Rush Fibers Reinforced Adobe for Sustainable Building

Wassef Ounaies

Abstract: ***Little consume energy materials have recently received increased attention as an ecological and sustainable alternative. We propose to study a building approach with raw earth (adobe) combined with plant fibers. The latter used as reinforcement in composite materials have specific competitive mechanical properties compared to those of synthetic fibers (glass, carbon, ...) and are an environmentally friendly alternative to these fibers because of their low cost, low density, biodegradability and availability. We describe adobe stabilization and reinforcement process with treated rush fibers. We introduce our approach to formulate an earth mortar allowing the making of blocks of adobe, intended for the construction of works such as walls, arches and domes.***

Key words: sustainable building, raw earth, plant fiber, adobe, rush fiber.

I. INTRODUCTION

Building domain generates not only millions of tons of mineral waste released into the environment, but also millions of tons of carbon dioxide emitted into the atmosphere which worsened the greenhouse effect causing climate change which our sulfur planet [1, 2]. Therefore, and as an act of awareness, new generations are demanding healthier building materials and environmentally friendly, which puts the embodied energy in the heart of the debate. This gray energy that comes from the extraction, processing, to deal with this crisis non-renewable energy and the depletion of natural resources need materials that carry a footprint with strong social expectations in terms of eco-housing and sustainable development has become a necessity to reconcile culture and the social, ecological and economics which are the pillars of sustainable development.

In our research work, we have opted to promote the use of local materials. In recent years, and following the increase in the price of fossil fuels, the decrease in non-renewable resources, the disruption of the climate with an increase in the proportion of greenhouse gases in the atmosphere, and as an act of taking awareness, the Tunisian State represented by the Ministry of Equipment, Housing and Spatial Planning participated in a twinning project with three member states of the European Union (France, Germany, and Portugal) whose objective is to support the Tunisian administration on three fundamental areas of work in the field of eco-construction:

- Strengthen laws and building regulations in favor of sustainable development in the proposed legal texts promoting the development of eco-constructed buildings.
- Develop and promote sustainable building throughout the territory, and for all types of buildings: The awareness centers of influence and target populations with well-based sustainable building, by the organization of seminars addressing all the actors of buildings in the chain from design and construction to provide essential knowledge of supplements in the field of ecological and sustainable construction.
- Strengthen the expertise and know-how of the mastery of public work in this area.

The earthen architecture flood is used quite widely in the dry regions of the world and it is estimated that currently one third of the world population lives in earthen houses based [2]. Unlike materials and semi-finished products including industrial manufacturing requires a lot of energy; the earth material requires very little energy production. The production of a cubic meter of concrete requires 400 to 800 kWh. The land, natural material, requires only 5 to 10 kWh per cubic meter [3].

II. RELATED WORKS

The problem of raw earth construction is that they suffer from a resistance deficit, from cracking systematic due to shrinkage and encounter problems related to their sensitivity to water. Raw earth material can be reinforced by fibers allowing improving its physico-mechanical performance and its sensitivity towards water, which has gave birth to several earth products: adobe, mud, earth block compressed and others.

Compared to the history of raw earth construction, Adobe technique is a very old technique, it allows to have blocks molded without compaction in terms of the masonry and can be integrated as well in a column-beam structure as a filling material that as the main material in a load-bearing wall.

To obtain better mechanical characteristics of the molded raw earth as to other types of bricks, for reducing its porosity, its dimensional change and improved resistance to erosion from wind and rain (reduce surface abrasion and permeability of the block), more stabilizers binders such as: cement, lime and bitumen can be used alone or in combination with the reinforcement of the earth matrix plant fibers such as: straw, hemp, bamboo, etc. [1, 2, 4, 5, 7]. The mechanical behavior of raw earth in general and in particular molded earth is similar to that of concrete. In fact the earth has a good compression behavior which is provided by the inherent strength of the grains that compose it. The other considerably remarkable problem with earth mortars in general and unstabilized (100% ground) in particular is the shrinkage which is a dimensional variation of the drying material being caused by the evaporation of the water just after the confection. This decrease in volume causes internal stress that can lead to shrinkage cracks. These cracks can change the homogeneity of masonry or structure built based on the land and its sustainability if there is no coating, and also can leak through cracks. This dimensional variation

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Dr. Wassef Ounaies, Assistant Professor, Department of Civil Engineering, College of Engineering, Jouf University, Sakaka, Kingdom of Saudia Arabia.

increases with the increase of this clay content in the soil matrix. When the plasticity index exceeds 20, the removal of drying increases rapidly.

The resolution of the mechanical fragility problem and dimensional change during drying may be made by stabilization by various hydraulic binders (cement, lime water), air (air lime) or organic (bitumen), which significantly improve the mechanical strength of the composite material crafted, the water resistance relative to the blocks of traditional adobe and also the dimensional stability is also improved [1, 6, 7]. These solutions already mentioned allowed the ground material to achieve physical and mechanical performance similar to the clay and masonry with concrete blocks, rather than the molded wet method by hand generally used for adobe. In order to address the excessive dimensional change problem of molded earth another solution was checked in [4, 5], which is the granular matrix correction by adding to the matrix of mineral inclusions. The fibers used as reinforcement, distributed throughout the mass of the material tensions caused by the removal of the clay [7], reduce the size of cracks caused by shrinkage and improves the durability and tensile strength.

III. OUR APPROACH: ADOBE STABILIZED AND REINFORCED WITH TREATED RUSH FIBERS

Our objective was therefore to formulate an earth mortar allowing the making of blocks of raw earth (adobe), intended for the construction of works such as walls, arches and domes. These earth blocks must have a compressive strength similar to that of fired bricks and dimensional stability characterized by limited shrinkage in order to avoid the appearance of microcracks. For this, three approaches have been adopted:

- Granular correction,
- Stabilization with hydraulic and aerial binders (cement, lime and plaster),
- Reinforcement with vegetable fibers from rush treated chemically.

Thanks to the chemical process by alkalization (8% NaOH with $Na_2S_2O_4$ and NaOCl) we were able to develop rush plant fibers of very high characteristics with a diameter reduced to 40µm, a high density of 1.25 g / cm^3, a breaking stress in tension of 1800 MPa and a modulus of elasticity of 122 GPa.

A. Origin of used Adobe

Our choice fell on the earth of the site of Sidi Amor (Borj Touil) in the governorate of Ariana, Tunisia, with which was carried out a pilot construction in classic adobe (mortar of raw earth mixed with straw and the water). Figures 1 and figure 2 show the location of the earth extraction site that is the subject of our research.

Fig. 1. Aerial photos of the earth extraction zone used in this study (Pilot site - GDA - Sidi Amor - Ariana)

Fig. 2. Adobe matrix extraction site (Pilot site - GDA - Sidi Amor - Ariana)

B. Grain size of the earth used

Raw earth is said to be exploitable if it has a continuous particle size and as linear as possible. The sizes of the grains constituting the earth chosen for this study were determined by two methods, namely:

- The particle size analysis by dry sieving for the granular fraction with a diameter greater than 80 µm in accordance with standard NT 21.07 (1984). This test is carried out at the mechanical laboratory of the national school of architecture and town planning (ENAU) - Tunisia.
- Granulometric analysis by laser diffraction granulometer (Brand: Mastersizer 2000 from Malvern) by dry method for the granular fraction with a diameter of less than 80µm. This test is carried out at the National Institute for Research and Physical-Chemical Analysis (INRAP) - Tunisia.

We carried out a particle size analysis on the soil sample in order to be able to locate its granularity compared to a conventional particle size spindle from CRATerre [5]. This test was repeated three times on three samples extracted from three different places from the stock brought from the site, in order to be able to ensure the exact granular distribution to be taken into account in our case study.

The particle size analysis shows that it is a very fine soil (50% <0.05 mm) (Figure 3) and its comparison with the limit zone characteristic of the earth developed by CRATerre for the preparation of adobe or of molded earth mortar [5], indicates the possibility of its use for the elaboration of adobe.

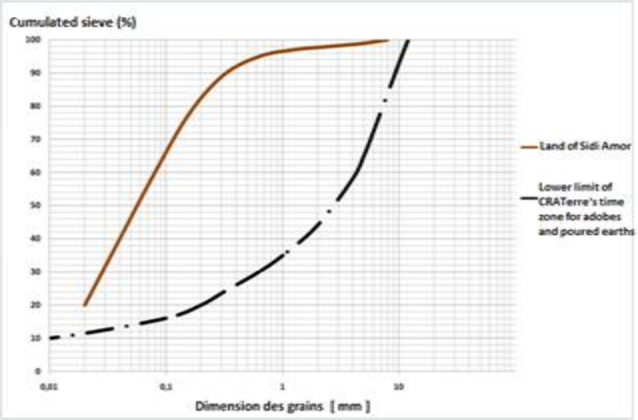

Fig. 3. Granulometry of the earth used compared to the reference curve

Having a particle size curve in the particle size zone in general or above and close to this lower limit of the particle size zone relating to adobes in particular means that it is an optimal particle size and this guarantees a certain security. in works constructed from this material. But that does not mean that if it is not, in whole or in part, located in the spindle it is not possible to build with this earth. But there will be major problems (withdrawal, etc.) that will have to be solved and it is possible, by mixing with another soil rich in elements missing from the first, to obtain a satisfactory product [4].

C. Plasticity of the earth used - The limits of Atterberg

To assess the effect of the earth's contact with water and to be able to quantify its passage from the solid state to the plastic state then to the liquid state and thus determine its plasticity index, we carried out limit tests of Atterberg on three samples of the earth used and which showed that the plastic limit is 16%, that the liquid limit is 22.5% and that the plasticity index is 6.5%. We deduce from the positioning of these values on the plasticity chart (Figure 4) according to the LCPC-USCS classification (ASTM D2487-11) [10], that this earth is classified as a little plastic silt which needs a large amount of water to be able to pour it into molds or formwork.

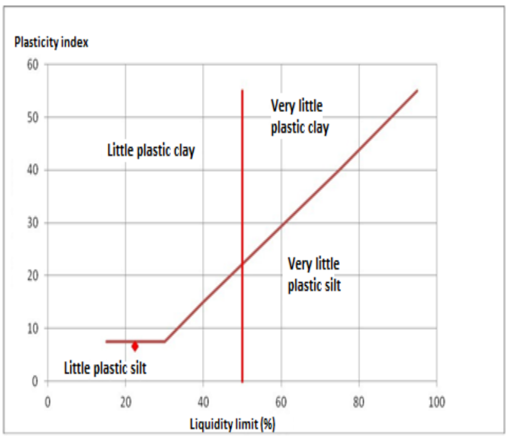

Fig. 4. Plasticity of used Adobe

D. Densities of used Adobe

- **Apparent density**

The apparent density (ρa) was determined from the ratio of the weight of the sample by its apparent volume according to the standard in accordance with standard NT 21.05 (2002).

- **Specific or actual density**

The actual or absolute density (γ) is determined according to ASTM D854 (Standard test methods for the density of soil solids using a water pycnometer) [11, 12]. The values found, presented in Table 1, show a large difference which reflects the strong presence of voids between the grains of the dry soil sample.

Table–I: Densities used Adobe

Properties	Value
Apparent density (**ρa**)	1 g/ cm^3
Actual density (**γ**)	2.4 g/cm^3

These two properties which we have just mentioned, will subsequently allow us to deduce the porosity by the formula:

$$P\,(\%)=\left(1-\frac{\rho_a}{\gamma}\right)x100 \quad (1)$$

E. The chemical composition of used Adobe

A chemical analysis was carried out on the earth used for the preparation of the mortar in order to know the chemical elements present in the earth and also to know if there are elements that are contaminants or pollutants for humans.

- **Elementary chemical composition**

The values found indicated in table 2 show that the soil of the Sidi Amor site used is highly siliceous (large presence of sand), moderately calcic (medium presence of limestone) and weakly aluminous (weak presence of clay) and very weakly ferruginous (very low presence of iron), but also it contains 17.55% of organic matter which was measured by the loss on fire test.

Table-II: Elementary chemical analysis of the earth used

Elements	(%)
SiO_2	52,15
Al_2O_3	6,71
Fe_2O_3	3,36
CaO	16,92
MgO	0,92
Na_2O	0,16
K_2O	0,92
SO_3	< 0,01

In addition, a check was made on the minor elements, presented in table 3, which show us that they are in majority in the trace state (a few ppm) with however a certain presence of the element P (Phosphorus) and the element Ti (Titanium). The land of Sidi Amor can therefore be considered to be land that does not contain concentrations of elements that are contaminating or polluting for humans.

Table-III: Elementary chemical analysis of the earth used

Element	Ba	Cd	Co	Cr	Cu	Mn	Mo
ppm	18,4	0,2	4,9	2,3	8,9	16,0	2,0
Element	Ni	P	Pb	Sr	Ti	Zn	-
ppm	1,1	148	2,5	13,1	92,0	16,0	-

- **Chemical bonds - Analysis by Fourier transform infrared spectrometry (FTIR)**

Fourier transform infrared spectrometry (FTIR) is an effective technique that will allow us to analyze the chemical and structural properties of raw earth. The IR spectra were recorded at ambient temperature using a device of the Nicolet IR 200 FT-IR brand with an ATR spectrometer, equipped with a diamond crystal and in a spectral range which extends in the interval [4000-400 cm-1].
The analysis by Fourier transform infrared spectrometry allows, by detecting the vibrations characteristic of chemical bonds, to perform the analysis of the chemical functions present in the material. It allowed us to note that the chemical bonds present in the earth used (Figure 5) are predominantly siliceous (SiO) with the presence of calcite (CaO) and a small percentage of hydroxyls (OH) attributed to Kaolinite and Illite clays.

Fig. 5. Fourier transform infrared spectrometry of the used Adobe

- **The mineralogy of the used Adobe**

In order to mineralogically identifying the soil used, we also performed an X-ray diffraction analysis to detect and quantify the minerals existing in the sample tested.

The raw earth was analyzed under ambient conditions on an X-ray diffractometer (D8 Advance, Brucker, AXS, Germany), with a voltage of 40kV and 30 mA, Cu Ka radiation (1.5418 Ǻ), at a scanning speed. 2˚ / min, and on a 2θ angle interval between 2˚ to 40˚.

The results of this XRD analysis (Figure 6) corroborate with those of the chemical analysis and infrared spectrometry, confirming that this earth is mainly siliceous (presence of Quartz), moderately dolomitic limestone and weakly clayey (Illite and Kaolinite). These proportions are acceptable in the case of adobes or molded earth [5].

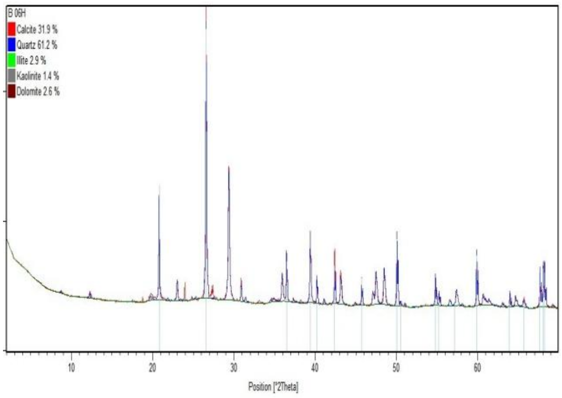

Fig.6. Earth X-ray diffraction

F. Characterization and treatment of rush fibers

- **Vegetable rush fibers**

Among the different plant species existing in Tunisia, our choice was fixed on the rush plant because of its presence throughout the Tunisian territory. The rush plant belongs to the Joncaceae family [8, 13], of which there are around 200 species that grow in wetlands such as the surroundings of lagoons, lakes and rivers [8]. It is currently used to make mats, rugs, baskets, fans and baskets. In addition, it could constitute a potential source of organic matrix reinforcement (polyester resins or epoxy components) or mineral (cement or lime mortar or gypsum or natural earth).

The rush used in our study (Figure 7) comes from the Amroun region in the governorate of Nabeul in north-eastern Tunisia, and the rush rod has an average length of around 125 cm.

Fig. 7. The rush plant (Nabeul - Tunisia)

G. Morphological characterization ("SEM" scanning electron microscope)

The rush plant is composed of a multitude of radiant contiguous stems as shown in Figure 7. Each of its stems is made of cellulose fibers located on the periphery and others trapped inside the stem and separated by empty alveolate cells as seen on the pictures (Figures 9 and 10) of SEM observations that we have made. The rod with its diameter of about 3300 µm cannot be used as it is as reinforcement in composites. Cellular lignin and hemicellulose cells should be removed to extract clumps of cellulosic fibers peripheral and internal fibers called ultimate fibers [9] which have a diameter of around 300 µm as seen in Figure 18.

Fig. 8. The scanning electron microscope with the sputtering device used

To evaluate and see the natural rush rod and also the influence of the different treatments on the defibration of the rush fibers, their surface condition and their diameter, we used a scanning electron microscope (SEM) of the JEOL JSM 5400 type (Figure 8). The observations were made on the natural rod, fiber bundles and on isolated fibers, coated with a thin layer of gold in a JEOL JFC 1100 sputtering device (Figure 16) and scanning electron micrographs of the fibers have been saved.

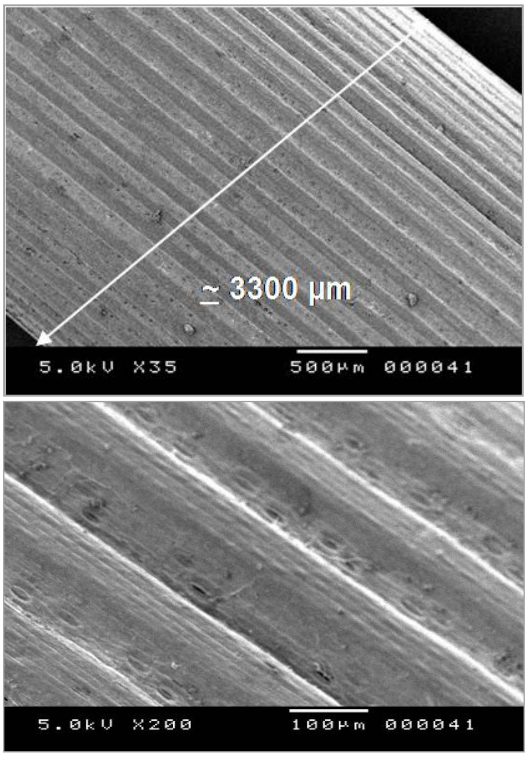

Fig. 9. Rod of rush observed with SEM respectively with a magnification 35 and 200 times

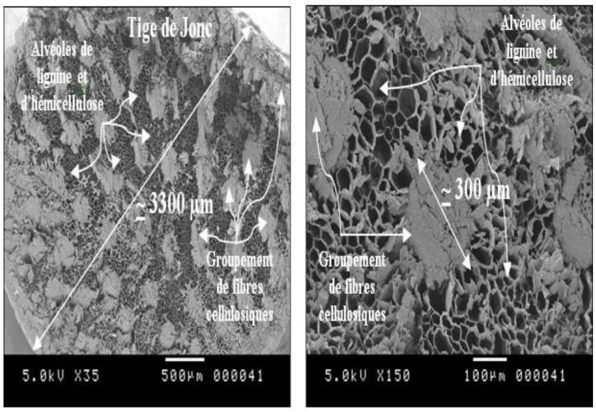

Fig. 10. Cross section of a rush rod observed with SEM respectively with a magnification 35 and 150 times

IV. RESULTS

Before starting the chemical treatment, the final tensile strength of the fiber obtained by mechanical defibrillation of the rod was 31 ± 8 MPa. Different modes of chemical treatment (including heat treatment) have considerably increased the tensile strength value of rush fibers (Figure 10).

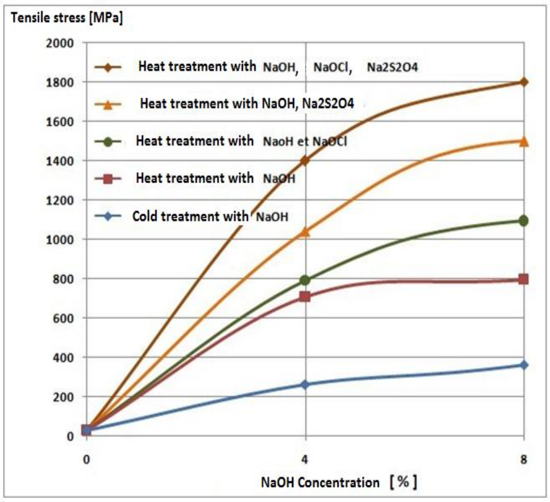

Fig. 10. Change in tensile strength of rush fiber after chemical treatment

Heat treatment with NaOH sodium hydroxide alone for concentrations of 4% and 8% increased the tensile strength to 730 ± 68 MPa and 800 ± 48 MPa respectively. Post processing with NaOCl increased it to 800 ± 20MPa and 1100 respectively ± 40MPa. Pretreatment with Na2S2O4 caused it to reach 1050 ± 50MPa and 1500 ± 45MPa respectively. The combined pre-treatment with Na2S2O4 and post-treatment with NaOCl made it possible to further increase the tensile strength of the rush fiber to 1400 ± 90MPa and 1800 ± 60MPa respectively.

Mechanical extraction of the rush plant resulted in an average fiber diameter (280 µm), an average density (0.71 g.cm-3), an average tensile strength (31 MPa) and a average elastic modulus (0.7 GPa).

The hot alkaline treatment resulted in the delignification of the fibers by elimination of the lignin and hemicellulose compounds enveloping the groups of cellulosic fibers. Consequently, this treatment made it possible to carry out a better extraction better than that with mechanical shelling. Under this heat treatment and with 8% NaOH, Na2S2O4 and NaOCl, the insulation of the fibers was most effective with a diameter reduced to a value of 40 µm, the density of the fibers increased to 1.25 g.cm -3, the tensile strength reached 1800 MPa and the modulus of elasticity increased to 122 GPa. These particularly interesting mechanical characteristics of rush fibers are better than those of certain vegetable fibers (alfa, kenaf, bagasse, bamboo, date palm) and are comparable to those of certain synthetic fibers (polypropylene, glass) commonly used to reinforce composites.

V. CONCLUSION

In this research work we are interested in the earth construction method which has become one of the ecological and sustainable alternatives allowing to save energy and preserve the environment. We started from the principle that all land could be valid for construction, even if its initial properties were not entirely suitable for the mode of construction (adobe, adobe, compressed blocks, etc.), with the application of correction particle size and / or stabilization by aerial or hydraulic binders or by reinforcement with vegetable rush fibers.

Among the different earth construction methods we have chosen to study the case of the adobe. However like other earth construction techniques, the Adobe raises certain problems of use due to its brittleness and its dimensional variation characterized by a significant shrinkage during drying.

To solve the problems of dimensional stability (drying shrinkage) and brittleness of the earth mortar, we have adopted in our study approaches of stabilization with mineral binders and reinforcement with vegetable rush fibers chemically extracted by alkalization.

In order to reduce the shrinkage phenomenon, we applied an approach of granular modification of the matrix by adding mineral inclusions. It was based on the one hand on the characterization of the material "Earth" from the granulometric, physico-chemical and mineralogical point of view, and on the other hand on the characterization of the earth mortar: the Adobe.

The addition of rush plant fibers had the effect of decreasing the thermal conductivity of the adobe on the one hand, thereby improving its thermal insulation capacity, and on the other hand improving its acoustic absorption, thereby adobe a building material having an improved capacity of thermal insulation and acoustic correction, without making it lose its property of acoustic weakening in spite of its lightening.

However, as perspectives and continuation of this work we can propose two lines of research: Study the fire behavior of materials already made other than the characterizations carried out and study the use of rush fibers in the reinforcement of the earth in other areas. other earth construction techniques (daub, mud, etc.).

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AUTHOR PROFILE

Dr. Wassef Ounaies is assistant professor at Civil engineering Department, College of Engineering, Jouf University, Sakaka, Kingdom of Saudia Arabia. His research areas are Geotechnical engineering and Sustainable building.