International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878 (Online), Volume-8 Issue-4, November 2019

Prediction of the Elastic Properties of the Clay-Rice Straw Composite by Numerical Homogenization Technique using Digimat

Christian Enagnon Adadja, Clément Adéoumi Labintan, Mohamed Gibigaye, Hamid Zahrouni, Mahdia Hattab

Abstract*: This paper deals with numerical modelling of the elastic properties of the rice straw-clay composite. This composite material is currently attracting interest because of its low impact on the environment but also for economic reasons. Benefiting from the advantages of a promising building material, straw reinforced composites attract more attention. This work allowed to model the effect of the straw inclusions on the elastic properties of the composite by a numerical approach considering the aspect ratio, the volume fraction, the orientation and the distribution of the straw inclusions. The Mori-Tanaka homogenization scheme for the RVEs is done using Digimat-MF software and the 3D composite microstructure models are generated by the Digimat-FE software. This made it possible to calculate the effective elastic properties of the clay-rice straw composites by numerical simulation. An empirical linear correlation between the volume fraction of the inclusions and the Young's modulus has been proposed. The results obtained can help to better control the formulation of the composite in developing countries.

Keywords: Composite, Homogenization, Young's modulus, Digimat

I. INTRODUCTION

The construction sector is highly dependent on conventional materials such as cement, lime and steel. The manufacturing process of these materials produces a large amount of carbon dioxide. These emissions contaminate soil and water as well as human health [1]. The relatively high cost of these materials considerably slows down the development of decent and affordable housing for most of the population in developing countries, particularly in rural areas. In the context of housing modernization in rural areas, exposed to the problems of rural depopulation and poverty in developing countries, there is an urgent need to find an alternative to conventional materials. Various research projects on the Development of locally available building materials have been undertaken. In order to preserve and preserve the environment, the use of environmentally friendly building materials, commonly known as green building materials, must be promoted to promote the idea of sustainable construction [2]. One of these green building materials is adobe [3]. According to Mrema [4], adobe or mud is the mixture of one or more types of earth with water. The main weakness of the earth as a building material lies in its poor mechanical properties. To overcome these difficulties, some generally add to the land an appropriate amount of the appropriate economic stabilizer, such as agricultural waste, to produce low-cost housing. For each country, according to the type of climate [5]. The mixture of clay soil and stalks of rice straw in Benin for the traditional construction of barns for food crops is an efficient and environmentally friendly material with interesting mechanical properties for structural elements [6]. For a professional use of this composite in the structural design of building structures, it is necessary to know its elastic properties, its Young's modulus and its Poisson's ratio. Most studies found in the literature had determined the mechanical properties of banco, using experimental approaches, which did not sufficiently consider the multiphase constitution of the material [7], [8].

The numerical homogenization methods that are used in this study are powerful tools for simulating the mechanical behaviour of many types of engineering materials, at a very reasonable computational cost. Many algorithms have been developed over the years, which can consider not only the fraction of volume and the shape of the inclusions in the composite, but also their spatial distribution, which can provide very accurate predictions. Many studies have focused on the homogenization of multiphase composites, but the modelling of the microstructure of composite materials based on clay reinforced with rice straw is not often studied or reported in the literature.

The present study aims at studying the elastic properties of the clay-rice straw composite by numerical methods. 3D microstructure models of the straw-clay composite were generated using Digimat software. Digimat calculates the multi-physics nonlinear behaviour of homogeneous models and digitizes microstructures of multi-phase materials.

Manuscript published on November 30, 2019.
* Correspondence Author

Clement Labintan*, Laboratory of Energetics and Applied Mechanics, University of Abomey-Calavi, Cotonou, Benin. Email: labintanclement@gmail.com

Christian Adadja, Laboratory of Microstructure Studies and Mechanics of Materials, University of Lorraine, Metz, France. Email: christian-enagnon.adadja@univ-lorraine.fr

Mohamed Gibigaye, Laboratory of Energetics and Applied Mechanics, University of Abomey-Calavi, Cotonou, Benin. Email: mohamed.gibigaye@uac.bj

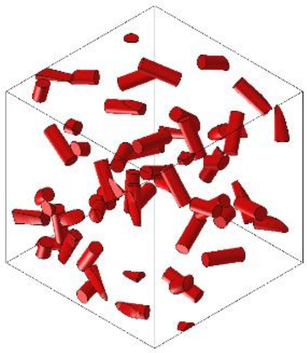
Hamid Zahrouni, Laboratory of Microstructure Studies and Mechanics of Materials, University of Lorraine, Metz, France. Email: hamid.zahrouni@univ-lorraine.fr

Mahdia HATTAB, Laboratory of Microstructure Studies and Mechanics of Materials, University of Lorraine, Metz, France. Email: mahdia.hattab@univ-lorraine.fr

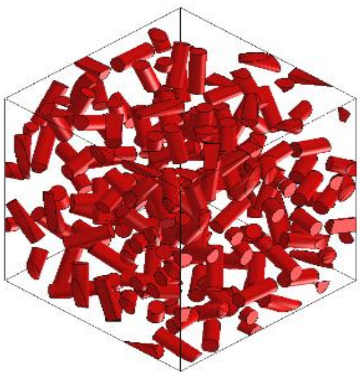
3D geometric modelling considered the distribution and variability of the fibre volume fraction. The results obtained were validated by comparison with the existing analytical models in the literature. The results obtained in this study could help improve the use of fibre-reinforced soils in the construction of modern buildings in rural areas of developing countries.

II. NUMERICAL HOMOGENIZATION DESCRIPTION OF THE NUMERICAL MODEL

In this study, a method based on composite VAR generation was used to predict effective properties. The different phases of the composite were created using the Digimat 6.1.1 program [9]. Digimat MF software is a multi-scale material modelling software based on Eshelby's unique inclusion solution and the Mori-Tanaka model for micromechanical analysis. The size, distribution, and position of the inclusions in a material can be defined by means of a parameter setting. A size of RVE should allow to include the essential microstructural characteristics of the phases of the composite. However, the size of the RVE should be as small as possible so that stress-strain relationships can be considered homogeneous throughout the RVE. The RVEs of the 3D microstructures of the composites were generated (Figure 1). The interface between the layers of the clay matrix and the inclusions was considered perfectly related.



(a) 10% of inclusions



(b) 20% of inclusions

(c) 40% of inclusions

Figure 1: RVE model generated by Digimat code

III. MODELING ASSUMPTIONS

For the smooth running of the calculation, it will suffice to supply the model with the following data:

- The volume fraction of the rice straw inclusions, the orientation and the aspect ratio of the rice straws
- The elastic properties of each constituent: clay matrix and rice straws
- It is assumed that straw and soil have isotropic behaviour and that adhesion is perfect between the two phases.

The mechanical properties of the matrix and the stabilizing fibres according to Young's modulus E are presented in ***Table 1***.

Table 1: Young's modulus and Poisson's ratio of clay matrix and fibres

Phases	Young's modulus, E (MPa)	Poisson's ratio, ν
Clay Matrix	175 [10]	0.3 [11]
Fibres	17 [12]	0.3 [13]

IV. NUMERICAL MODELLING OF STRAW/EARTH

The Young's modulus is also estimated in the present work by a finite element and semi-analytical numerical method using the Digimat software with semi-analytical digital modules MF and FE. The inclusions of randomly oriented ellipsoids are represented by cylindrical inclusions.

DIGIMAT is a software platform for the predictive simulation of composite materials [8]. This tool is used in many industrial applications to model the behaviour of composites considering the local orientation of the fibre and the manufacturing process. It can also be applied to our equipment. This justifies our choice for this digital homogenization software. DIGIMAT presents four modules: Digimat MF, Digimat FE, Digimat MX and Digimat CAE [8]. For our study, only the first two modules (Digimat MF, Digimat FE) were used.

V. ESTIMATE BY DIGIMAT MF

Digimat-MF is a medium-field homogenization software used to predict the non-linear behaviour of multiphase materials. For this purpose, he uses two main semi-analytical methods: Mori-Tanaka and the double-inclusion interpellation method (Lielens model) [14].

The number of phases of inclusion can be greater than one. The inclusions may have an ellipsoid, cylindrical shape, cavities, embedded inclusions and rigid or quasi-rigid inclusions. In our case we considered that our inclusions have a cylindrical shape because it is straws. At the end of the simulation, Digimat-MF gives us the stress-strain curve, the stiffness matrix and consequently the elasticity moduli.

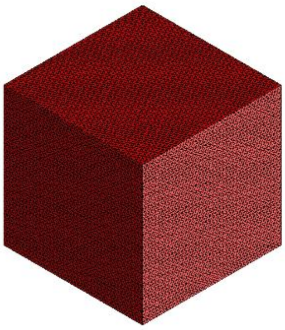
VI. ESTIMATE BY DIGIMAT FE

Digimat-FE is a software for homogenization of non-linear behaviour of Representative Elemental Volume (VER) microstructure of complex materials. This module uses the finite element method (FEM) for the analysis of the VER structure.

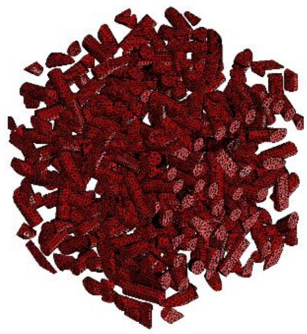
To generate the VER and the mesh it is necessary to enter the characteristics of each phase as well as the orientation and the report of form of the inclusions. He uses Abaqus / CAE to generate the mesh (Figure 2) of a microstructure via a Python script. It serves inter alia to compare the results of the MEF method (Digimat FE) with those of the semi-analytical method (Digimat MF).

VII. GENERATING AND MESHING OF STRAW/EARTH MODEL

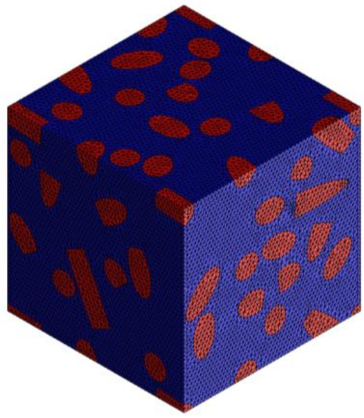
In order to model the microstructures of composites reinforced with a random distribution of inclusions, [15]–[17] and [18] presented various kinds of model adapted for this situation. According [19], only 27 inclusions randomly oriented in a composite domain suffice to give an accurate prediction of the mechanical properties. Two recent studies [20] and [21] have shown that an RVE of 50 rigid spheres is the minimum volume size needed to provide a realistic prediction. Qualitatively, the µ-CT morphology of Straw/Earth composites showed that the microstructure contained two scales: the scale of the matrix and the scale of the inclusions.
In our computation, 200 inclusions were randomly implanted in soil domain with the possibility of contact in order to create an aggregates phase. In this study, we have generated the RVE with the maximum number of inclusions. The algorithm of inclusions implementation was already described in previous works [16], [20] and proposed by Digimat-FE software. Figure 18 shows examples of created RVE microstructures. Several techniques are available to mesh the RVE microstructure of composites. The priority had been given to create a FE mesh model that considers the interface and the different constituents. Digimat software was used to mesh the created RVE with internal coarsening of the mesh. An example of the RVE meshing is presented in Figure 19.



(a) Mesh of the matrix



(b) Mesh of the inclusion



(c) Mesh of the composite

Figure 2: RVE meshing

VIII. BOUNDARY CONDITIONS AND GLOBAL CONVERGENCE

It is necessary to define boundary conditions in order to solve the constitutive equations in the case of elasticity. One distinguishes: the homogeneous conditions on the contour in deformation (KUBC), the homogeneous conditions on the contour in stresses (SUBC) and the periodic conditions (PBC). According to [22] and [23] the periodic conditions (PBC) are preferable for finite element calculations (MEF). These PBC boundary conditions are used by many researchers because of its rapid convergence. For this, in our work, we have chosen these periodic type boundary conditions (PBC). According to the periodic type boundary conditions, two homologous points of opposite faces have the same characteristic. Similarly, the efforts $\sigma \cdot n$ in two homologous points are opposed.

IX. STUDY OF THE CONVERGENCE OF THE YOUNG MODULE AS A FUNCTION OF THE MESH

The convergence of the mesh has been studied. We tried to get the minimum FE needed to mesh the RVE. To this end, a specific 3D RVE has been generated and meshed with a different number of elements ranging from 1,000 to 400,000 elements. The number of inclusions and the RVE dimensions were unchanged, but different mesh resolutions were considered. Figure 20 shows the results of Young's modulus calculations as a function of the number of elements.

It appeared that the mechanical properties decreased rapidly for the finer meshes and tended to stabilize for the large meshes. It also appears that in the case of 300000 FE, convergence is obtained. This density of mesh allowing to reach the convergence of the results is considered in the continuation of our simulations with the conditions of periodicities.

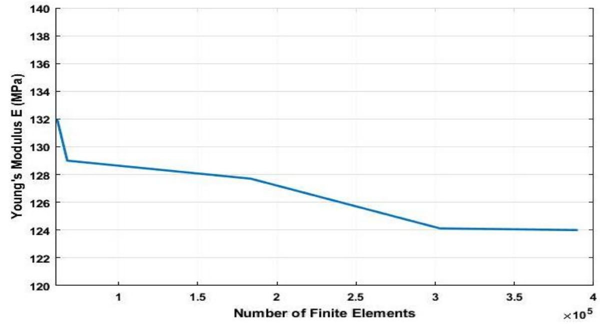


Figure 3: Convergence of the Young's modulus as a function of the number of FE for the different grids of mesh.

X. RESULT AND DISCUSSION

A simple uniaxial test was applied to the generated RVE microstructures of the Figure 2. The traction load was applied on one face of the RVE and the opposite one was fixed, and all the other faces were free. The homogenized Young's modulus for different volume fractions were then calculated using Stress-Strain curves and presented in Figure 4.

The predictions of FE and MF simulation were compared with experimental data from the literature.

The experimental results are close to the numerical results for different volume fractions. It appeared that the elastic properties decreased by increasing the volume fractions. The values of the FM simulation, inspired by the Mori-Tanaka analytical homogenization model, are closer to the experimental data. This is entirely normal according to Benveniste's interpretation of the Mori-Tanaka model [24], when the matrix is the most rigid phase, the Mori-Tanaka model corresponds more to the values of the most rigid phase. In our case, the clay matrix was the most rigid, which justifies the comparison of the MF simulations of the experimental data. Considering the intrinsic characteristics of the constituent materials of the Banco composite, the numerical methods gave us the real characteristics of the composite material.

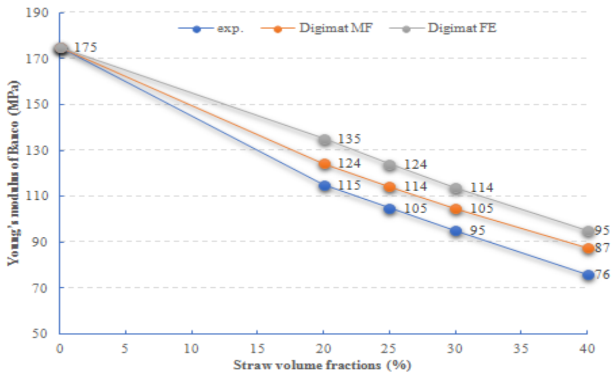
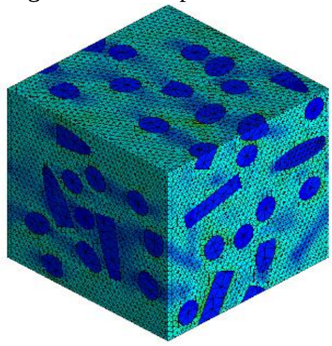
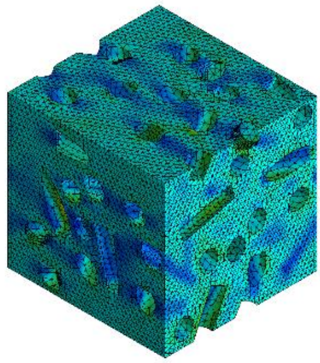


Figure 4: Estimation of the Young's modulus of the Banco composite as a function of the volume fraction of rice straws.

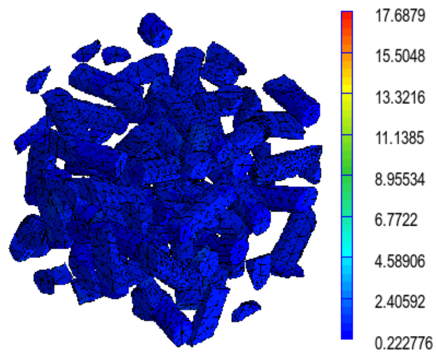
Figure 5 showed the distribution of the stress into RVE after the tensile tests. In the case of natural fibres reinforced soil composites, the numerical model showed a fundamental change in the distribution of the stress. It is apparent that the distribution of the stress was drastically changed between the matrix-fibres interface. The maximum of the stress was observed in this zone. For the case of particles reinforced composites, the onset damage occurred at this zone, where the stress concentration was the highest due to difference between properties of phases. For that purpose, it was important to create a homogenous distribution of the rice straws in order to decrease the initiation and the evolution of the damage throughout the composites.



(a) Composite



(b) Only matrix



(c) Only inclusions

Figure 5: Illustration of the FE simulations in the case of the simple uniaxial tension and the distribution of von Mises for 20% of inclusions

XI. CONCLUSION

The present study presents the numerical prediction of the elastic properties of the clay matrix composite reinforced with rice straws with a variation of the formulations. Using the Digimat-MF and Digimat-FE software, the effective properties of the composites were evaluated on RVEs. The results obtained show that numerical models make it possible to predict the elastic properties of the composite. The actual properties agree with the values of the literature. These prediction methods make it possible to estimate the effective properties of clay-straw rice composites. This study offers a better control of the elastic properties of the clay-rice straw composite, its Young's modulus, for a professional use of banco in the structural design of building structures.

REFERENCES

1. M. Safiuddin, Z. Jumaat, M. A. Salam, and R. Hashim, ‘Utilization of solid wastes in construction materials’, *International Journal of the Physical Sciences*, vol. 5, no. 13, pp. 1952–1963, 2010.
2. C. A. Oyelami and J. L. Van Rooy, ‘A review of the use of lateritic soils in the construction/development of sustainable housing in Africa: A geological perspective’, *Journal of African Earth Sciences*, vol. 119, pp. 226–237, 2016.
3. A. P. Olukoya Obafemi and S. Kurt, ‘Environmental impacts of adobe as a building material: The north cyprus traditional building case’, *Case Studies in Construction Materials*, vol. 4, pp. 32–41, Jun. 2016.
4. G. C. Mrema, L. O. Gumbe, H. J. Chepete, and J. O. Agullo, *Rural structures in the tropics. Design and development*. Rome: FAO, 2011.
5. A. Kriker, A. Bali, G. Debicki, M. Bouziane, and M. Chabannet, ‘Durability of date palm fibres and their use as reinforcement in hot dry climates’, *Cement and Concrete Composites*, vol. 30, no. 7, pp. 639–648.
6. C. Labintan, R. Benelmir, M. Gibigaye, and A. Donnot, ‘Characterization of the “Banco”, a Building Material for a Tropical and Rural Environment’, *International Journal of Energy, Environment and Economics*, vol. 23, no. 2, p. 203, 2015.
7. V. Sharma, H. K. Vinayak, and B. M. Marwaha, ‘Enhancing sustainability of rural adobe houses of hills by addition of vernacular fiber reinforcement’, *International Journal of Sustainable Built Environment*, vol. 4, no. 2, pp. 348–358, Dec. 2015.
8. V. Sharma, H. K. Vinayak, and B. M. Marwaha, ‘Enhancing compressive strength of soil using natural fibers’, *Construction and Building Materials*, vol. 93, pp. 943–949, Sep. 2015.
9. E-Xstream engineering, *Digimat user’s manual*. Louvain-la-Neuve, 2016.
10. L. Miccoli *et al.*, ‘Mechanical behaviour of earthen materials: A comparison between earth block masonry, rammed earth and cob’, *Construction and Building Materials*, vol. 61, pp. 327–339, Jun. 2014.
11. N. Mondol, ‘Elastic properties of clay minerals’, *The Leading Edge*, Jan. 2008.
12. Q. Piattoni, E. Quagliarini, and S. Lenci, ‘Experimental analysis and modelling of the mechanical behaviour of earthen bricks’, *Construction and Building Materials*, vol. 25, no. 4, pp. 2067–2075, Apr. 2011.
13. M. J. O’Dogherty, ‘A review of the mechanical behaviour of straw when compressed to high densities’, *Journal of Agricultural Engineering Research*, vol. 44, pp. 241–265, 1989.
14. I. Doghri and A. Ouaar, ‘Homogenization of two-phase elasto-plastic composite materials and structures study of tangent operators, cyclic plasticity and numerical algorithms’, *International Journal of Solids and Structures, Elsevier*, vol. 40, no. 7, pp. 1692–1694, 2003.
15. A. El Moumen, T. Kanit, A. Imad, and H. E. L. Minor, ‘Effect of overlapping inclusions on effective elastic properties of composites’, *Mechanics Research Communications*, vol. 53, pp. 24–30, 2013.
16. A. El Moumen, M. Tarfaoui, O. Hassoon, K. Lafdi, H. Benyahia, and M. Nachtane, ‘Experimental Study and Numerical Modelling of Low Velocity Impact on Laminated Composite Reinforced with Thin Film Made of Carbon Nanotubes’, *Applied Composite Materials*, vol. 25, no. 2, pp. 309–320, Apr. 2018.
17. A. El Moumen, M. Tarfaoui, and K. Lafdi, ‘Computational Homogenization of Mechanical Properties for Laminate Composites Reinforced with Thin Film Made of Carbon Nanotubes’, *Applied Composite Materials*, Springer Netherlands, pp. 1–20, Aug-2017.
18. L. Bouaoune, Y. Brunet, A. El Moumen, T. Kanit, and H. Mazouz, ‘Random versus periodic microstructures for elasticity of fibers reinforced composites’, *Composites Part B: Engineering*, vol. 103, pp. 68–73, Oct. 2016.
19. H. Ma, G. Hu, and Z. Huang, ‘A micromechanical method for particulate composites with finite particle concentration’, *Mechanics of Materials*, vol. 36, no. 4, pp. 359–368, 2004.
20. A. El Moumen, T. Kanit, A. Imad, and H. El Minor, ‘Effect of reinforcement shape on physical properties and representative volume element of particles-reinforced composites: Statistical and numerical approaches’, *Mechanics of Materials*, vol. 83, pp. 1–16, 2015.
21. D. Beicha, T. Kanit, Y. Brunet, A. Imad, A. El Moumen, and Y. Khelfaoui, ‘Effective transverse elastic properties of unidirectional fiber reinforced composites’, *Mechanics of Materials*, vol. 102, pp. 47–53, Nov. 2016.
22. A. EL MOUMEN, ‘Prévision du comportement des matériaux hétérogènes basée sur l ’ homogénéisation numérique : modélisation , visualisation et étude morphologique’, *Thèse doctorale*, pp. 43–47, 2014.
23. T. Kanit, S. Forest, I. Galliet, V. Mounoury, and D. Jeulin, ‘Determination of the size of the representative volume element for random composites: statistical and numerical approach’, *International Journal of Solids and Structures*, vol. 40, no. 13–14, pp. 3647–3679, 2003.
24. Y. Benveniste, ‘A new approach to the application of Mori-Tanaka’s theory in composite materials’, *Mechanics of Materials*, vol. 6, no. 2, pp. 147–157, 1987.

AUTHORS PROFILE

ADADJA Christian Enagnon, Researcher, Laboratory of Microstructure Studies and Mechanics of Materials, University of Lorraine, Metz, France.

LABINTAN Adéoumi Clément, Researcher, Laboratory of Energetics and Applied Mechanics, University of Abomey-Calavi, Cotonou, Benin.

GIBIGAYE Mohamed, Professor, Laboratory of Energetics and Applied Mechanics, University of Abomey- Calavi, Cotonou, Benin

ZAHROUNI Hamid, Professor, Laboratory of Microstructure Studies and Mechanics of Materials, University of Lorraine, Metz, France.

HATTAB Mahdia, Professor, Laboratory of Microstructure Studies and Mechanics of Materials, University of Lorraine, Metz, France.