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Mechanical Characterization And Water Resistance Of Raw Earth Materials Made According To Malagasy Traditional Technique

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Abstract – This study aims to contribute to a more responsible world, by stimulating the applications of natural building materials and the enhancement of the prestige of the Malagasy traditional building technique, more respectful of the environment.
To this end, preliminary investigations were carried out to formulate the tested samples and to study the preparation processes of the earthen pastes. Three different lateritic soils were studied and stabilized with cow dung and rice straw.
The results show that the soils used are rich in SiO_2, Al_2O_3 and Fe_2O_3. Introducing cow dung and rice straw with fermentation improves sample characteristics. Consequently, the sample density increases from 1728 to 1913 Kg/m^3. It also increases the dry and wet compressive strengths of our samples. From the 2nd week of the paste maturation time, the dry compressive strength increases from 0.64 MPa to 1.2 MPa and at the 24th week, it is 9 times higher than that of the beginning of the tests (5.4 to 6.5 MPa).
Regarding water resistance, the results show that from the 4th week of the maturation time, the samples withstand more than 24 hours of immersion in water and this resistance increases until the 24th week, becoming comparable to that of the Malagasy ancestral walls aged more than 100 years, which is equivalent to 7 days.

Keywords – Sustainable Construction; Eco-Materials; Formulation; Traditional Wall; Compressive Strength; Water Resistance.

INTRODUCTION

Earth is a traditional building material used throughout history in many places of the world [1]. Nowadays, we are also witnessing an important revival of its use due to its ecological value and architectural performance.

In Madagascar, ancestral walls called "*Tambohon'ny Ntaolo*", made of lateritic raw earth, are great emblematic works of the Central Highlands since the 19th Century ([2], [3], [4]). Currently, these walls are no longer exploited and their traditional making processes are forgotten. At best, new methods and design purely and simply downgrade the one which prevailed in the time of our ancestors. Indeed, recent constructions can hardly compare with those of the past. Under constant weather exposure, they can collapse quite easily, while in 100 years of existence, these old walls remain almost intact.

Thus, our objective is to enhance the prestige of this Malagasy heritage. We will thus try to research, from oral traditions and preliminary investigations, the forgotten processes and reformulate raw earth materials imitating the durability of these walls.

The present work studies the effects of the different types of soil and soil stabilization with cow dung and rice straw, as well as the effects of the paste fermentation time on the raw earth materials.

The first part will deal with the explanation of the preparation processes of the earthen paste. Then, in the second part, the physical characteristics, and the chemical and mineralogical compositions of the soils were studied. And finally, the compressive strengths and water resistance of the samples were measured.

I. MATERIALS AND METHODS

I.1. Raw materials

The three types of soil used in this study came from three different locations (Figure 1).The first was collected at Vontovorona (18°58′51.34″ South Latitude, 47°24′42.96″ East Longitude), located at 21 Km West of Antananarivo, and is labelled soil A. It is the reddish-brown soil. The other two were taken at Manandriana (18°48′49.94″ South Latitude, 47°35′05.25″ East Longitude), located at 25 Km North-East of Antananarivo and at Ambohinaorina (18°46′16.66″ North Latitude, 47°27′40.41″ East Longitude), at 35 km North West of Antananarivo, respectively labelled sol B and C. These two soils are reddish in color. The soils were extracted at a depth of one meter.

Rice straws belong to the *Poaceae* family and it is the part of the stalk cut during harvest that is used. The straws used in this study were obtained after rice harvest in a field near Ambohinaorina whereas the cow dung used was from the farm in Ambohinaorina Mahitsy. Well water was used in all mixtures.

Figure 1 : Visual aspect of the different types of soils used

I.2. Mixture preparation and sample design

The test formulations and making processes were compiled from conducted preliminary surveys and collected oral traditions.

Three formulations were made for the three different types of soil:

- Formulation 1 : without stabilization
- Formulation 2 : with stabilization by using cow dung
- Formulation 3 : with stabilization by using cow dung and rice straw.

The tests were conducted with 10 % cow dung and 1 % rice straw by weight of soil material for Formulations 2 and 3.

I.2.1. Earthen paste preparation

Paste preparation processes are common for the tests in order to have the same workability and consistency of the pastes. The amount of water used was calculated by applying the relation

$$w\ (\%) = (w_L + w_P)/2 \qquad (1)$$

This value indicates the average between the Liquid Limits (W_L) and Plastic Limits (W_P).

The cow dung was liquefied and mixed well in a container (Figure 2). That solution, together with the rest of the water, was gradually added to the soil, and the whole thing was well mixed and trampled to get a homogeneous mixture. After this, the dried rice straws, which had already been cut to about 10 cm in length, were added to it and the mixture was trampled intensively again for twenty minutes until a homogeneous mixture and a paste with the required perfect plasticity qualities was obtained. Then, the pastes were put in a sealed plastic box and left to rest for the desired times (2; 4; 8; 12; 24 weeks) to allow the cow dung and rice straw to ferment before the samples were made (Figure 3).

After the fermentation stage, the pastes were mixed and kneaded again after a slight re-wetting (Figure **4**).

Figure 2 : Cow dung preparation

Figure 3 : Earthen paste preparation stage

Figure 4 : Paste kneading after fermentation

I.2.2. Moulding and drying

The mixture was placed in a wooden prismatic mold of size 4*4*16 cm3. The molds were immersed in water for some time before the start of molding, so that they would become saturated. This ensured that they would not absorb water from the fresh mixture, and thus, the mixture would not stick to the mold during casting. The molds were then filled with the manually compacted wet mix. The top surface was straightened with a wooden tool and special attention was given to filling the four corners. Once the casting was complete, the molds were removed.

Drying was done naturally by placing the test pieces in the shade at room temperature. They were covered with a dark colored plastic film in order to ensure its tightness. This method is intended to avoid thermal shocks that could cause cracks. The drying process lasted for about 21 days, until a constant mass was obtained.

I.3. Experimental procedures

I.3.1. Physical, chemical and mineralogical characterization of soils

Water content was determined by oven drying method, according to the standard (NF P94-050, 1995) [5].

The soil size distribution was analyzed using two techniques: the coarser fraction (>80 µm) by wet sieving (NF P94-041, 1995, pp.94-041) [6] and the finer fraction (<80 µm) by analysis using the method based on the measurement of the sedimentation time of solid particles suspended in a solution of water mixed with sodium hexametaphosphate ((Na_6 $(PO_3)_6$,$10H_2O$) as a deflocculating agent (NF P94-050, (1995) [7].

The specific weight was measured using a pycnometer. Samples were crushed to obtain material grains of sizes less than 0.2 mm.

The geotechnical characteristics of the soils were determined by measuring Atterberg limits in accordance with the standard NF P94-051, 1993, pp. 94-051 [8].

The pH was measured by diluting soils in a distilled water with the mass ratio of 1:5 according to NF ISO 10390 standard. The pH was measured with a pH meter.

The chemical composition was identified by inductively coupled plasma atomic emission spectrometry (ICP-AES). The loss on ignition was evaluated after calcination of the sample at 1000°C.

X-ray diffraction (XRD) and thermogravimetric analysis (TGA) were used to evaluate the mineralogical composition of the soil. The XRD apparatus used was a Brucker D8-Advance equipped with a SOLLER rear monochromator and a cobalt anticathode (CoKα). The identification of the minerals is carried out with the EVA software. The TGA equipment is composed of a furnace (METLER TOLEDO) coupled with an HP 34970A acquisition system associated with the STAR ev.15 software.

The soils were crushed using an agate mortar until a powder was obtained; a powder which passed through a sieve with an 80 µm mesh for the chemical and mineralogical characteristics.

I.3.2. Physical and mechanical characterization of the materials

Density was measured using hydrostatic weighing of the samples. The volume is determined by measuring the dimensions with a caliper.

The simple compressive strength was measured using a Labotest-type concrete press with a load cell of 1250 - 1500 KN capacity. For the simple compressive strength in wet condition, we adopted the provisions of the CEB (Compressed Earth Blocks) standard (XP P 13-901, 2001, pp. 13-901). The samples are immersed in a water tank for 2 hours. Then, they are removed and wiped with a slightly damp towel. Then, they are placed in an airtight bag and stored for 48 hours. After this storage time in the airtight bag, the samples are subjected to simple compressive strength testing.

Water resistance is one of the key parameters for determining the durability of materials. This time, we used a simple immersion method. Dry samples are immersed completely in a box filled with water. The time to total dislocation is measured and considered as the water resistance of the material.

Each value indicated for the physical and mechanical test represents the average value for three tested samples.

II. RESULTS AND DISCUSSION

II.1. Soil characterization

II.1.1. Chemical and mineralogical characteristics

The oxide mass percentages of the samples, as well as the loss on ignition, are presented in **Error! Reference source not found.**.

The result shows that the most abundant oxides in the three soils are SiO_2, Al_2O_3 and Fe_2O_3, while the other oxides (K_2O, CaO, MgO, Na_2O, TiO_2, MnO, Mn_2O_3, SO_3, Cr_2O_3 and P_2O_5) are present only in small quantities.

Soils B and C contain more SiO_2 than soil A. Soil A, on the other hand, has a significant amount of iron oxide compared to the other two, which gives it its reddish-brown color. The other important element in soil A is TiO_2 (4.4 %).

The chemical compositions of the soils were comparable to those found in the literature. The reference [9] states that the average chemical compositions expressed in main elements of the soils of the Malagasy Highlands are about 50.70 % SiO_2; 34.40 % Al_2O_3 and 11.70 % Fe_2O. And according to [10], the soil of Vontovorona contains on average 21 % Fe_2O_3.

Table1 : Soil chemical composition

Oxides	Soil A	Soil B	Soil C
SiO_2	32.54	53.88	53.54
Al_2O_3	26.6	18.27	20.26
Fe_2O_3	22.34	9.78	9.18
TiO_2	4.4	1.75	1.69
CaO	0.20	0.11	0.54
P_2O_5	0.40	0.09	0.11
K_2O	0.08	0.09	0.06
MnO	0.12	-	-
Na_2O	0.02	0.04	0.02
MgO	-	0.05	0.08
Mn_2O_3	-	0.06	0.05
SO_3	0.04	0.04	0.03
Cr_2O_3	-	0.03	0.02

LOL	13.28	15.82	14.43
Total	100	100	100

Figure 5, Figure **6** and Figure **7** show the X-ray diffractograms for the mineral phase contents of the three soils.

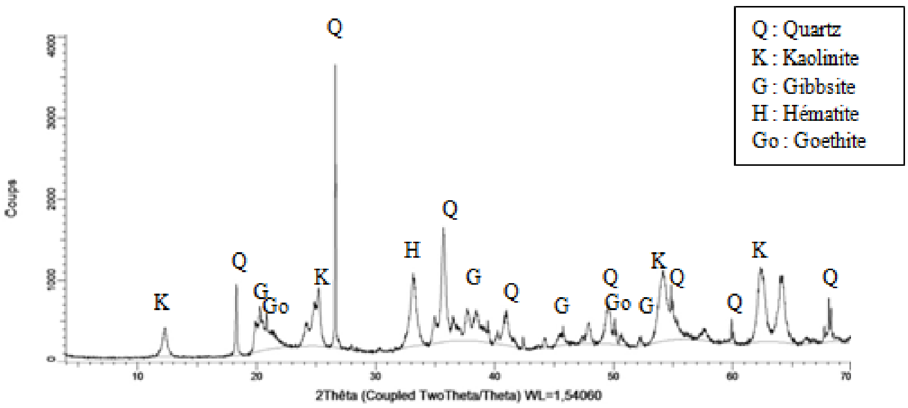

Figure 5 : Soil A X-ray diffractogram

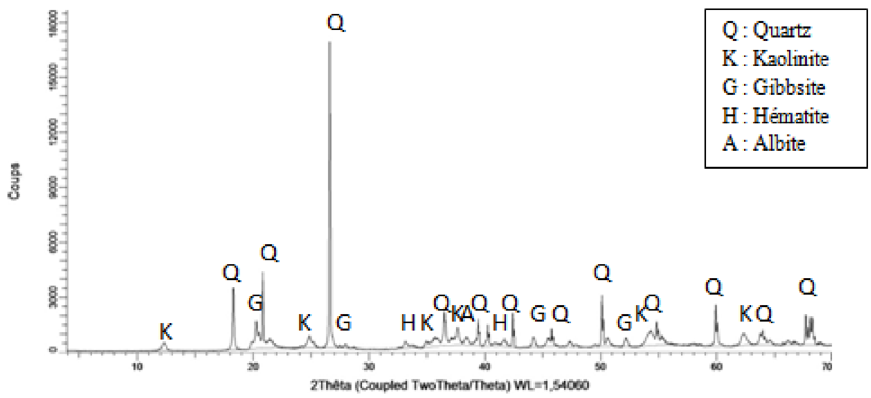

Figure 6 : Soil B X-ray diffractogram

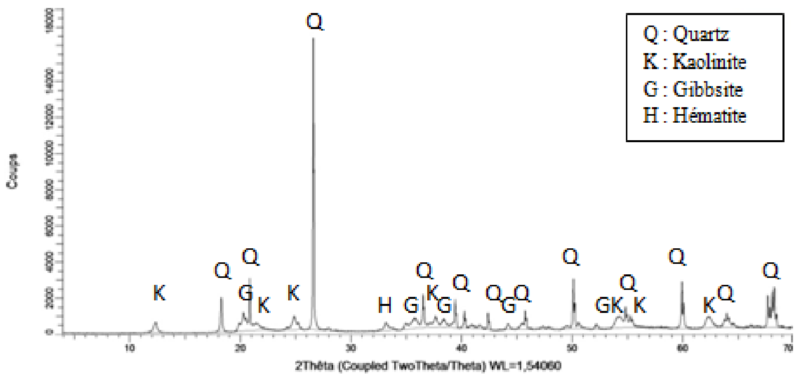

Figure 7 : Soil C X-ray diffractogram

According to the XRD analysis, the main constituent of the three soils is Quartz (SiO_2), which is consistent with the chemical composition that showed that SiO_2 is the majority oxide of these three soils. The minerals commonly encountered in the three samples are Quartz, Kaolinite $Al_2Si_2O_5(OH)_4$, Gibbsite $Al(OH)_3$ and Hematite Fe_2O_3, which also confirms the results of the chemical analyses (silicon oxide, alumina oxide and iron oxide are the major oxides). In addition, Sol A contains a large amount of iron hydroxides in the form of Goethite (FeOOH) and a significant amount of titanium oxide in the form of Pseudorutile. A small amount of Albite $NaAlSi_3O_8$ is found in soil C.

Figure 8 describes the TGA curves of the soils. It can be seen in the curves that three endothermic peaks have appeared for the three soils. The first peak, which appeared at a temperature of about 100°C, is due to water removal [11]. The second peak, which appeared at a temperature of about 297°C for soil A, 298 - 300°C for soil B and C, is due to the degradation of organic matter or dehydroxylation reaction of aluminum and iron hydroxides [11], possibly due to the presence of goethite for soil A. The endothermic peaks, which appeared at a temperature of about 507 - 527°C for all three soils, are due to the kaolinite loss reaction from the amorphous phase of kaolinite, called metakaolin [11].

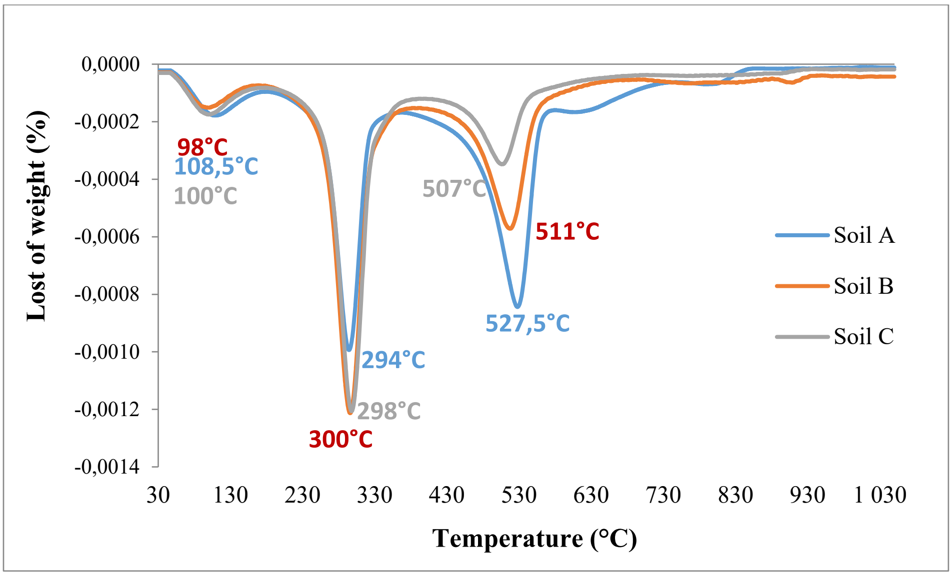

Figure 8 : Soil thermal gravimetric analyses

II.1.2. Physical and geotechnical soil properties

The results of the physical and geotechnical property analyses of the soils studied are presented in Table 2. The value indicated for all tests represents the average value for three samples tested.

Table 2 : Soil physical and geotechnical characteristics

Characteristics		Soil A	Soil B	Soil C
Water content W (%)		3.41	2.45	3
Specific weight γ_s (T/m3)		3.02	2.64	2.79
pH		4.64	6.12	5.28
Atterberg limits	Liquid limit W_L (%)	35.95	37.8	32.2
	Plastic limit W_P (%)	24.35	22.9	19.5
	Plasticity index I_P (%)	11.60	15	12.7

The soil's water content values range from 2.45 to 3.41. It is a physical quantity that characterizes the moisture content of the raw materials. Its value varies according to the time of sampling. Our samples were collected in the month of July (a period without rain) and this is the reason why this moisture content is low.

The specific weight is approximately 2.64 to 3.02. This value is close to that of quartz due to the fact that all three soils have high quartz content. Soil A is the densest (3.02) because it is the richest in iron. In all cases, these values are consistent with those of lateritic soils studied by different authors ([12], [13]).

All three soils are acidic with pH values ranging from 4.64 - 6.12. These pH values correspond to the chemical compositions of the soils which are rich in Alumina and Iron oxides [14].

The results show that the soil samples have plasticity index values ranging from 11.60 % to 15 %. Based on the classification of soils on the Casagrande diagram, the three soils can be classified as low plastic clay soils.

The results presented in Figure **9** show that soil A has an excess of fine particles compared to soils B and C, and the particle size characteristics of soils B and C are quite similar. Overall, all three soils are rich in fine fractions. Soil A is outside the limits recommended by the French standard NF XP 13-901 on CEB (AFNOR 2001) [15] while soils B and C correspond to them.

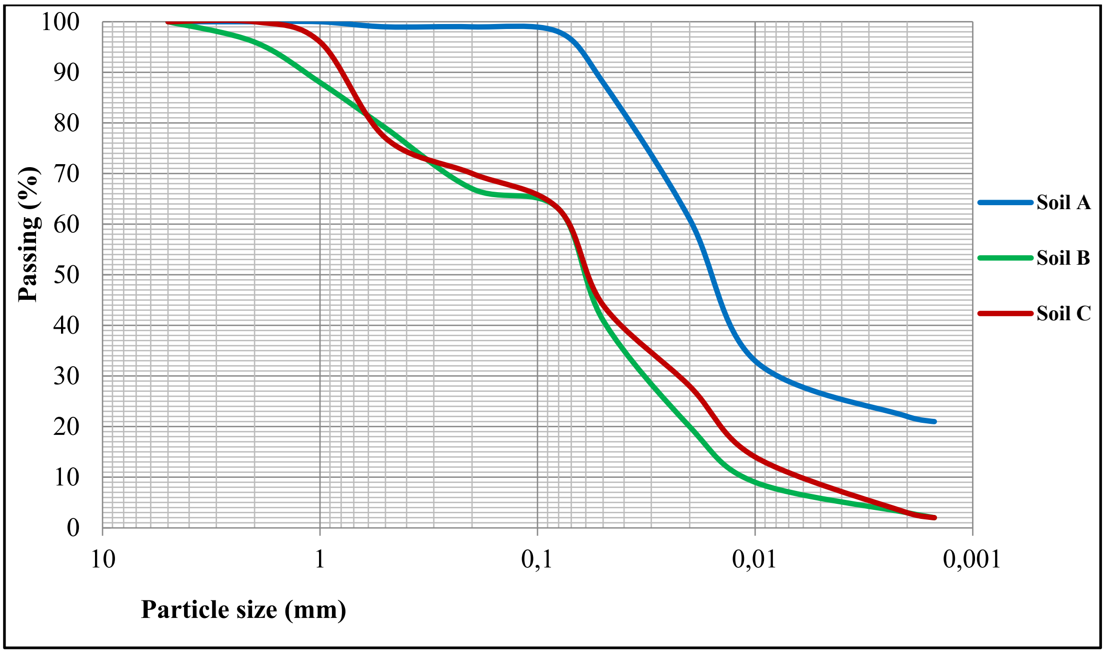

Figure 9 : Particle size distribution of the soil (wet sieving and size analysis by sedimentation)

II.2. Physical and mechanical characteristics

II.2.1. Density

The densities of the samples are presented in Figure 10, Figure **11**, Figure **12**.

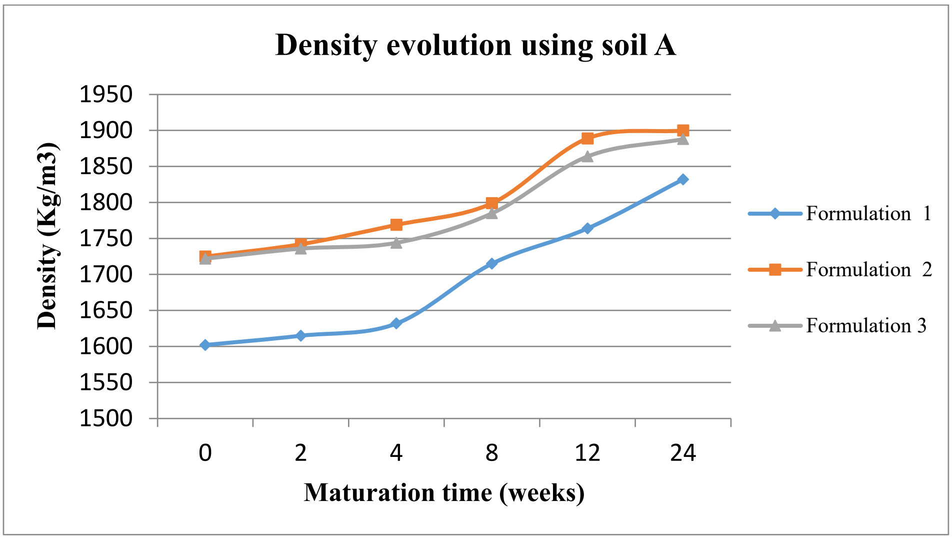

Figure 10 : Density evolution using soil A

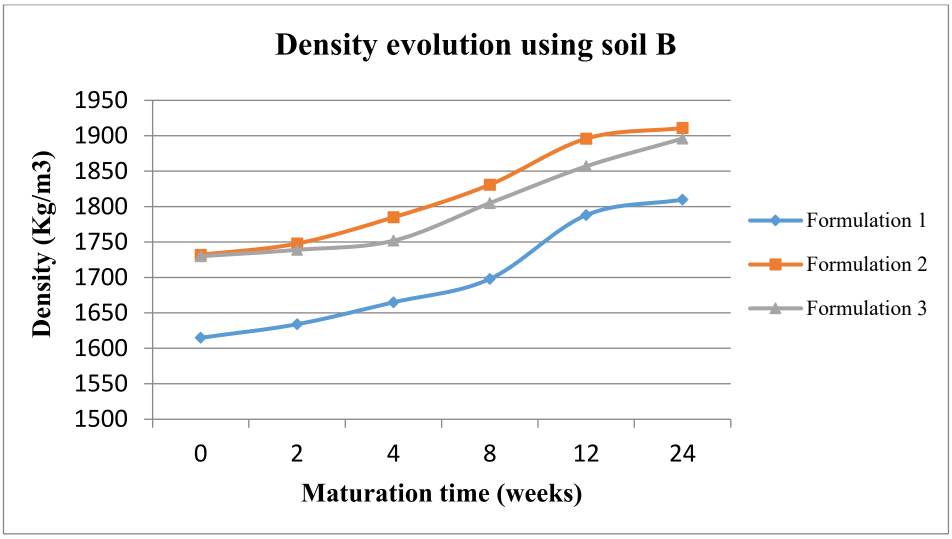

Figure 11 : Density evolution using soil B

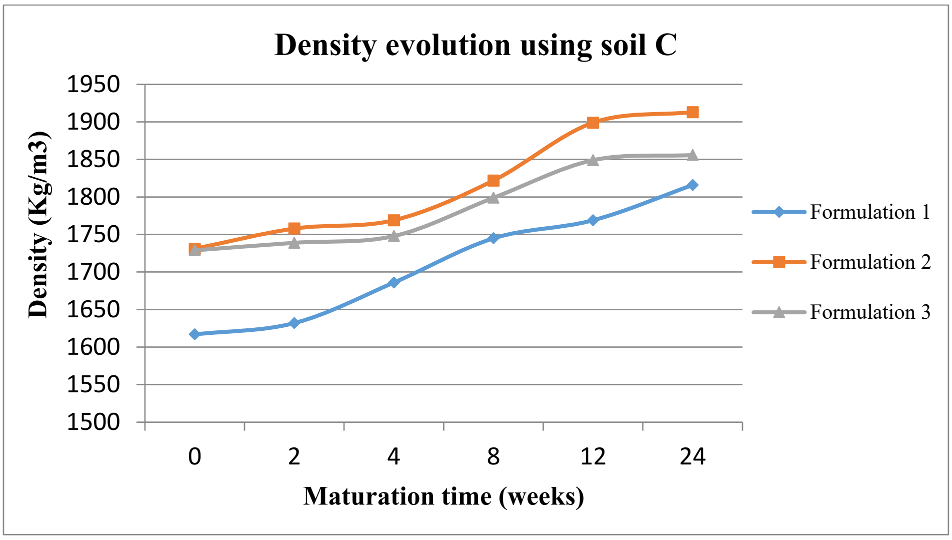

Figure 12 : Density evolution using soil C

The densities of the samples vary between 1602 and 1913 Kg/m3, increasing with the maturation time of the paste. The results show that there is not a great difference between the different uses of the soils, although the density of the solid grains of soil A is practically greater than that of soils B and C. The addition of cow dung was somehow related to the increase in density. They increased to about 1596 Kg/m3 on average for the test without stabilization and to about 1728 Kg/m3 for the soil stabilized with 10 % cow dung, that is, an increase of about 8 %.

On the other hand, the addition of straw leads to a decrease in the density of the samples. This decrease is due to the introduction of an additional porosity almost proportional to the fiber content [16].

II.2.2. Dry Compressive strength

The dry compressive strengths are presented in Figure 13, Figure **14**, Figure **15**.

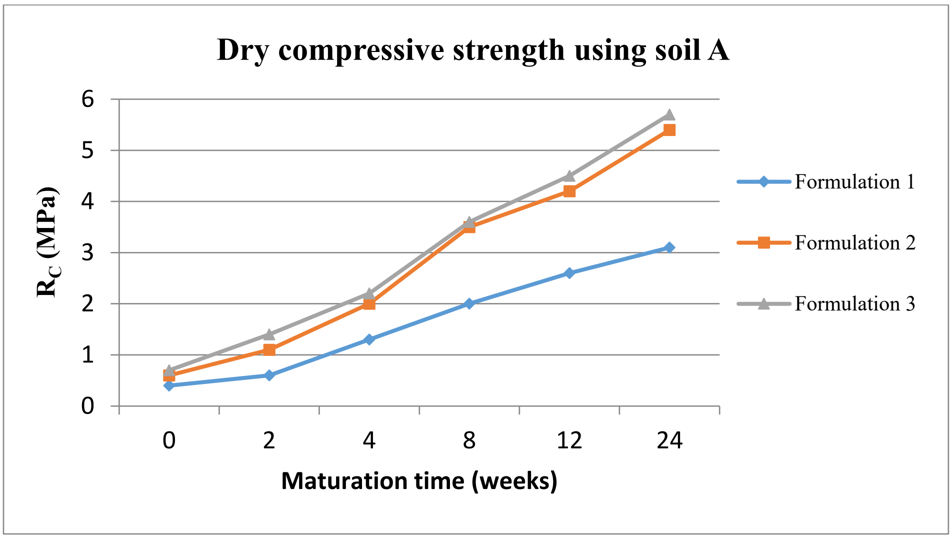

Figure 13 : Dry compressive strength using soil A

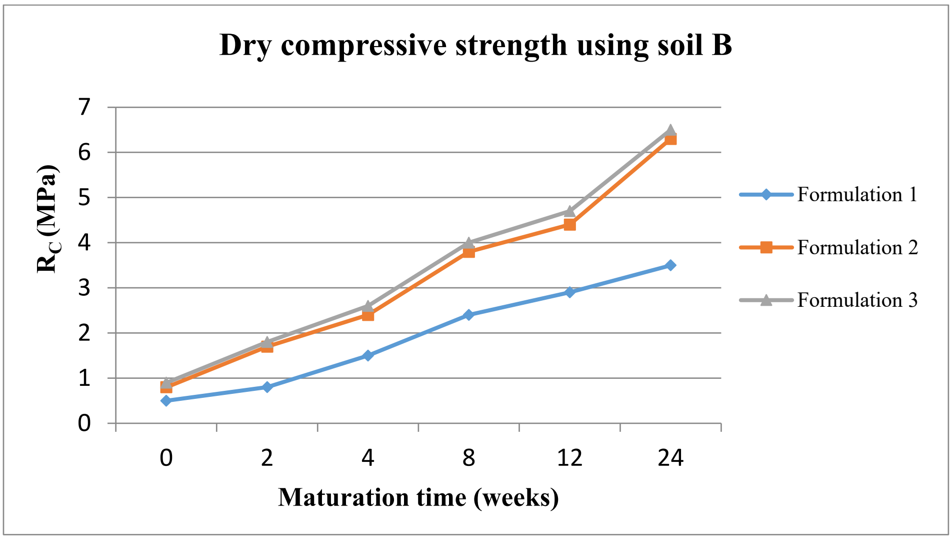

Figure 14 : Dry compressive strength using soil B

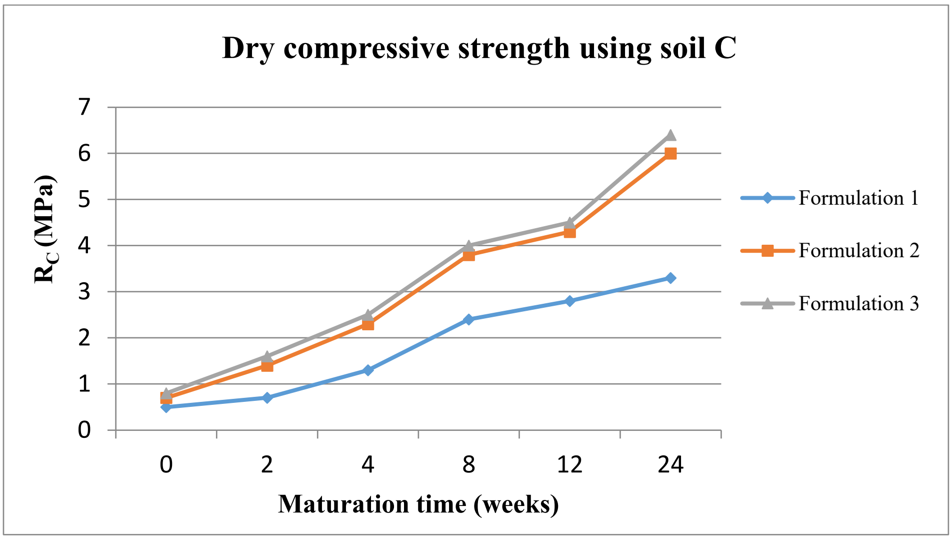

Figure 15 : Dry compressive strength using soil C

The use of the different types of soil affects the dry compressive strength. The increase in compressive strength is seen on all three soil types but is much less noticeable on soil A than on soils B and C.

The addition of cow dung significantly improves the dry compressive strength. On average, there is a 66 % increase with 10 % cow dung compared to the unstabilized samples. The hydration products of the cow dung filled the pores of the matrix and increased the rigid structure of the soil.

With rice straw addition, the dry compressive strength increased but slightly compared to that obtained with cow dung alone, i.e. 8 % on average. The presence of the fibers prevents the propagation of cracks, which increases the compressive strength [16].

The results also show that the length of the maturation time of the paste increases the compressive strength. It increases with time even on unstabilized specimens. The compressive strength increased on average from 0.64 MPa at the beginning to 1.2 MPa after the 2nd week, i.e. an increase of about 2 times. It increases quickly until the 8th week. From the 8th week of maturation, the strength evolves slowly until the 12th week. At the 24th week of maturation time, the dry compressive strength reached 5.4 to 6.3 MPa for the samples stabilized with cow dung and 5.7 to 6.5 MPa for the samples stabilized with cow dung and rice straw, i.e. about 9 times higher than at the beginning.

II.2.3. Wet Compressive strength

The wet compressive strengths are graphed in Figure 16, Figure **17** and Figure **18**.

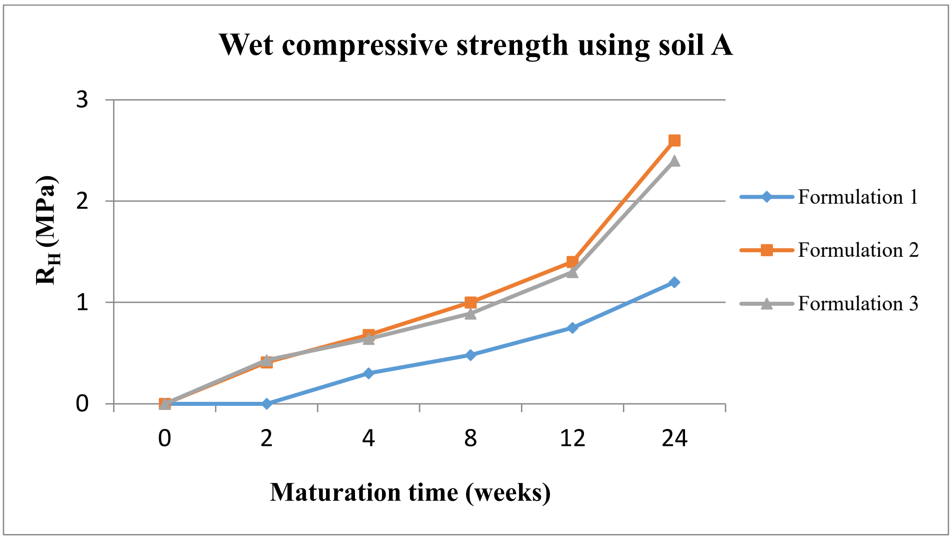

Figure 16 : Wet compressive strength using soil A

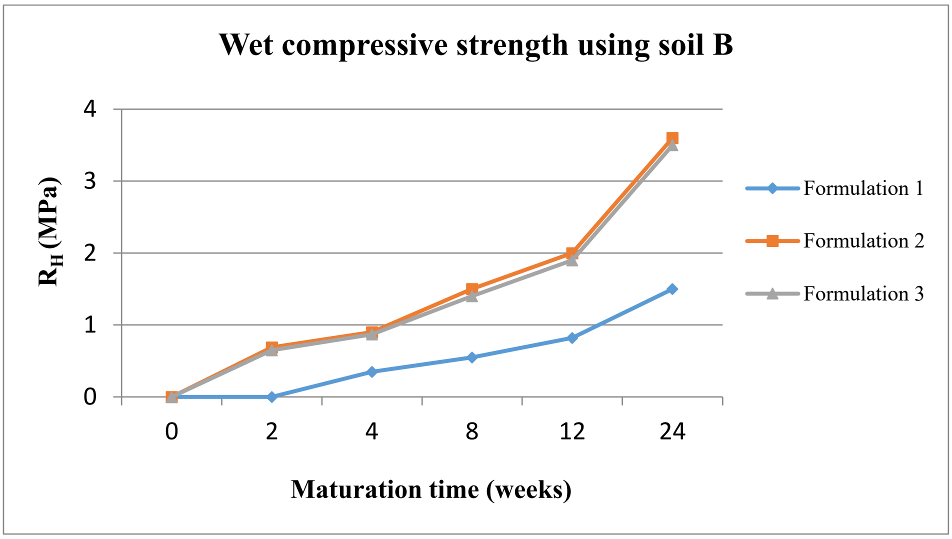

Figure 17 : Wet compressive strength using soil B

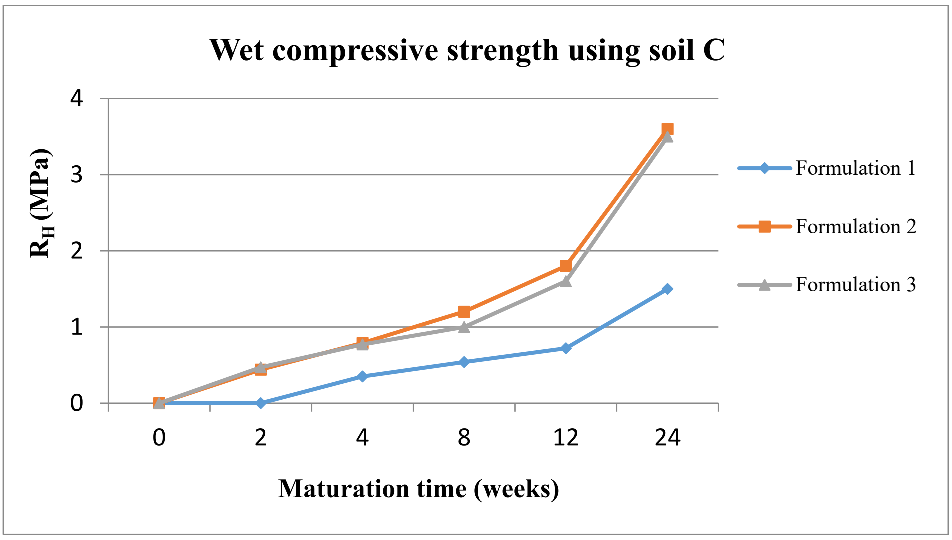

Figure 18 : Wet compressive strength using soil C

The results show that all the samples that did not go through the fermentation stage could not pass the wet compressive strength test. Complete disintegration of the samples was observed a few minutes after their immersion in water.

After the 2nd week of maturation time, the unstabilized samples did not withstand the expected 2 hours of water immersion. They partially disintegrated and the wet compressive strength test could not be performed.

The addition of cow dung significantly improved the strength of the wet samples. From the 2nd week of maturation time, the samples remain almost intact after two hours of immersion in water and can undergo the test. The wet strength gradually increases from this time.

The results show that the wet compressive strength of test 3 compared to test 2 is low. The addition of rice straw did not give any significant improvement in wet strength. This could be attributed to the presence of cellulose in the straw, which is a very hydrophilic component so it absorbs water easily [17].

II.3. Water resistance test

Figure 19, Figure **20** and Figure **21** present the results of the water resistance expressed in duration (corresponding to the time before disintegration of the samples in water) by the different soils used.

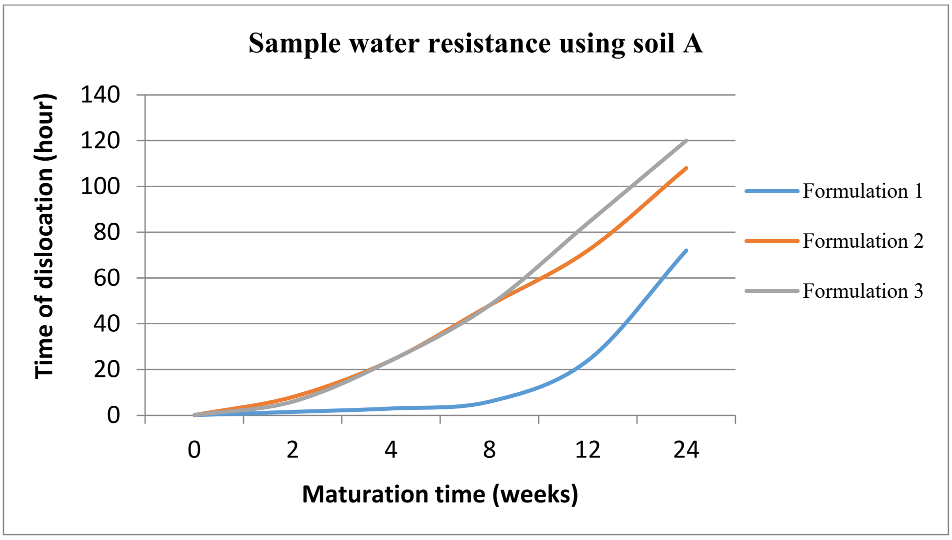

Figure 19 : Sample water resistance using soil A

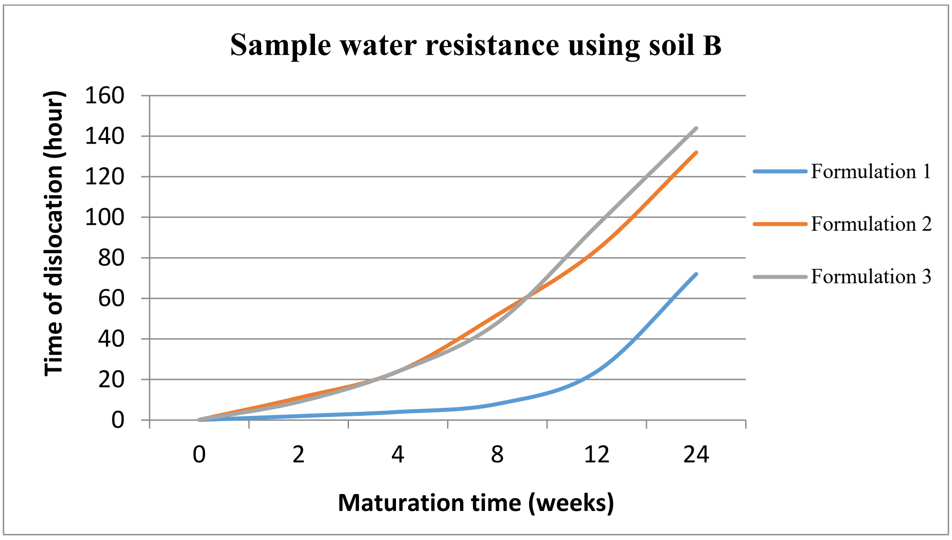

Figure 20 : Sample water resistance using soil B

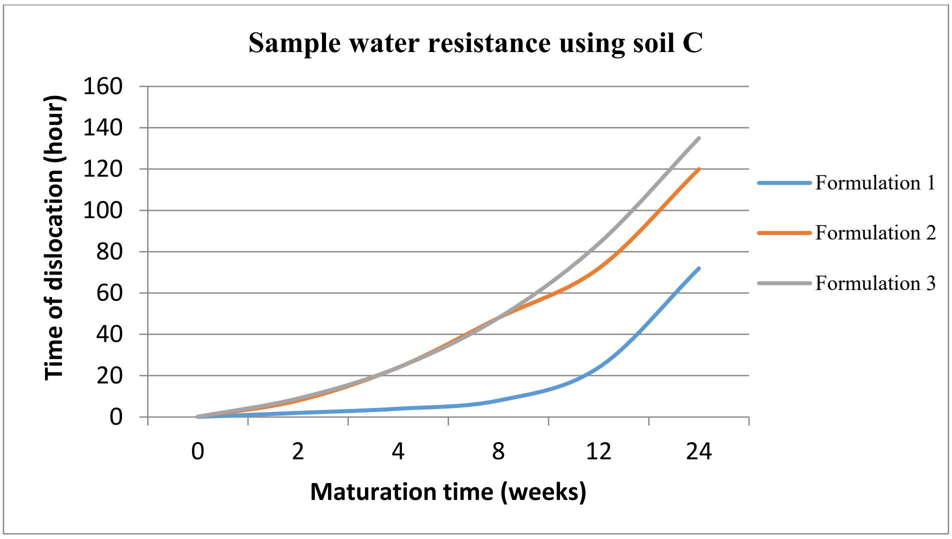

Figure 21 : Sample water resistance using soil C

The results show that unstabilized samples that do not go through fermentation time are not resistant to water. They break up completely after 10 minutes of immersion in water.

However, the addition of cow dung and straw makes the samples more resistant. The constituents of the rice straw and the fiber contained in the cow dung provide the elements necessary for a rapid multiplication of microorganisms. Reference [18] shows that, during fermentation by microbial action, there is a production of organic amino materials. These compounds react with the quartz and silica of the kaolinite to produce $Si0_4\ (NH_3)_4$ which is an insoluble silicate amine [18]. They stick to the soil particles. This leads to a lower migration in water and the microstructure of the materials becomes more homogeneous with fewer pores resulting in better water resistance.

From the 4th week of paste maturation time, the samples resist to more than 24h of immersion and it increases until the 24th week.

As for the results on compressive strength, we observe that soils B and C are more resistant than soil A.

Compared to soil A, which is finer, the grains of soils B and C are fairly coarse. The interstitial spaces are thus more important for the latter. The cement formed have then more facility to circulate between the soil grains to better seal them, thus offering a better resistance thanks to the good cohesion of the whole. In addition, soils B and C are richer in SiO_2, thus more favorable to the formation of the cement according to the mechanisms of the reference [18].

At the 24th week of paste maturation time, we obtained a good water resistance for our samples which is 6 days for soil A and 7 days for soils B and C. This result is comparable to that of ancestral walls aged over 100 years.

III. CONCLUSION

In view of the challenges of sustainable development, the current trend is for building materials to be increasingly based on local materials. The *Tambohon'ny* Ntaolo is an ancestral raw earth construction in the Central Highlands of Madagascar, which has many environmental advantages. These forgotten walls are an exploitable solution for that purpose.

This study allowed the use of local laterite and to study the effect of cow dung and rice straw fermentation time on the strength of the earthen construction, based on the results of our preliminary surveys and oral traditions collected.

The chemical characteristics of the soils used showed that they were mainly composed of SiO_2, Al_2O_3 and Fe_2O.

The results showed that the additions of cow dung and rice straw improved the physical and mechanical properties of our samples and especially their water resistance. The highest water resistance of 7 days was obtained with the stabilization by cow dung and rice straw fermented for 24 weeks.

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