

# Mechanical Behavior of The Earth-Straw Composite: Experimental Aspect and Analytical Modeling

Omar Khtou , Issam Aalil, Mohamed Aboussaleh

Laboratory Of Sciences And Engineering

Ensam, Moulay Ismail University Meknes, 50000, Morocco

**Abstract**— Raw earth construction is a traditional, ecological and economic type of construction that is present in several regions of the world. This type of construction has experienced a renaissance in recent years for the qualities mentioned. Scientific research is increasingly interested in the earth material and this work is part of a more global research work dealing with fiber reinforced earth construction in south-eastern Morocco. The purpose of this paper is to propose an analytical model that represents the "soil-straw" composite well.

After carrying out the simple compression tests, we explored the bibliography to find suitable models. We studied the models of Voigt, Reuss, Popovics, Hashin, Halpin-Tsai and Hirsh-Dougill, and we compared the experimental results with the analytical results.

**Keywords**— *Earth construction; Analytical modeling; Young's modulus; Fiber reinforced earth*

## I. INTRODUCTION

To reduce the carbon footprint of the building and construction sector, several countries propose to use locally available materials, which are naturally adapted to geographical and climatic conditions and which have very interesting hygrothermal performances. Thanks to the latest advances in scientific research, these materials have better mechanical characteristics and require very low energy consumption (Morel et al. 2005).

Among these materials, we cite raw earth. Indeed, the construction in raw earth is widespread thanks to the availability of the earth material and its proximity to the various construction sites as well as for the ease of its implementation, although requiring a particular know-how, but which requires tools. rudimentary and inexpensive.

In order to better understand this material, this paper focuses on the analytical modeling of earth reinforced with wheat straw, considered as a composite material whose matrix is raw earth and fibers, wheat straw.

After giving the characteristics of the materials used as well as different analytical models, we will make a comparison with the results obtained experimentally.

## II. MATERIALS AND METHODS

### 2.1. Raw Materials

Raw earth is made up of gravel, sand, silt and clay, the proportions of these elements are among the things that greatly influence the mechanical behavior of the earth, among other things.

For this study, we extracted the earth used in Tinejdad, an oasis town in southeastern Morocco, an area known for its earthen construction. In order to avoid the presence of organic matter in the material used, the earth is extracted at a depth of 15cm.

The straw used in this study is that of wheat and comes from the same area.

#### 2.1.1 earth

We have characterized the grain size and the plasticity of the earth used.

The grain size determines the different proportions of the different grain sizes, it was made in two stages:

Particle size analysis by sieving NF P 94-056, then by NF P 94-057 sedimentation for fractions below 80  $\mu\text{m}$ .

The plasticity was characterized by two methods, the determination of the Atterberg limits and that of the methylene blue value:

- The plasticity index (PI) was measured on the fraction of soils between 0 and 400  $\mu\text{m}$ . The (PI) was calculated using the equation  $\text{PI} = \text{WL-WP}$  where WL is the liquidity limit and WP is the limit of plasticity WP. The Atterberg limits WL and WP were determined following the NF P94-051 standard.
- The methylene blue (BV) test was carried according to the NF P94-068 standard. It characterizes the specific surface of a soil. It turns out to be an indicator of the activity of the clays present.

#### 2.1.2 Wheat straw

Straw fibers are traditionally used in the reinforcement of earthen constructions, being available and providing good adhesion as well as a surplus of resistance, in particular in traction, there are mainly two types of straw frequently used: wheat straw and straw. of barley.

The mechanical properties of wheat straw are given by (Magniont 2010) the Young modulus given is 17MPa .

### 2.2. Test plan and samples preparation

#### 2.2.1. Samples preparation

The dimensions of the bricks used are: 4 x 4 x 16 cm<sup>3</sup>, by mixing the raw earth with straw, at different mass rates, as described in the table 1, six samples were made from each sample.

The fiber volumic rates to study are given in table 1 and the length of the straw used was 4cm, based on previous studies (H. Houben and H. Guillaud 2006) . The fresh samples are then left in the prismatic mold for a period of 3 days before demolding. The minimum duration before the drying tests required is 28 days (van Damme and Houben 2018). The tests were carried out after 6 months.

Table 1 : Samples's definition

Specimen	Volumic percentage of wheat straw
R	0%
W1	14%
W2	20%
W3	28%
W4	35%
W5	42%
W6	45%

## 2.2.2 Compression test

In order to determine the influence of the reinforcement of the adobe with wheat straw on the resistance to compression and the Young's modulus. We carried out the simple compression test, the specimen is subjected to an increasing load up to at the breakup. The press was motorized, with an imposed loading speed of 3 KN/min (Khtou et al. 2021). The deformations were obtained thanks to a displacement sensor of 20 mm.

Young's modulus is obtained from the linear, elastic part of the stress-strain curve

### 2.3 Homogenization models

homogenization is a modeling technique that assimilates a heterogeneous material to an equivalent fictitious homogeneous material, whose characteristics must be determined (Gibigaye et al. 2019). Adobe being a heterogeneous material, its mechanical behavior depends on its constituents, mechanisms at the interfaces but also on the adhesion of its constituents. To predict its behavior or optimize these mechanical characteristics, scaling models that take into account the characteristics of the microstructure are the most appropriate.

The objective of this paper is to understand the mechanical behavior of the composite material: matrix-fiber, in this case, "earth-straw", and to propose a model taking into account the percentage of fibers and which gives values of equivalent modulus of elasticity close to the experimental results.

This homogenization technique is complex and quite extensive, being described in detail in many books and works that specifically deal with this issue (Miranda Guedes 1990). As for the first technique, many models have been proposed. these models range from the simplest, as Voigt and Reuss presented above, to the most complex. We consider "soil-straw" as a two-phase material (matrix + fiber), with perfect adhesion between the two. Such patterns are usually determined by boundary analysis: upper bound analysis, lower bound analysis, and a linear combination of the two. The analytical expressions of these models are functions of the modulus of elasticity and of the volume fractions of the components of the composite. In the upper bound analysis, the fibers are assumed to be continuous and oriented in the direction of loading, along which the modulus is determined.

At the lower limit, the fibers are discontinuous and normal to the loading.

In the following, we present the equations giving the expression of the equivalent longitudinal elasticity modulus, for each model used in this study (Alwan 1994; Hill 1963; Reuss 1929).

- *Voigt Model:*

$$E_c = E_i V_i + E_m V_m \quad (1)$$

- *Popovics model*

$$E_c = \frac{1}{2} (E_c \text{Voigt} + E_c \text{Reuss}) \quad (4)$$

- *Reuss Model:*

$$\frac{1}{E_c} = \frac{V_i}{E_i} + \frac{V_m}{E_m} \quad (2)$$

- *Halpin Tsai model*

$$E_c = \frac{3}{8} E_c \text{Voigt} + \frac{5}{8} E_c \text{Reuss} \quad (5)$$

- *Hirsh-Dougill model:*

$$\frac{1}{E_c} = \frac{1}{2} \left( \frac{1}{E_c \text{Voigt}} + \frac{1}{E_c \text{Reuss}} \right) \quad (3)$$

- *Hashin model*

$$E_c = \frac{(E_m + E_i) + (E_i - E_m) v_i}{(E_m + E_i) - (E_i - E_m) v_i} \cdot E_m \quad (6)$$

These simpler models, which consider a perfect adhesion between the two phases (matrix + fiber), can overestimate the phenomenon, since in reality, a perfect adhesion does not exist.

Where  $E_m$  is the modulus of elasticity of the soil matrix,  $E_i$  is the modulus of elasticity of the inclusion phase (fibers),  $E_C$  is the equivalent modulus of elasticity given by the model.  $V_m$  is the volume fraction of soil as matrix and  $V_a$  is the volume fraction of straw.  $E_C$  Takes the indices of the composite model used for the estimation of the modulus of elasticity. For example,  $E_C$  Voigt expresses the modulus of elasticity of soil-fibers estimated using the composite model of Voigt.

### III. RESULTS

#### 3.1 Raw Materials

The results of the particle size analysis indicate that the soil contains about 13 % of gravel, 63 % of sand, 12% of silt and 12% of clay. The Atterberg limits are 20% for the liquid limit and 7.5% for the plasticity index, respectively. These results were presented in the study. (Khtou et al. 2021).

#### 3.2 Mechanical characteristics

The table gives the Young's modulus as well as the compressive strengths of the different specimens studied.

Table 2 : Young modulus and compressive strength results

Specimen	Volumic percentage of wheat straw	Young Modulus (Mpa)	Compressive strength (Mpa)
R	0%	735	3,00
W1	14%	510	3,22
W2	20%	477	3,27
W3	28%	470	3,29
W4	35%	366	3,18
W5	42%	310	3,04
W6	45%	299	2,87

The wheat straw reinforcement effect gives greater resistance to compression. The maximum resistance increases until it reaches its maximum for a fiber intake of 2% then the value of the resistance decreases beyond this intake.

This opposite effect can be explained by the increase in the void ratio.

The optimum gain in terms of resistance to compression is 10%.

As shown in Table 2, the Young's modulus decreases with fibrous reinforcement, the results found in the literature are quite close and show Young's moduli ranging from 250MPa to 750MPa depending on the fiber content (Illampas, Loizou, and Ioannou 2017; Miccoli, Müller, and Fontana 2014).

#### 3.3 Analytical modeling

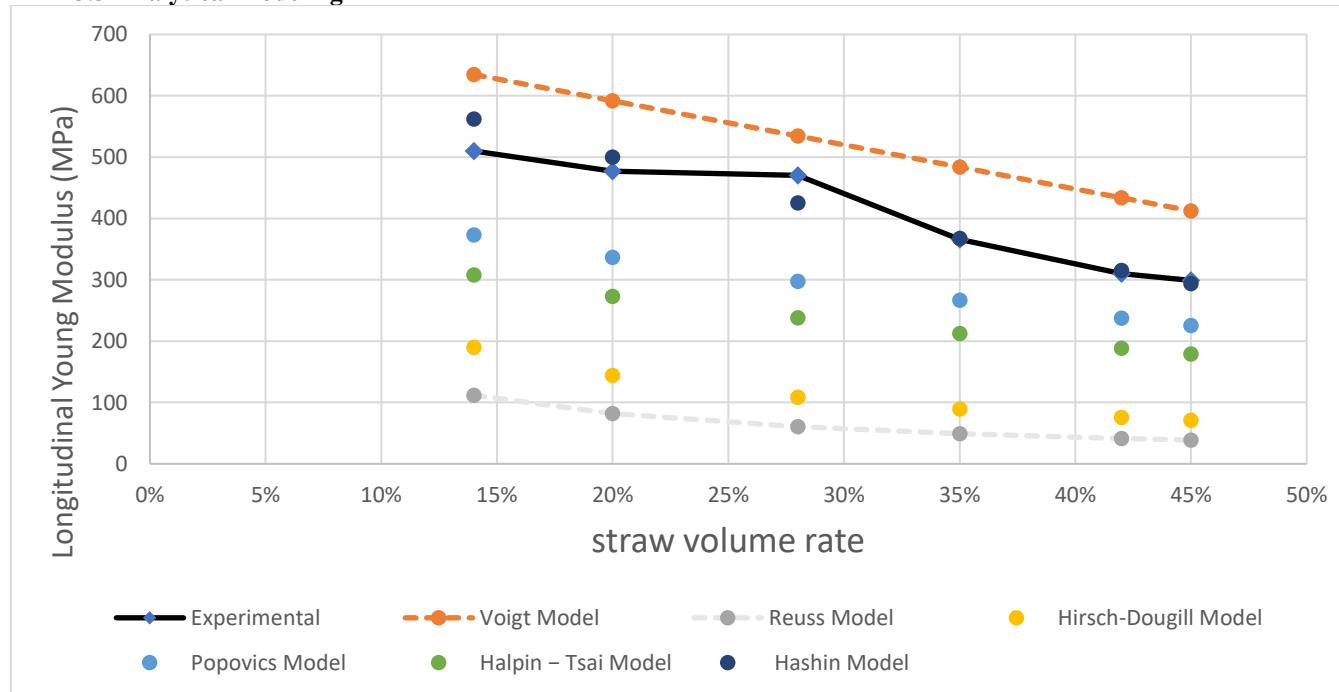


Figure 1 : Comparison of Analytical Young's Modulus and Experimental Results for Wheat Straw Reinforced Earth Bricks

The Fig 1 shows the different results of equivalent Young's modulus obtained with the models mentioned above for different volumetric reinforcement rates in wheat straw.

The model that comes closest to the experimental results is that of "Hashin", the largest difference noted between the Young's modulus given by the model of Hashin and the experimental value is 9%, obtained at a fiber volume rate by 28%.

We note that the different curves have a general trend with the exception of the experimental value at this same rate, which is 28% by volume and which corresponds to 2% by mass.

#### CONCLUSION

The purpose of this research is to characterize the mechanical behavior in compression of earth reinforced with wheat straw and to find a mathematical analytical model capable of giving the equivalent modulus of elasticity of the "straw earth" composite, for this we have explored several models used for composites and applied at different volumetric rates of straw reinforcement. wheat. Reinforcement with wheat straw gave a gain of 10% for a straw volume rate of 28%. The model which gave good results, close to the experimental one, is that of Hashin.

#### REFERENCES

- [1] Alwan, J. M. 1994. "Modeling of the Mechanical Behavior of Fiber Reinforced Cement Based Composites under Tensile Loads." University of Michigan.
- [2] van Damme, Henri, and Hugo Houben. 2018. "Earth Concrete. Stabilization Revisited." *Cement and Concrete Research* 114:90–102. doi: 10.1016/j.cemconres.2017.02.035.
- [3] Gibigaye, Mohamed, Fructueux Gildas Godonou, Crespin Prudence Yabi, and Gerard Degan. 2019. "Estimation of Elastic Properties of Oil Palm Kernel Shell Concrete by Semianalytical Methods of Homogenisation." *Advances in Civil Engineering* 2019:1–12. doi: 10.1155/2019/9256260.
- [4] H. Houben, and H. Guillaud. 2006. *Traité de Construction En Terre*.
- [5] Hill, R. 1963. "Elastic Properties of Reinforced Solids: Some Theoretical Principles." *Journal of the Mechanics and Physics of Solids* 11(5):357–72. doi: 10.1016/0022-5096(63)90036-X.
- [6] Illampas, Rogiros, Vasilios G. Loizou, and Ioannis Ioannou. 2017. "Effect of Straw Fiber Reinforcement on the Mechanical Properties of Adobe Bricks." Pp. 1331–38 in *Poromechanics VI*. Reston, VA: American Society of Civil Engineers.
- [7] Khtou, Omar, Issam Aalil, Mohamed Aboussaleh, and Fatima Zohra el Wardi. 2021. "Mechanical Analysis of Fiber Reinforced Adobe." *Civil Engineering and Architecture* 9(7):2160–68. doi: 10.13189/cea.2021.090705.
- [8] Magniont, C. 2010. "Contribution à La Formulation et à La Caractérisation d'un Éco-Matériau de Construction à Base d'agroressources." Université Toulouse III.
- [9] Miccoli, Lorenzo, Urs Müller, and Patrick Fontana. 2014. "Mechanical Behaviour of Earthen Materials: A Comparison between Earth Block Masonry, Rammed Earth and Cob." *Construction and Building Materials* 61:327–39. doi: 10.1016/j.conbuildmat.2014.03.009.
- [10] Miranda Guedes, Jose. 1990. "Nonlinear Computational Models For Composite Materials Using Homogenization." University of Michigan.
- [11] Morel, J. L., C. Schwartz, L. Florentin, and C. de Kimpe. 2005. "URBAN SOILS." Pp. 202–8 in *Encyclopedia of Soils in the Environment*. Elsevier.
- [12] Reuss, A. 1929. "Berechnung Der Fließgrenze von Mischkristallen Auf Grund Der Plastizitätsbedingung Für Einkristalle ." *ZAMM - Zeitschrift Für Angewandte Mathematik Und Mechanik* 9(1):49–58. doi: 10.1002/zamm.19290090104.