INFLUENCE OF FIBER ON UNCONFINED COMPRESSIVE STRENGTH OF RAW EARTH MATERIAL BY MIXTURE DESIGN

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Abstract

Building construction technology using raw earth material is already known and used since ancient times. The raw earth material is low cost, abundant, requires very low energy to manufacture and does not generate waste. Thanks to such advantages, raw earth material is used in various construction sites all over the world. This eco-material of the future, may eventually be a good alternative to cement concrete, which is very energy-intensive in terms of gray energy.

The shrinkage and swelling can cause cracks in raw earth material. To minimize the cracks, either natural or synthetic fibers have been included in raw earth materials. Then, a raw earth treatment by binders and vegetal fibers is one of the techniques applied to improve strength and ductility. In this research work, the statistical combinations of five-component mixtures composed of fiber, lime, Portland cement, water and silt, were formulated with a D-optimal mixture design to evaluate how fibers affect the raw earth material. The effect of fibers in raw earth material was evaluated in term of the Unconfined Compressive Strength (UCS). Economical, ecological and workability constraints are considered to set up a mixture design.

The purpose of this paper is to study the influence of flax fibers on the unconfined compressive strength of a raw earth material. In that goal, the design of experiments has been used to establish model formulations targeting the sought strength after 28 and 90 days curing-times. The obtained results indicate that the mixture design approach can be an important tool to study the effect of fibers on the unconfined compressive strength of raw earth materials consisting of several components.

Keywords: Raw earth material, Fibers, Shrinkage, Unconfined compressive strength, Mixture design

1 INTRODUCTION

Since the earliest civilizations and across all continents, earth has been used as a major building material [Fontaine, et al., 2009]. However, after World War II, the huge needs in reconstruction have required the use of materials, such as concrete and steel, as well as fast building techniques, without taking into account their impact on the environment. Since then, in developed countries, raw earth constructions have practically been abandoned. Nowadays, raw earth construction techniques can adapt to current needs and standards.

The raw earth construction comes in different forms, and adopt different manufacturing processes such as adobe [Millogo et al., 2014], rammed earth [Loccarini 2017], or poured earth concrete [Eid et al., 2015 a]. From an energy point of view, the raw earth is a material that consumes a low energy in terms of gray energy, compared to conventional building materials [Zak et al., 2016]. In addition, its inertia gives it exceptional hygro-thermal regulation characteristics. Moreover, being a natural material having undergone little or no transformation, it is almost infinitely recyclable.

Raw earth accumulates these qualities because it is recyclable, requires very low energy for its transformation into building material and needs only simple technology. Using local earth also means avoiding energy-intensive transport. The natural raw earth replaces gravel and sand, which are noble materials and increasingly rare, requiring the opening of quarries for exploitation and mechanical transformation, and therefore of gray energy.

In using earth materials, few undesirable properties such as the shrinkage and swelling, the cracking, erosion can be observed. Today, these problems can be minimized or controlled significantly by stabilizing the soil using lime, cement and fibers. These materials enhance the engineering properties of the soil and produce an improved construction material.

Recent studies have shown the influence of the binders such as lime and cement on the raw earth material properties [Al-Mukhtar et al., 2014], [Imanzadeh et al., 2018]. However, for the raw earth materials shrinkage, as an undesirable property, is responsible for the development of cracks. To reduce this effect, their plastic behavior requires to be improved to prevent brittle failures and then minimize cracking [Araldi et al., 2018]. Vegetal fibers are natural, economical and biodegradable materials. Their addition to materials has several benefits. Their principal role is to minimize the fissures happening during the drying phase, by allowing the dissipation and the distribution of the tensile stresses due to shrinkage of the clay fraction of the raw earth material [Eid et al., 2015 b], [Eid 2017]. This paper presents a new poured raw earth concrete developed by a French company from Normandy called Cematerre, in collaboration with University of Le Havre Normandie. Its novelty is its ability to be cast in place as a conventional concrete. The raw earth concrete is a mixture of several materials. The purpose of this paper concerns the study of the influence of flax fibers on the Unconfined Compressive Strength (UCS) of a raw earth material. To fulfill this objective, combinations of five-constituent mixtures composed of flax fibers, lime, cement, water and silt were formulated using a D-optimal mixture design to study the influence of flax fibers on the unconfined compressive strength. The experimental domain was determined according to three different constraints. A series of laboratory tests was conducted to establish model formulations targeting the sought strength after 28 and 90 days curing-times. Thereafter, the derived models were validated. The effect of flax fibers on the unconfined compressive strength of a raw earth concrete was then analyzed through response trace plots.

2 MATERIALS AND EXPERIMENTAL METHODS

The used soil material is natural silt, chosen because locally available material in abundance at the site of the planned construction. For this soil, the effective diameter, the Hazen uniformity factor and the curvature factor are respectively equal to 32 µm, 4.37 and 0.94. The Atterberg limits are respectively 20% for the liquid limit and 6% for the plasticity index [Imanzadeh et al., 2018]. Lime and Portland cement as two binders are used to prepare a raw earth concrete. The used lime comes from the Proviacal® DD range. More information about these binders' properties was given in details in [Eid 2017]. The used flax fibers are extracted locally from the region of Normandy. These used fibers are natural fibers which have not undergone any chemical surface treatment. Their diameters are between 10 and 15 µm [Abbar et al., 2017 a, b]. Concerning preparation of specimens, it should be noted that incorporating fibers without favoring any fiber orientation and with a final homogeneous distribution in the material is a hard task. Thus, fiber content was fixed in the range 0.3% - 0.45% in mass: 0.3% was considered as a low level and 0.45% as a high level of fiber content in specimens. This proportion that could be considered as small in mass is actually important in volume. A constant amount of adjuvant (SIKA VISCOCRETE TEMPO-10) fixed to 5 ml/ m^3 has been added for each sample preparation in accordance with NF EN 934-2 standard [Standard AFNOR 1998]. A potable tap water from the pipe in the laboratory was used for preparing the raw earth concrete.

The mixing procedure was done in a laboratory mixer with a capacity of four liters. Thereafter, the molds of 100 mm in height and 50 mm in diameter were filled by vibration for two minutes with a vibrating table. Then, the samples were stored for 28-day and 90-day curing-times in controlled laboratory environment. Laboratory prepared raw earth concrete samples with different mix proportion were studied, conducting Unconfined Compressive Strength (UCS) test. The samples were sheared on unconfined compressive strength path according to NF P94-420 [Standard AFNOR 2000] and NF P94-425 [Standard AFNOR 2002] French standards. The unconfined compressive strength test is used to plot stress-strain curve.

3 STATISTICAL ANALYSIS OF REGRESSION MODELS

Quadratic polynomial model was performed for five-constituents to obtain the model that fulfilled the best fit to the experimental data to make predictions of the unconfined compressive strength (UCS) of a raw earth concrete for any mixture of components. The Analysis Of Variance (ANOVA) includes several diagnostic tools to validate models [Fisher 1971], [Box et al., 2005]. The two first diagnostic tools are the regression coefficients (R^2 and R^2_{adj}), informing on the ability of the model to fit the measured data. In addition, Q^2 coefficient estimates the model validity *that means* its ability to estimate new data. Thereafter, the first F-Test and the second F-Test should be verified. The first F-Test is the regression model significance test. It compares regression variance to residual variance. For the second F-Test, residual error is divided in two parts: lack of fit due to imperfection of the model and pure error estimated from replicates data error [Goupy 2001].

4 EXPERIMENTAL DESIGN

Three constraints must be taken to account: i) fundamental constraint where the sum of the constituents of the mixture is equal to 100 % in weight for all the mixes of the design. ii) ecological and economical mixture constraints: the raw earth material has to be designed to provide the suitable mechanical properties to be used as a construction building material. Furthermore, it should be non-energy-intensive or low energy consumption. Then, the percentage of the cement and lime as binders should be limited. Therefore, the maximum quantities of cement and lime are respectively limited to 16% and 12% and a condition of maximum binder proportion was chosen: Cement % + Lime % < 16 %. In accordance with the mentioned constraints above, the mixing range chosen for each of the components, using fiber, is summarized in Table 1. iii) workability constraint: workability plays a significant role on the mechanical properties. Some properties such as plasticity, cohesion and consistency can influence the workability of a raw earth concrete [Bui et al., 2014]. In this study, a S3 level of consistency calibrated by standard slump test was used to ensure a fluidity close to a very plastic concrete in accordance with the standard NF EN 206-1 [Standard AFNOR 2012].

In this paper, experimental region is constrained by three mentioned conditions to an irregular 3D-polyhedron. Next, D-optimal design relying on a computer-aided is adapted to generate the set of experiments. The 27 formulations were performed in the random run order proposed using MODDE© software [Umetrics 2016] including two repetitions. Thereafter, the mixture design was done to study unconfined compressive strength of a raw earth concrete relying on the proportion of mixture components.

Table 1: Mixing range

x_i	Lower limit	Upper limit
x_1: Fiber	0.3 %	0.45 %
x_2: Lime	0	12 %
x_3: Cement	4 %	16 %
x_4: Water	20 %	25 %
x_5: Silt	47 %	75 %

5 RESULTS AND DISCUSSION

The unconfined compressive strength test was performed to study the stress-strain curve. For a raw earth material stabilized with lime, cement and fibers, the engineering stress-strain curve is not straightforward. As an example, the stress-strain curve for 90-day curing time for a formulation with the quantities of fiber, lime, cement, water and silt respectively equal to 0.45 %, 0 %, 16 %, 23 % and 60.55 % is presented in Fig. 1. The y- axis designates the unconfined compressive stress and the x- axis designates the axial strain. For the mentioned formulation, the value of the unconfined compressive strength is equal to 6.73 MPa (Fig. 1). From this figure, it can be noted that for small strains, the curve is concave. This can be explained by both the experimental conditions with the implementation of a homogeneous contact between the press and the sample and to a physical process: the closure of natural micro cracks in the porous material stabilized with binders. As axial strain is increased more, the raw earth material already goes through large deformations. A linear portion of the curve is detected with a constant rate of stress-hardening. Thereafter, a plastic zone is exhibited. The post-peak zone relates to the material behavior after the presence of a failure plane. It reveals the ductile character of the raw-earth material reinforced with flax fibers.

Quadratic polynomial models were first fit to the measured experimental data following a thorough examination of R^2, R^2_{adj} and Q^2 to determine the most suitable models representing the measured experimental data (Table 2). As it was shown in Table 2, for 90-day curing time the values of R^2, R^2_{adj} and Q^2 are bigger than those for 28-day curing time. However for these two curing times the values of R^2, R^2_{adj} and Q^2 are higher than 0.91 and can be considered as good. In addition, these models illustrate a very good predictive relevance (Q^2 >0.9, see Table 2). Then, chosen models can be considered as valid.

Response trace plots were produced to show the effect of the variation of each mixture constituent while holding all the constituents at a constant ratio for two curing times characterizing short term and long term of the drying process. The response (i.e. unconfined compressive strength) was plotted around a reference mixture. In this research study, the considered reference mixture is the centroid of the constrained experimental domain with the quantities of fiber, lime, cement, water and silt respectively equal to 0.375 %, 3.015 %, 8.402 %, 23.953 % and 64.255 %. Response trace plots of UCS with deviation from reference mixture in proportion for each curing time are shown in Fig. 2. They show how each component influences the UCS relative to the reference mixture. For the reference mixture, the UCS values are 2.4 and 3.3 MPa respectively for 28 and 90-day of curing times. The values of unconfined compressive strength are very sensitive to variations in cement and water proportions for these two curing times. As expected, the steep slope for cement indicates the major influence of this component. An increase of the proportion of cement in the mixing increases the unconfined compressive strength. This positive effect is reinforced with longer curing time. It can be principally associated to the required time for pozzolanic reaction to effectively take place. Water shows a significant negative impact that increases with curing time. The higher compressive strength of a raw earth concrete is achieved with the lower quantity of water. In addition, the straight line for water for these two curing times demonstrates an insignificant role of interactions with respect to the important main effect of water constituent. Regarding the silt effect, Fig. 2 demonstrates that an increase of silt proportion in the mixing tends to decrease the value of the unconfined compressive strength (UCS) at 28-day and 90-day curing times. In fact, in the long term, raw earth material hardens but at the same time it dries. The drying process leads to shrinkage provoke micro-cracking of raw-earth concrete which decreases the mechanical strength [Kanema et al., 2016]. Concerning the influence of lime, its slope denotes the very slight positive effect of this component on the UCS. One can consider that the response trace plots for lime is mostly a horizontal line for these both curing times. This shows that over 4 % of added lime, this component has very little effect on the unconfined compressive strength. In fact, the high percentage of lime required for the chemical reactions is around 3 % to 4% as was pointed out by several researchers [Basma et al., 1990], [Delfaut 1990], [Hibouche 2013]. Beyond this percentage, lime no longer reacts, and the excess lime behaves as a very fine granular additive in the mixture. Concerning fiber component, response trace plots for fiber component cannot be represented on Fig. 2 because of the small fiber content in mass associated to fiber (between 0.3% and 0.45%, see Table 1). Response trace plots of UCS for fiber component was plotted separately in Fig. 3 with an adapted scale for the two different curing times. An increase of the proportion of fibers in the mixing slightly increases the unconfined compressive strength for the short curing time (28-day). This effect becomes negative for the long curing time (90-day). This could be explained by the fact that, in the short term, pozzolanic reactions due to hydraulic binders are weak and the fiber-matrix friction remains dominant for the strength of the material. On the other hand, in the long term, these pozzolanic reactions, especially in the case of lime, reach their peak, and become dominant in relation to the effect of the fibers friction. In this case, the increase in the fiber content counteracts the formation of the cementing bridges in the matrix due to pozzolanic reactions, resulting in a slight decrease in strength. The influence of fibers on the mechanical properties of raw earth materials is not straightforward and is greatly influenced by many parameters. Laborel-Préneron et al., (2016) reported recently in a review paper about the role of plant aggregates and fibers in earth construction materials. Their review paper was based on 50 published studies of earth-based composites with plant aggregates and fibers. They pointed out that the effect of fiber addition on the compressive strength of earth-based composites can differ from one study to the other. In eight references, compressive strength was increased by adding aggregates or fibers under different conditions. In four other references, no significant influence was reported. Finally, the compressive strength was found to decrease in 11 references [Laborel-Préneron et al., 2016].

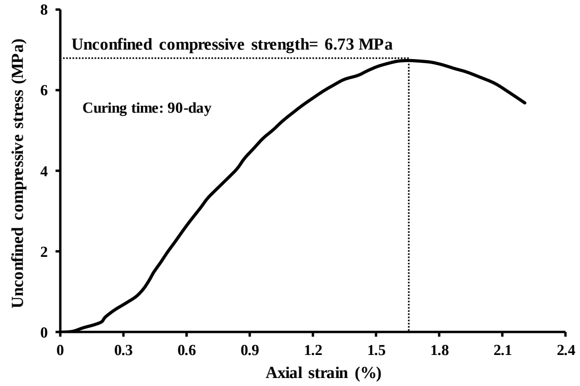
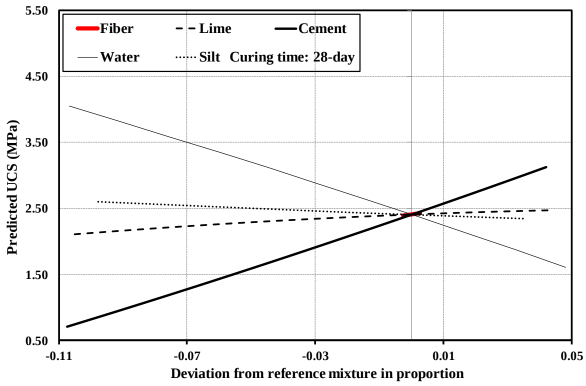
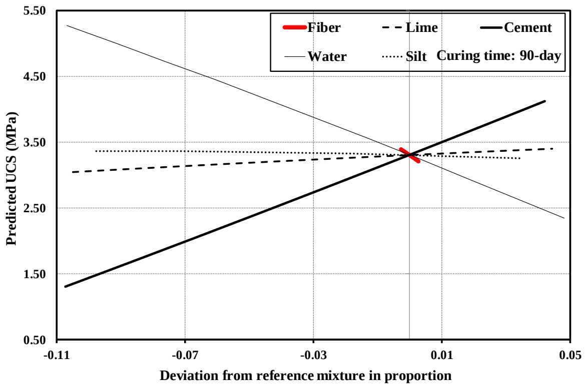


Fig. 1: Unconfined compressive stress versus the axial strain (formulation: fiber: 0.45 %, lime: 0%, cement: 16 %, water: 23 % and silt: 60.55 %)



a)



b)

Fig. 2: Response trace plots of UCS for two different curing times: a) 28-day and c) 90- day

Table 2: Values of R^2. R^2_{adj} and Q^2

	Quadratic model (UCS)	
	28-day curing time	90-day curing time
R^2	0.976	0.978
R^2_{adj}	0.944	0.949
Q^2	0.910	0.928

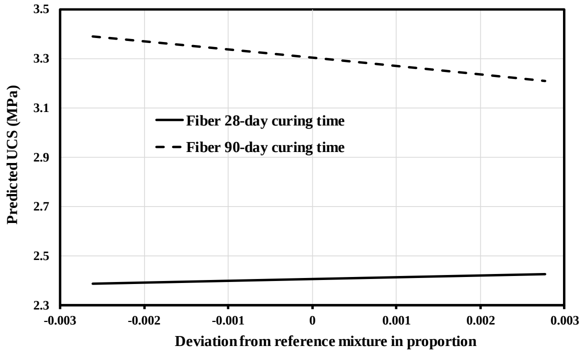


Fig. 3: Response trace plots of UCS for fiber component for two different curing times: 28-day and 90- day

6 CONCLUSIONS

In the present study, it was pointed out that Design of Experiments method is an optimization tool adapted to investigate unconfined compressive strength of a raw earth material. The design tests were determined by considering three constraints: economical, ecological and workability. The curing time was varied from 28 to 90-day to study the mechanical response of a raw earth concrete during the drying process. For the two curing times (28-day and 90-day) the negative role of the increase of the proportion of water and silt in the mixture was demonstrated using the trace plots around a reference mixture. As expected, the positive role of the increase of the proportion of the cement in the mixture on the unconfined compressive strength was illustrated. Concerning lime, very slight positive effect of this constituent on the unconfined compressive strength (UCS) was demonstrated. Its response trace plots was mostly a horizontal line for the both curing time.

For the flax fiber tested and the operation mode described herein, it was shown that for short curing time, (i.e. 28-day) an increase of fiber proportion in the mixing very slightly increases the unconfined compressive strength of the raw earth concrete. On the contrary, for long curing time (i.e. 90-day), an increase of fiber proportion leads to the reverse effect with a slight decrease of the unconfined compressive strength values when the fiber content increases. The trend of fiber influence to decrease the maximum strength when its proportion is increased could be explained by the pozzolanic reactions within the matrix that become dominant in the long term and that, a high fiber content can prevent the formation of some of these bonds.

The addition of fiber in the studied earth material is useful, focusing on other mechanical properties such as ductility or hygro-thermal properties and for its influence on propagation of cracks.

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