chemical composition, chemical bond) were chosen for their simplicity, accuracy, and speed of measurement:

- **Particle size** was defined by wet sieving according to NF P94-056 on fraction (0-2 mm).
- **Colors** were defined using a digital Munsell Soil Color Chart. Soil samples (0-2 mm) were moistened until a liquid paste was obtained, poured on a metal plate in a 3cm-diameter disk, and photographed after dry 6 h in laboratory conditions (25°C±3°C- 80%±15 RH) (Fig. 3a). Colors are defined according to a hue (H), a value (V), and a chroma (C). Hue letter (H = 0.0, 2.5, 5.0, 7.5 and 10.0) corresponding to Munsell sheets 10R, 2.5YR, 5YR, 7.5YR and 10YR (R for red, YR for yellow-red) (Table 1). Value represents the brightness of the color, from 0 (corresponding to absolute black) to 10 (absolute white). Chroma represent the relative purity of the spectral color. Color can help predict soil mineralogy (Ajayi, 2012).
- **Elemental composition** was measured by energy dispersive x-ray scanning electron microscopy (EDS-SEM) spectroscopy. Three semi-quantitative EDS analyzes per sample were carried out on an area of 0.03 mm2 of uncoated soil sample (passing to 63 µm) placed on a carbon substrate.
- **Chemical composition** determined by Attenuated Total Reflectance-Fourier Transformed Infrared (ATR-FTIR) in the range of 4000-400 cm^{-1} with a 4 cm-1 resolution was realized on the same sample used in the EDS-SEM.

C. Mortar formulation and characterization

Two types of formulation were studied (F1 and F2). F1 is composed of only soil and distilled water, and F2 of soil, distilled water, and 0.5% HMP by dry mass. Preparation of the mortars is summarized in Fig.2. Shortly, the soil was first air-dried, and 2 mm sieved. Then, the elements passing through the sieve (2 mm) are oven dried at 105°C until a constant mass is reached. For F2 formulation, HMP (0.5% dry mass) was measured directly at the oven outlet on 2.5 kg of soil and directly mixed with a trowel before air cooling. 500 grams of the soil (F1) or of the mixed soil with HMP (F2) were left aside before adding water. Finally distilled water was gradually added to the soil (F1) or to the soil+HMP(F2) mix, and mix (2 min 65 rpm). To control the plasticity of the mixture, 3 penetrometer tests were carried out. A consistency of 15mm±2.5 mm (cone penetrometer depth measurement) was selected to ensure the paste's plastic consistency and allow easy molding. The consistency was adjusted by adding soil or soil+HMP mix when the penetration depth was greater than (>17.5 mm). However, when the targeted penetration depth was not reached(<12.5 mm), water was added. Water content of the fresh mortar was directly measured (ISO 17892-1). Mortars were cast by hand in 40x40x160 mm molds, previously lubricated with mineral oil, and stored in an air-conditioned room (25°C ± 1°C and 80\% ± 15 RH). Molds were removed at 72h, and mortar prisms dried under the same condition for 21 additional days. At 21 days, volumetric shrinkage, density, and mechanical strength were performed. Volume and density were measured with a caliper (±0.05mm) and balance (±0.05g). Flexural and compressive strength was realized with a 10 kN sensor at a constant speed of 0.01 kN/sec and 3 kN/sec, respectively. All measurement uncertainties of soil and mortar properties were calculated as the standard deviation of 3 measurements.

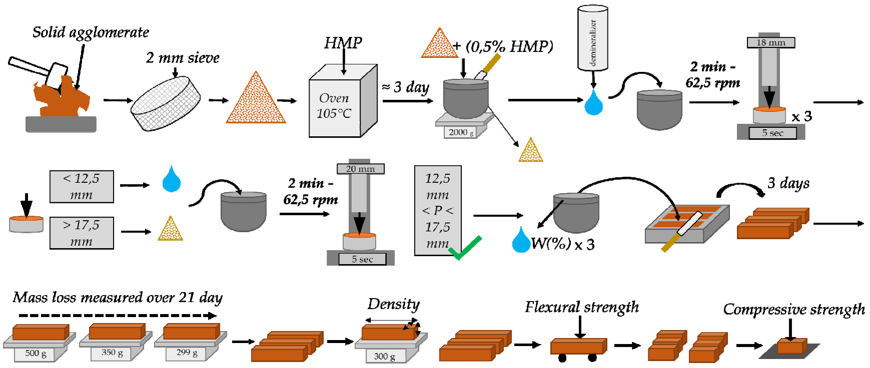

FIGURE 2. Protocol for the manufacture of 4*4*16 cm earth prismatic mortar specimens

III. RESULTS

A. Soil characterization

The color of tropical soils can help to understand the mineralogy (Ajayi, 2012). Colors of the 14 soil samples were evaluated using the Munsell soil color chart (Fig.3.a). Colors was defined in a hue (H), value (V) and chroma (C) (Table 1) ranged from green, white, pink to dark red and brown, representing the diversity of colors found in tropical soils.

Particle size is the characteristic most used to determine the suitability of a soil for earth construction (Jiménez Delgado and Guerrero, 2007). Particle size of the 14-soil varied importantly (Fig.3.b). Fine-grains content (<63 µm) of the mortar fraction (0-2mm) (Table 1) ranged from 41% to 89%, except for M2 soil (16%). These values were outside of the boundaries often suggested in the literature and standards for earth construction, which usually recommend a fine-grains (<63µm) content lower than 40% (Jiménez Delgado and Guerrero, 2007; Ronsoux et al., 2014). The soils selected presented various particle sizes with very high levels of fine-grains, which is typical of tropical soils.

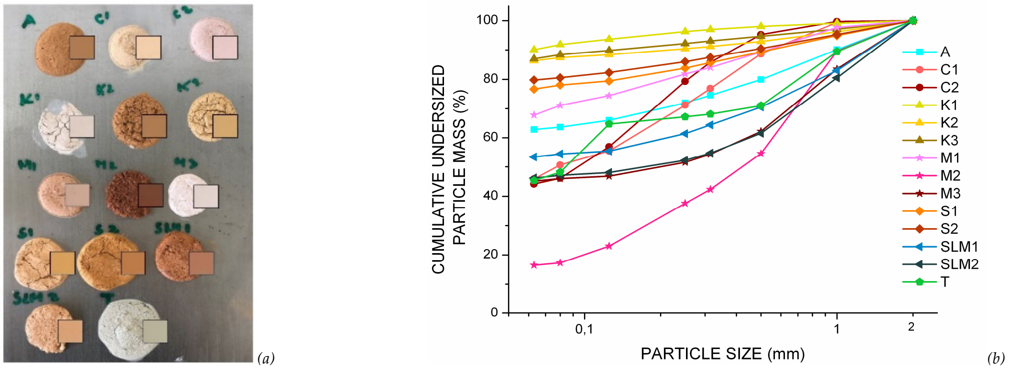

FIGURE 3. Color of the 14 samples defined with Munsell soil color charts (a), particle size of the 14 soils samples (b)

Soil mineral composition was measured using Fourier Infrared Spectroscopy (FTIR), which identifies chemical bonds present in soil by peak absorbance. All soil samples contained characteristic kaolinite peaks (Fig.4). In addition, K2, S1, S2, SLM1 and T presented peaks characteristic of gibbsite. Gibbsite is an aluminum oxide composed of stacked octahedral sheets of Al(OH)3. OH-stretching modes of gibbsite are commonly found around 3373, 3393, 3455, 3526, and 3620cm^{-1} (Balan et al., 2006). However, the peaks identified at 3452 cm^{-1} and 3396 cm-^{1}

coincide with the OH-stretching modes of goethite (Negrão et al., 2021) (Prasad et al., 2006). Besides, the peak found at 3377 cm^{-1} had low intensity. Goethite is a polymorph iron oxyhydroxide FeO(OH). The low intensity broad band found around 3150cm^{-1} coincides with OH-stretching modes of goethite (Prasad et al., 2006). To distinguish between goethite and gibbsite, the area under the peak at 3526 cm^{-1} was chosen to unequivocally measure the proportion of gibbsite, while the area under the peak at 3150 cm^{-1} was chosen to identify goethite. In summary, FTIR revealed the presence of three types of minerals in the 14 soils: kaolinite, gibbsite, and goethite.

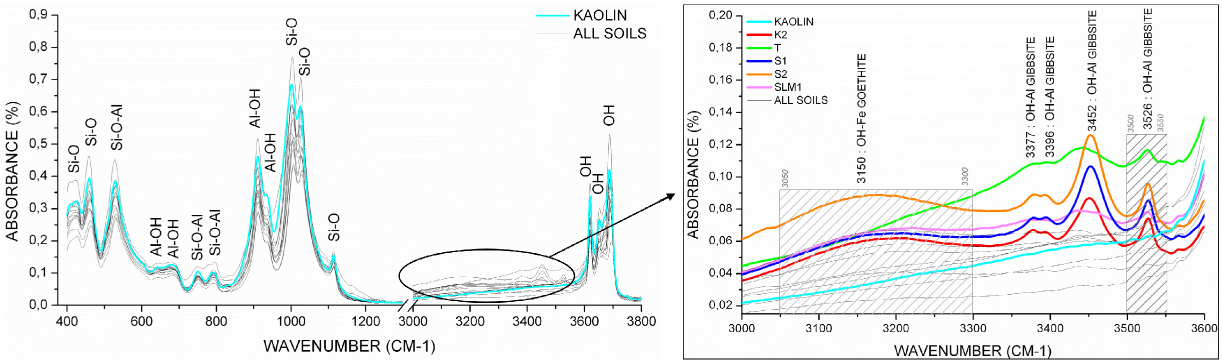

FIGURE 4. **FTIR spectra of the 14 soil samples and pure kaolinite in the range 400-4000cm^{-1} with a zoom on the region 3000-3600 cm^{-1}.**

The determination of the chemical composition of the soils revealed only eight elements (C, O, Si, Al, Fe, Ti, K, S). The substrate of the analyses sample was in carbon, soil samples are subject to oxidation. Thus, carbon and oxygen were removed from the results to better interpret the results. Silicon was the principal element followed by aluminum and iron. The total elementary mass of the other elements (K, S, Ti) systematically represents less than 6% of the sample. The 14 soil samples were composed mainly of silicon, aluminum, and iron in different proportions, which is characteristic of tropical soils.

TABLE 1. **Measured soil properties**

Soil Sample	Passing	Color			FTIR : Peak area		EDS: wt (%)(excluding carbon and oxygen)					
	<63µm	H	V	C	Gibbsite	Goethite	Al	Si	Ti	Fe	K	S
A	62.83	7.5	6 ± 1	6 ± 1	3.3	80.2	33.57±0.5	47.1 ±0.7	2.8 ±0.1	16.3 ±1	0.3 ±0.1	0 ±0
C1	45.90	5	8 ± 1	4 ± 1	3.6	35.4	37.7 ±2.6	53 ±3.5	0.8 ±0.2	8.5 ±0.8	0 ±0	0 ±0
C2	44.18	0	8 ± 1	3 ± 1	4.1	2.3	40.6 ±1.7	50.5 ±1.8	0.9 ±0.2	6.4 ±1.6	1.6 ±0.4	0 ±0
K1	90.07	5	8 ± 1	2 ± 1	5.2	5.4	40.5 ±0.4	50.9 ±1.4	2.7 ±0.9	5.9 ±1.0	0 ±0	0 ±0
K2	86.36	7.5	6 ± 1	6 ± 1	37.6	169.9	35.8 ±1	34.1 ±0.6	2.5 ±0.5	27.6 ±1.8	0 ±0	0 ±0
K3	87.00	7.5	7 ± 1	6 ± 1	9.7	131.2	40.2 ±0.1	43.5 ±0.2	1.3 ±0.1	15.1 ±0.1	0 ±0	0 ±0
M1	67.80	2.5	7 ± 1	4 ± 1	5	34.5	40 ±0.7	46.6 ±0.4	2.7 ±0.1	9.8 ±0.4	0.9 ±0.1	0 ±0
M2	16.47	2.5	4 ± 1	6 ± 1	6.6	145.3	26 ±1.2	38.9 ±1.1	2.7 ±0.1	31.8 ±0.9	0.6 ±0.1	0 ±0
M3	45.11	2.5	8 ± 1	2 ± 1	6.1	8.0	39.4 ±0.6	53.4 ±1	1.5 ±0	4.6 ±0.7	1.1 ±0.1	0 ±0
S1	76.65	7.5	7 ± 1	8 ± 1	39.7	142.3	35.7 ±0.1	36.5 ±0.9	3.6 ±1.4	23.4 ±0.4	0.6 ±0	0.3 ±0
S2	79.77	5	6 ± 1	8 ± 1	46.1	211.9	32.5 ±0.7	31.8 ±0.7	2.9 ±0.2	31.8 ±1.6	0.6 ±0.1	0.5 ±0.2
SLM1	53.37	5	6 ± 1	6 ± 1	14.5	131.6	37.6 ±0.3	40.4 ±1.4	1.9 ±0.1	19.6 ±1.6	0.5 ±0.1	0 ±0
SLM2	46.20	2.5	7 ± 1	6 ± 1	3.7	101.9	39.8 ±0	45.4 ±1	1.2 ±0.1	12.2 ±1.2	1.4 ±0.3	0 ±0
T	45.36	10	7 ± 1	2 ±1	21.3	-12.0	29.3 ±0.6	58.8 ±0.5	1.5 ±0.2	6.4 ±0	4.1 ±0.9	0 ±0

The 14 characterized soils showed different particle sizes, colors, and chemical compositions, representing the diversity of Guyanese soils. Soil samples from an identical parent rock (same quarry) encountered varied physicochemical characteristics.

B. Mortar characterization

The physical and mechanical properties of earth mortar were evaluated after sieving at 2mm, for each of the 14 soils sampled. Earth mortars were prepared with two formulations F1 and F2, without or with the presence of dispersant (0.5% of HMP), respectively. Mortar consistency was measured with a target penetration depth of 15mm±2.5 mm. The ratio of water and soil was adjusted during mortar preparation until the target consistency was attained. Of note, with the F2 formulation, the presence of dispersant fluidified the mixture more than expected, which prevented F2 mortars to reach our target consistency. Water content was measured after mixing. Mortars were then molded into a prismatic specimen (4*4*16cm) and cured for 21 days of drying. The water content (%), penetration depth (mm) of the fresh state, the volumetric shrinkage (%), density (g/cm3), flexural strength (MPa), and the compressive strength (MPa) of the hardened earth mortar (21-day drying) are summarized in Table 2. Values in **red** indicate measurements outside the target range of penetration depth (≠15mm±2.5), values in **blue** indicates shrinkage values accepted by the DIN 18945 standard (VS ≤7.9% equivalent to LS≤2.5%), and in **green**, compression values accepted by the DIN 18945 and XP 13-901 standards (>2MPa).

TABLE 2. Measured properties of mortar formulation

Soil sample	Penetration depth		Water content (%)		Volumetric shrinkage (%)		Density (g/cm³)		Flexural strength (MPa)		Compressive strength (MPa)	
	F1	F2	F1	F2	F1	F2	F1	F2	F1	F2	F1	F2
A	14.73 ±1.1	22.04±2	39.57 ±0.2	21.1 ±0.3	16.24±0.7	**6.29 ±1**	1.58 ±0.01	1.79 ±0.02	0.49 ±0.1	0.81 ±0.1	1.2 ±0.1	**3.96 ±0.2**
C1	15.5±1.7	28.23±1	32.04 ±0.3	16.45 ±0.1	10.9±0.3	**6.9 ±0.7**	1.62 ±0.01	2 ±0.01	< 0.3	0.81 ±0	0.55 ±0.1	**2.75 ±0.1**
C2	14.71±0.8	20±1.6	31.12 ±0.2	24.18 ±0.1	10.58±1.1	8.19 ±0.9	1.62 ±0	1.71 ±0	< 0.3	< 0.3	0.64 ±0	1.04 ±0.1
K1	14.84±1.0	-	59.54 ±0.3	28.5 ±0.2	24.39±0.3	13.11 ±1.5	1.4 ±0.03	1.71 ±0.02	0.35 ±0	0.69 ±0.1	0.66 ±0	**2.32 ±0.3**
K2	15.26±1.2	13.55±1.6	52.33 ±0.1	37.34 ±0.2	19.99±0.5	15.01 ±0.6	1.49 ±0.02	1.66 ±0.02	0.38 ±0	0.85 ±0.1	1.3 ±0.1	**3.53 ±0.3**
K3	16.12±0.6	13.85±0.9	58.84 ±0.2	38.46 ±0.8	20.54±0.8	15.66 ±0.3	1.4 ±0.03	1.59 ±0	< 0.3	0.52 ±0	0.67 ±0	1.76 ±0.1
M1	14.8±0.8	-	52.76 ±0.3	22.94 ±0.2	25.93±0.1	7.96 ±1.2	1.53 ±0.02	1.76 ±0.01	< 0.3	0.75 ±0	1.04 ±0.1	**2.76 ±0.2**
M2	14.86±0.9	12.18±0.9	22.08 ±0.3	12.22 ±0	**1.78±0.4**	**-0.52 ±0.7**	1.68 ±0.01	1.84 ±0.01	< 0.3	0.57 ±0	0.42 ±0.1	**2.3 ±0.1**
M3	15.29±1.2	-	31.78 ±0.3	17.82 ±0.1	10.9±0.8	**5.28 ±0.3**	1.6 ±0.01	1.88 ±0	< 0.3	0.37 ±0	0.21 ±0	1.3 ±0.1
S1	15.82±1.2	17.48±1.6	43.21 ±0.2	28.36 ±0.4	15.54±0.7	11.1 ±0.7	1.55 ±0.01	1.77 ±0.01	0.39 ±0.1	1.29 ±0.1	1.51 ±0.1	**4.27 ±0.2**
S2	14.16±0.7	19.05±2.2	42.68 ±0.2	37.18 ±0.1	17.9±0.2	17.58 ±0.6	1.62 ±0	1.74 ±0.01	0.8 ±0.1	1.52 ±0.1	**2.53 ±0.2**	**4.06 ±0.3**
SLM1	16.57±1.5	17.32±0.9	41.21 ±0	20.72 ±0	15.87±0.4	**5.61 ±0.2**	1.55 ±0.01	1.81 ±0	0.32 ±0.2	1.2 ±0	1 ±0.1	**3.79 ±0.2**
SLM2	12.55±1.5	34.42±1.5	34.72 ±0.4	15.74 ±0.1	10.91±1	**2.58 ±2.4**	1.57 ±0.01	1.94 ±0.02	< 0.3	1.38 ±0	0.57 ±0.1	**3.25 ±0**
T	13.78±0.9	14.63±4.1	23.41 ±0.1	13.85 ±0.3	10.09±0.6	**7.25 ±1.3**	1.83 ±0.01	2.06 ±0.03	0.63 ±0	1.06 ±0	1.65 ±0.1	**3.91 ±0.1**

Earth construction standards generally define two fundamental criteria to qualify the suitability of earth materials for construction : compressive strength (CS) and shrinkage. The XP P13-901 (French standard) and DIN 18946 (German standard) recommends compressive strengths greater than 2 MPa for earth brick. In this study, only 1 soil of F1 and 11 soil of F2 met this standard (green in Table 2). Shrinkage threshold is often presented as maximum linear shrinkage (LS) in standards, although volume shrinkage (VS) is considered to better represents total shrinkage (Lagouin et al., 2021). The German standard (DIN 18946) recommends LS≤2.5%. There is not standardized threshold for volumetric shrinkage. Linear shrinkage (LS) was deduced from volumetric shrinkage (VS) using equation (1). With this relation LS≤2.5% correspond to VS ≤7.9%. Only one soil for F1 and seven soils for F2 met these criteria (blue in Table 2).

$$LS=100*(1-(100/(100+VS))^{\wedge}(1/3))) \qquad (1)$$

To conclude 6 F2 formulations (A, C1, M2, SLM1, SLM2, T) was found suitable for earth construction CS≥2 MPa and VS≤7.9 %. For these 6 soils, fine-grains content is less than 65 %. But the highest compressive strength CS=4 MPa ± 0.1 obtained for 4 soils in F2 formulations (A, S1, S2, T) were found for fine-grains content comprising between 45% and 80%.

C. Influence of formulation on mortar physical properties (shrinkage, density)

For formulation F1 (soil + distilled water) only the water content varied between samples (constant penetration depth). For formulation F2 (soil+0.5% HMP + distilled water), water content and penetration depth varied. Water content was found to be linearly correlated with all physical properties of mortar for all formulations combined (F1 and F2). Indeed, water content positively linearly correlated with volumetric shrinkage ($R^2=0.89$) and negatively linearly correlated with density ($R^2=0.82$). During drying, the water evaporates and increases the surface tension between the grains, causing the grains to come together and the mortar to contract. As the water evaporates, the mass loss increases, and air porosities decrease density. Between F1 and F2 formulation, water content was highly reduced (an average of 41% decrease), showing that the dispersant addition's efficiency since lowering water content increases all the mortar properties. Altogether, we found that water content was a key parameter to control during the formulation since it directed all the physical properties of the mortar.

D. Influence of particle size on formulation

Particle size is the most measured soil characteristic. It is observed that the proportion of fine-grains (<63µm) correlated with the water content require for formulation (F1 and F2). Indeed, fine-grains fraction composed of clay and silt (<63µm) of the mortar formulation was found to be positively linearly correlated with water content for F1 ($R^2=0.82$) and F2 ($R^2=0.75$) formulation (Fig.5a). The water content necessary to reach the targeted consistency increased with the fine-grains fraction content (<63µm) but was significantly lower with the dispersant (F2) showing the dispersant effect.

For each formulation, the higher the proportion of small grains, the greater the water content necessary to cover the surface of all the grains and thin the mixture. These results are in agreement with published studies. They also confirm the observation that fine-grains fraction content measured by particle size is a critical characteristic, since it controls the water content, which itself determine the physical properties of the mortar (Lagouin et al., 2021; Meimaroglou and Mouzakis, 2019).

E. Influence of particle size and water content on mortar mechanical properties

The W/C ratio is defined as the ratio between the water content and the mass of clay in the mixture. This ratio, inspired by cement techniques (water content/cement content) was used in earth construction and particularly to study poured earth (Ardant et al., 2020). In this study the W/(C+S) ratio was calculated, corresponding to water content (W) divided by the fine-grains fraction (<63µm) composed of clay and silt (C+S=Clay+Silt) of the mortar fraction (0-2mm). A linearly negative trend ($R^2=0.69$) was found between the compressive strength and the W/(C+S) ratio (Fig.5b). However, the linear regression is calculated without the formulations made with soil M2. This could be explained by the very different particle size of M2 (Fig.3b).

In summary, water content at fresh state and grain size are controlling the physical and mechanical properties of earth mortar.

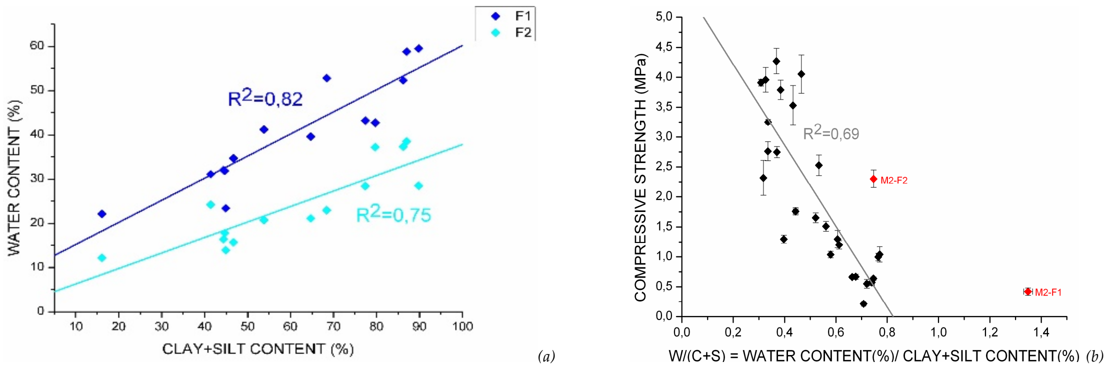

FIGURE 5. **Water content (%) versus Clay+Silt content (%) for each formulation (F1 and F2) (a) Compressive strength of all formulation (F1 and F2) versus ratio between water content (%) and Clay+Silt content (%) (b)**

F. Influence of iron and aluminum oxide on earth mortar mechanical strength

Soil chemical properties are known to have a strong influence on mechanical strength of earth mortar (Lagouin et al., 2021; Meimaroglou and Mouzakis, 2019). However, these studies are not based on tropical soil which is known to behave differently. In this study, it was found that iron and aluminum oxide acted positively on compressive strength. The ratio of Fe on the three principal element (Fe/(Si+Al+Fe)) was calculated and exponentially correlated with compressive strength for formulation F1 (R^2=0.83) (Fig.6a). Goethite FeO(OH) relative content (Table 1) linearly correlated with ratio of Fe (Fe/(Si+Al+Fe)) (R^2=0.85) (Fig.6.d) which validates that the peak 3150 cm^{-1} corresponds to Fe-OH bonds. Goethite also exponentially correlated with compressive strength for formulation F1 (R^2=0.69).The higher the iron content, the higher compressive strength. The relation was calculated without the M2 and T formulation. M2 seem to respond to different dynamic due to very low binding phase. T soil seem also to behave differently. All the soils were collected on subsoil (horizon B) except T soil which was collected directly above the granite. The color of T soil was markedly different compared to the other soil with a tint pulling on the green (Fig.2). Finally, gibbsite (aluminum oxide) also appeared to increase compressive strength. Results indicate than compressive strength of F1 for soils rich in gibbsite (K2, S1, S2, SLM1,T) was significantly higher (1 < RC < 2.45 MPa) than that of the 9 other soil (0.2 MPa < RC < 1.2 MPa). A linear trend was observed between gibbsite and compressive strength for all F1 formulations (R^2=0.67)(Fig.6c). In summary, the presence of gibbsite and iron oxide greatly increased compressive strength.

G. Influence of iron oxide on soil color

Soil color is known to be a good indicator of iron content (Curi and Franzmeier, 1984). Munsell Soil Color Chart have been used to predict iron content of soil. Indeed, the redness ratio (RR=(10-H)*C)/V) and the redness factor (RF=(10-H)+C/V) are good indicators of iron and aluminum oxide in soil (Ajayi, 2012). No correlation was observed between RR or RF and iron content. However, the C/V ratio, defined as Chroma/Value calculated with Munsell Soil Color Chart correlated in a logarithmic relation with iron content *(R^2=0.94)*(Fig.6.e) and linearly correlated with goethite content *(R^2=0.84)*(Fig.6.f). The measurement uncertainty of the C/V ratio, display Fig.6.e was calculated by considering C±1 and V ±1. The C/V ratio could be described representing intensity/brightness, the more the color is intense or dark the more the ratio C/V increase. The iron content measure with SEM-EDS and goethite content measure with FTIR seems to be correctly related with color intensity and darkness.

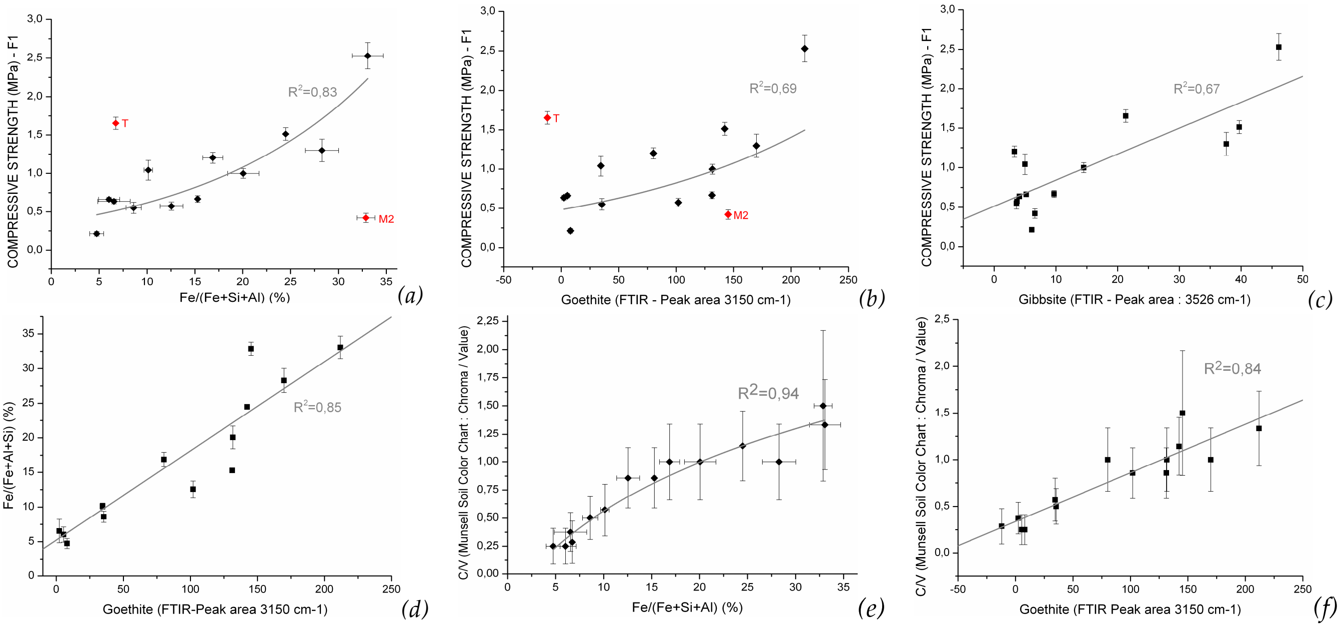

FIGURE 6. **Compressive strength versus iron ratio (a), Compressive strength versus goethite (b), Compressive strength versus gibbsite (c) Iron ratio versus goethite (d), C/V (Chroma/Value : Munsell soil color chart) versus the iron ratio (e), C/V (Chroma/Value : Munsell soil color chart) versus goethite (f)**

IV. CONCLUSION

This preliminary study showed than tropical soil of French Guiana seems suitable for earth construction when a low dosage of dispersant was added. Indeed, four soils were found to have compressive strength up to 4 MPa ± 0.1 which correspond to the compressive strength of one of the most-used concrete block. Among the 14 soils, six soils met two earth construction criteria (compressive strength > 2 MPa and volumetric shrinkage < 7.9 %) with low dispersant dosage. 11 soil meet the compressive strength criteria when mixed with dispersant, but high fine-grains content (> 65%) led to high volumetric shrinkage >7.9 %. However, the shrinkage criteria could be achieved by mixing a soil which has a high fine-grains content with sand or an equivalent.

It was found than some physical soil properties (fine-grains) were found highly influencing earth mortar properties. Indeed, the fine-grains content direct water content at fresh state and water content direct physical hardened mortar properties (density, shrinkage). Water content over fine grains content was found negatively correlated with earth mortar mechanical strength. Dispersant addition, low the water content over fine-grains ratio and therefore highly increase compressive strength. A chemical soil property (Al and Fe-oxide) measured by FTIR, and EDS-SEM was found to increase compressive strength and was found to be predict by soil color. Suitable tropical soil for earth construction seem to depend on two criteria, fine-grains content, and Al and Fe oxide content. Decreasing water content with dispersant was found highly effective. We propose for soil selection criteria to choose rich Al and Fe soil and sufficient fine-grains content (>40%) allowing high strength.

Different building techniques for earthen material–compacted, molded, extruded, poured, exists, and depends on the territory, local traditions, and available equipment. Importantly, earthen material properties were shown to strongly correlate with the soil properties, and not with the various building methods (Guihéneuf et al., 2021). For a given soil, an optimized water content for each forming technique leads to a similar range of dry density and strength. Consequently, the mechanical characteristics measured with one building technique, such as earth mortars, can be generalized to other methods.

Three aspects of the study could have been improved. First, all the usual characterizations were not carried out, which would have made it possible to compare the results better. Second, a drying of only 21 days was selected, not allowing complete drying of the specimens, particularly for the F1 formulations, thus probably lowering the mechanical strengths. Third, most of the F2 formulations had an overly fluid consistency and, therefore, a slightly increased water content, which likely decreased the mechanical properties of the mortar. However, the purpose of this preliminary study was to quickly determine the selection criteria for the soils of French Guyana, allowing good physical and mechanical earth mortar properties. This objective was obtained.

It must be pointed out that the region experiences a humid equatorial climate with high precipitation. Given the high sensitivity of earth construction to water ingress and the French Guiana's high precipitation, earth stabilization will still be needed. Biopolymer-stabilization (tannin, plant mucilage, seed extract, latex) could be used to prevent earth material from water degradation. An earthen material stabilized by local biopolymers would be a relevant economic and ecological choice.

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