ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 7, Issue 10 , October 2020

Modelling the thermomechanical behaviour of earth bricks stabilized with Portland cement

Mbuh Moses Kuma*, Ngapgue Francois, Kagou Dongmo Armand, Mofor Nelson Alakeh ,Penka Jules Bertrand

Department of Earth Science, Faculty of Science, University of Dschang, Dschang, Cameroon and Department of Civil Engineering and Forestry Techniques, Higher Technical Teacher Training College, The University of Bamenda, Bambili, Cameroon
Department of Earth Science, Faculty of Science, University of Dschang, Dschang, Cameroon
Department of Earth Science, Faculty of Science, University of Dschang, Dschang, Cameroon
Department of Civil Engineering and Architecture, National Higher Polytechnic Institute (NAHPI), The University of Bamenda, Bambili, Cameroon
Department of Civil Engineering and Architecture, National Higher Polytechnic Institute (NAHPI), The University of Bamenda, Bambili, Cameroon
Corresponding author email: mbuhmoses@yahoo.com

ABSTRACT: The thermomechanical behaviour of earth bricks stabilized with Portland cement (CPJ 35) has been studied by the finite element method. This was done by subjecting earth bricks to heat transfer during the firing process. A physical model, taking into account the mechanisms of heat transfer by convection, was employed and the earth bricks followed a visco-plastic elastic constitutive law. Heat greatly influenced the mechanical properties of the bricks during firing and as firing went on, volumetric plastic deformations appeared and the development of stresses in the bricks increased as temperature was increasing. The more the earth brick was enriched with stabilizer dosage, the more it was likely to tolerate large deformations during firing. The stresses increased rapidly at the edges, stabilised to a stage where their magnitude increased as stabilizer was added. In addition, the stresses in the middle of the stabilized bricks evolved up to the stress peak, then gradually decreased, tending towards a zero value. The use of stabilizers in the manufacture of earth bricks was found to be more effective and can be more sustainable compared to unstabilized earth bricks.

KEY WORDS: thermomechanical behaviour, stabilized earth brick, heat transfer, finite element method.

I. INTRODUCTION

Nowadays, earth bricks are the traditional materials most used in the world [1]. They have interesting mechanical properties resulting from the formation of a strong bond between clay particles at higher temperatures, which can be attributed to the melting of silica in clay [2].
In recent years, the production of earth bricks has reached 1.4 trillion units per year [3]. This increase can be justified by the environmental threats caused by the ever-increasing human activities. Interest in green building materials and the valuation of by-products from multiple industries has increased to contribute to this state of affairs [4]. It is in this perspective that much research has been carried out in order to demonstrate the impact of adding organic and inorganic materials during the mixing procedure on the behaviour of earth bricks [4], [5], [6].
The implementation of compressed stabilized earth bricks seems to be a sustainable solution for our environment, due to its energy efficiency, low cost and ecological importance [7]. These stabilized bricks have already proven their worth in several countries around the world: in Europe, the United States of America, Africa and Asia [7]. Compressed stabilized earth brick is a combination of three different materials; namely cement, ground and sand, which are mixed with water in defined proportions. These blocks use the same base material as unstsabilized mud bricks, but offer the significant advantage of compressive strength in wet conditions [8, 9]. Studies have shown that the bulk density of bricks decreases when a given quantity of clay is replaced by organic material, leading to higher porosity and very low thermal conductivity of fired clay bodies [10,11, 12]. Other parameters, such as particle size also have a considerable

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 7, Issue 10 , October 2020

effect on the mechanical and thermal properties of earth bricks. During firing, the added material is consumed, leaving voids which increase porosity.
The question that arises is as follows: how can the formulation, in terms of percentages of materials (sand, water and firing temperature) be improved in order to obtain an industrial product with good thermal, mechanical and ecological characteristics for the future? Taking into account the cost of manufacturing industrial products, it is necessary to work with laboratory samples, while keeping in mind that their manufacture induces anisotropies in the properties of materials. The idea is to identify the influence of different parameters on these properties as a first step and to validate the passage from a laboratory sample to the industrial scale in a second step.
In view of the above and in order to optimize the thermomechanical properties of earth bricks, it was important to focus on the bulk density of the bricks, their thermal conductivity, geometry and the thermal load at the boundaries of the brick. Specifically, this research was aimed to find optimized parameters which improve the mechanical properties of stabilized clay bricks subjected to heat transfer during firing. As the industrial products were too heavy and with à high cost of manufacturing them with the different research formulations, the study was conducted on cubic block samples. Numerical calculations were performed on industrial scale bricks (220 x 110 x 8.4 mm) to estimate thermal and mechanical resistance.

II. MATERIALS AND METHODS

A. Fabrication of stabilised earth bricks

The soil samples were taken from Menjung-Nkwen in Bamenda III (UTM 32, E0632814, N0662929 with an altitude of 1277 m) in the North-West region of Cameroon. The organic part of the clay was removed by digging three feet deep to expose the subsoil. The basement samples were then collected and air dried. The clay was homogenized by removing coarse fragments and sieved using a 5 mm mesh sieve. Ordinary Portland cement was that of CIMENCAM with an initial setting time of 2h 50, a final setting time of 3h 40 and a standard consistency of 35%. A dosage amount of 3% and 10% were used depending on the nature of the clay to be stabilized. Potable water was used for hydration reactions leading to the gradual hardening of Portland Cement. These stabilised earth bricks were fabricated with moulds of 220 x 110 x 8.4 mm according to [5].

B. Numerical calculations

The chemical composition of the constituent bricks used for the numerical calculations are given in Table 1.

Table 1: Chemical composition of clay [5]

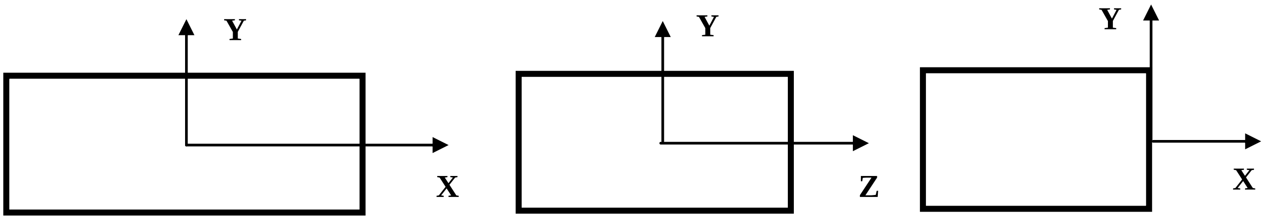
SiO_2 (mg/L)	Al_2O_3 (mg/L)	Fe_2O_3 (mg/L)	TiO_2 (mg/L)	Na_2O (mg/L)	MgO (mg/L)	P_2O_5 (mg/L)	SO_3 (mg/L)	Cr_2O_3 (mg/L)	ZrO_2 (mg/L)	CaO (mg/L)	MnO (mg/L)	NiO (mg/L)
63.69	18.86	5.42	0.72	0.47	0.08	0.06	0.03	0.02	0.02	0.02	0.01	0.01

The soil sample contained negligible organic matter and a low sand content. The sedimentation value was 3.96; Atterberg's liquid limits at 25 shocks was LL = 50.18%. The plastic limit was, PL = 37.20% and the plasticity index (PI) = 13.00%. The soil had a methylene blue (MBV) test value of 1.13 and specific gravity (Gs) value of 2.25. The soil compaction test (Proctor test) showed a maximum dry density (γ_{dmax}) of 1.780 t / m^3 and an optimum water content (W_{opt}) equal to 15.5% [5].

C. Geometric model and mesh

The geometrical model retained was axisymmetric, made of the stabilized earth brick (Figure 1).
The main hypotheses of the study made in the (o, x, y) plan were:
-Stabilized earth brick was considered homogeneous and isotropic.
-The quadrangular finite elements with quadratic interpolation (qua8: quadrangle with 8 nodes and 2 degrees of freedom by node (Ux; Uy)) were used for the meshes of the brick. The resolution being partly carried out at the nodes of the mesh, this thus made it possible to densify the nodes in the model and to approach the real solution as much as possible.

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 7, Issue 10 , October 2020



a) System in the x-y plan

b) System in the z-y plan

c) Partial representation due to the symmetry of the problem

Figure 1: Physical model of the problem

Figure 2 illustrates the mesh of the geometry of the study area. In the (o, x, y) plane, this mesh of the stabilized earth brick has 15.301 nodes and 5,000 quadrangular finite elements.

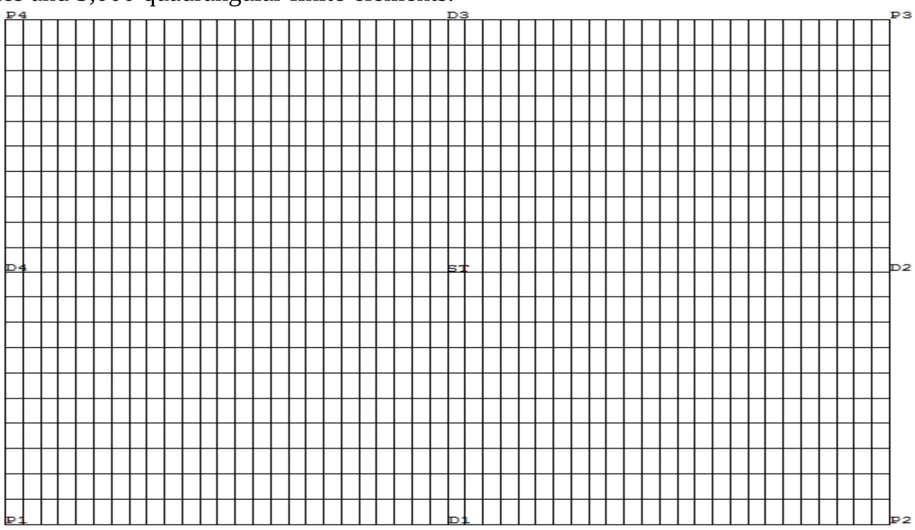


Figure 2: Discretization mesh detail of the brick

D. Behaviour models of stabilized earth bricks

The stabilized earth brick has a model of visco-plastic elastic mechanical behaviour. The total strain (ε) and the temperature (T) are observable state variables for the material [12]. The internal variables generally highlighted for this model are the following:

-Plastic or viscoplastic deformation (Eq. 1)

$$\varepsilon^{p} = \varepsilon + \varepsilon^{e} \qquad (1)$$

Where:

ε^{p} = Plastic or viscoplastic deformation

ε^{e} = Elastic strain

ε = Total strain

-The variable of scalar nature, characterizing isotropic hardening (Eq. 2)

$$P = \int_0^t \left(\frac{2}{3}\dot{\varepsilon}^{p}(\tau):\dot{\varepsilon}^{p}(\tau)\right)^{1/2} d\tau \qquad (2)$$

Where:

p = internal variable of scalar nature characterizing isotropic hardening

$\dot{\varepsilon}^{p}$ = Plastic strain rate tensor

τ = Stress applied to a dislocation

t = time

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 7, Issue 10 , October 2020

-The tensor variable of order 2 characterizing the kinematic hardening α,
In the space of constraints, the flow surface is represented by the function f.

$$f = f(\sigma, p, X, \dot{p}, T) \quad (3)$$

Where:
σ = Constraint
X = tensor force variable of second order associated with kinematic hardening
$\dot{p}$ = Time derivative of isotropic hardening
T = absolute temperature
Kuhn and Tucker reported by Farah have shown that for plastic flow to occur, two conditions must be met [12]:
-The stress state (σ*) representative point must belong to the flow surface (Eq. 4):

$$f = f(\sigma^*, p, X, \dot{p}, T) \quad (4)$$

Where:
σ* = Representative point of the stress state
X = tensor force variable of second order associated with kinematic hardening
$\dot{p}$ = Time derivative of isotropic hardening
T = absolute temperature
-Throughout the flow, the point representative of the stress state must not be able to leave the surface:

$$df(\sigma^*) = \frac{df}{d\sigma} d\sigma^* + \frac{df}{dp} dp + \frac{df}{dX} dx + \frac{df}{d\dot{p}} d\dot{p} + \frac{df}{dT} dT = 0 \quad (5)$$

The charge / discharge criteria implies that:

- f < 0 is equivalent to the elastic behaviour
- f = 0 and df = 0 is equivalent to plastic flow
- f = 0 and df <0 is equivalent to the elastic discharge

E. Thermal loading at the boundaries of the brick

The thermal loading of the brick took place at the limits (Figure 3a); the calculation being carried out step by step, the multiplying coefficient of the loading increments is defined by a monotonic curve as a function of the time increments (Figure 3b). Thus, the thermal loading is defined by equation 6:

$$T(t) = k(t).T_{max} \quad (6)$$

Where:
T (t) = temperature imposed on the time index t,
k (t) = the multiplication coefficient of displacement at the considered time index
T_{max} = the maximum temperature at the end of the simulation.
No mechanical loading is applied to the brick during the simulation.

$$\frac{\partial T}{\partial x} = H(T_b - T_a) \quad (7)$$

Where:
H = Exchange coefficient
T_b = Temperature at the edge of the brick
T_a = Ambient temperature
x = abscissa

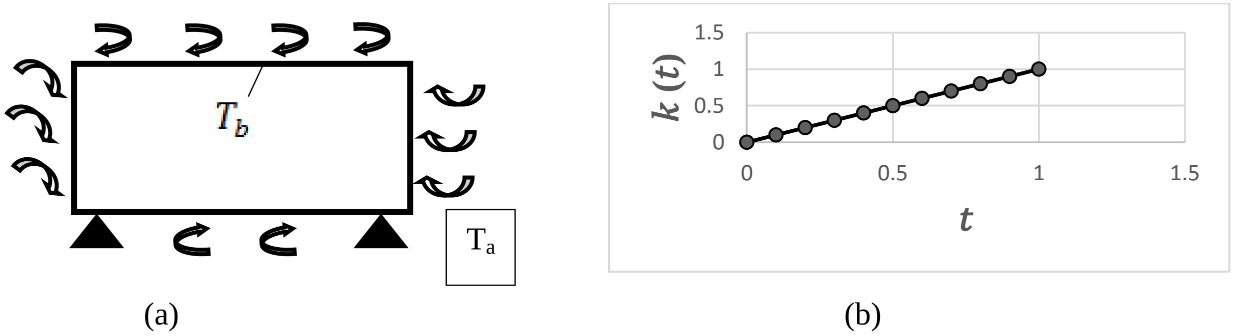


Figure 3: Thermal loading by convection on the edges of the brick: (a) forced convection on the edges, (b) monotonic curve of the temperature increment coefficient as a function of time

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 7, Issue 10 , October 2020

F. Load displacement imposed at the base of the brick

The mechanical blockages were applied to the geometry of the brick as illustrated on Figure 4. Thus, these relate to the vertical (Uy) and horizontal (Ux) displacements blocked at the base of the brick, respectively at points P_1 and P_2 from line D_1. Moreover, because of the cut due to the symmetry of the geometry and the thermal loading, the horizontal displacements (Ux) are blocked on the lateral side of the brick (lines D_4).

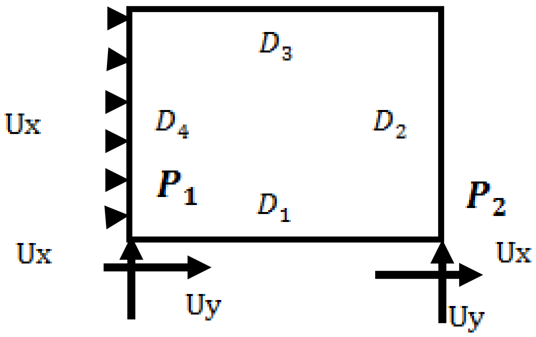


Figure 4: Mechanical blockages at the base of the brick

G. Numerical calculation procedure in Cast3m

The finite element calculation was performed step by step using the Cast3m finite element code. The parametric studies were done in two stages. The first consisted, for a fraction of stabilizer added to the earth matrix, in varying the temperature and analysing its influence on the mechanical behaviour of the stabilized brick (temperature-stress curves, temperature-strain curves); then in the second step, the influence of variations in the stabilizer fraction on the thermomechanical behaviour of the brick was considered. The results were extracted at the nodes and elements of the mesh as illustrated on Figure 5.
Figure 5.

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 7, Issue 10 , October 2020

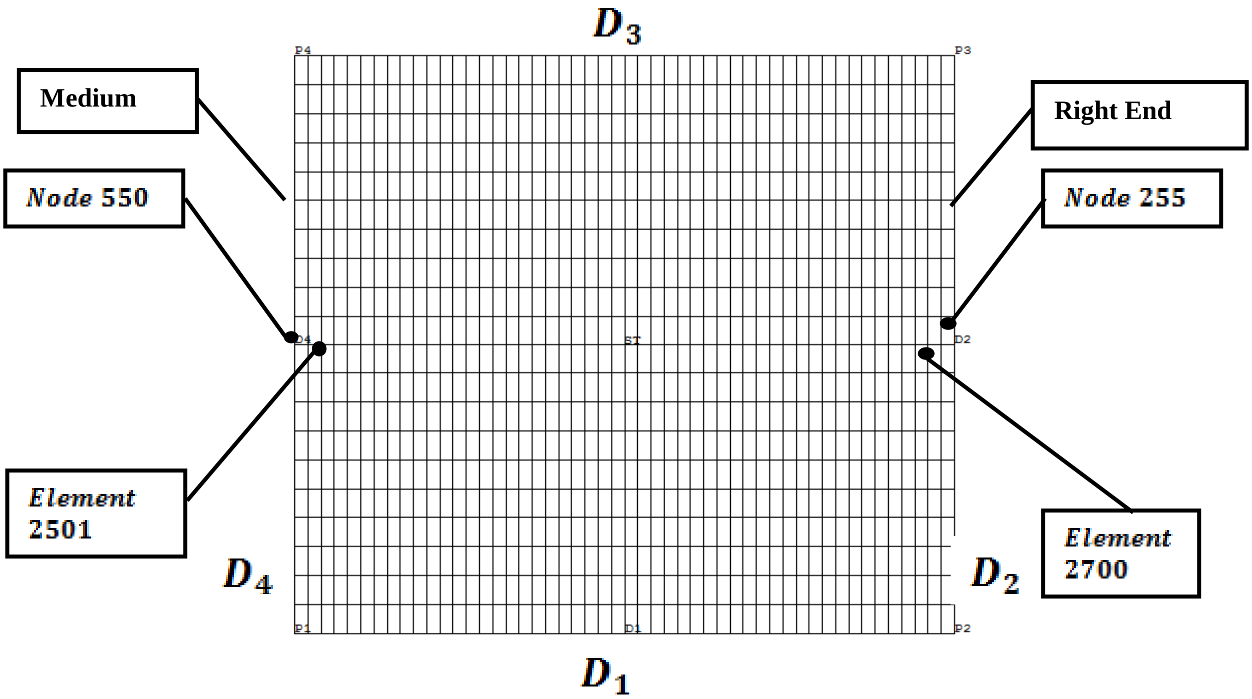


Figure 5: Location of nodes and elements for the extraction of results and the plotting of curves

III. RESULTS AND DISCUSSION

A. Influence of temperature on the mechanical behaviour of the brick

To demonstrate the influence of temperature on the mechanical behaviour of the earth brick, the maps on Figure 6 shows the spatial distribution of temperature in the brick at various times of simulation and for a fraction of 0% stabilizer. In addition, the curves on Figure 7 shows, respectively, the temporal changes in this temperature at two points of the brick; one in the middle and the other on the edge. These curves are qualitatively in agreement with those obtained by Meukam [14], who correlated the rise in temperature and the duration of heat diffusion on the face of the brick.

The maps on Figure 6 shows a temperature gradient that attenuates as you move from the edge of the brick to its middle. This can be explained by the fact that the edges of the brick are in direct contact with the heat source, and the convection that generates leads to a thermal equilibrium more quickly reached between the edges of the brick and the surrounding environment; while the heat conduction to the middle, further from the edge, takes place more slowly. The curves of the temperature as a function of time on Figure 7 also support this assertion.

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 7, Issue 10 , October 2020

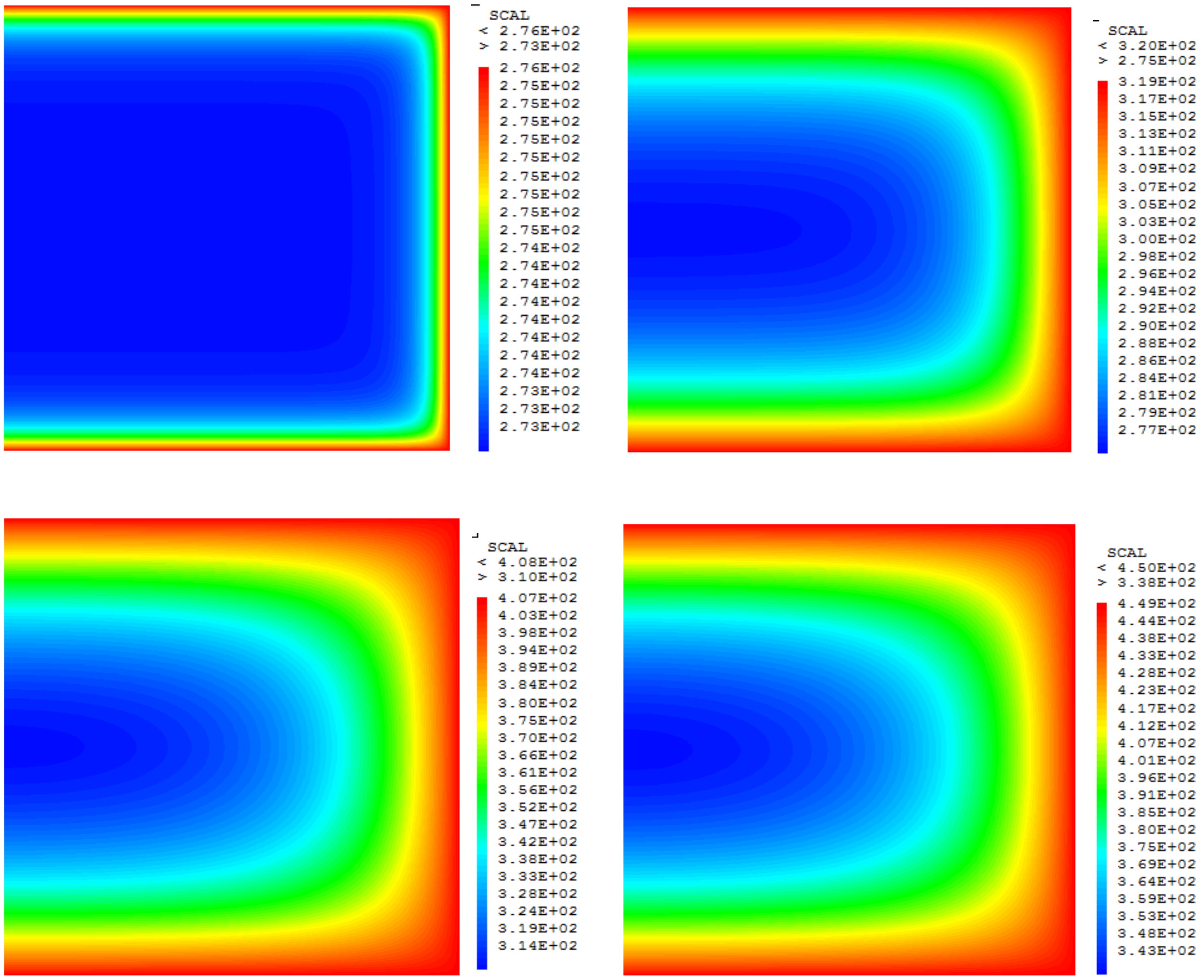


Figure 6: Temperature map at different simulation times for an earth brick with 0% stabilizer

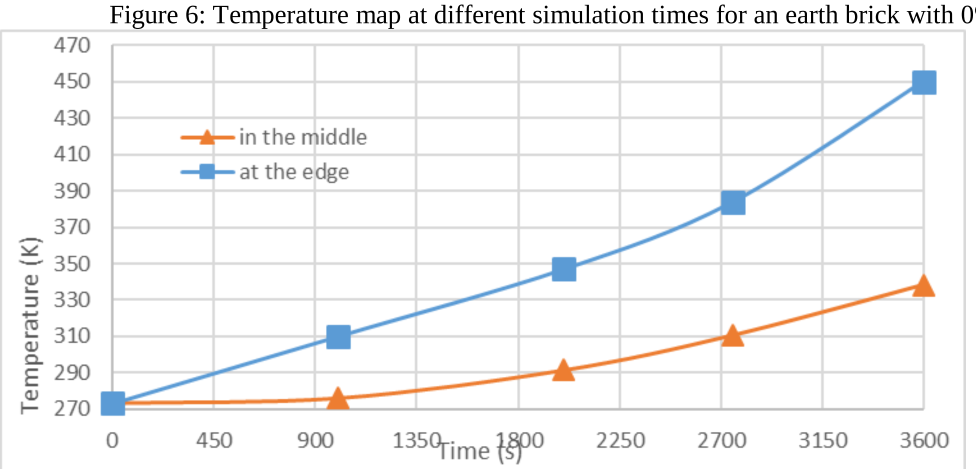


Figure 7: Temperature evolution as a function of time in the middle (element 2501) and at the right edge (element 2700) for an earth brick with 0% stabilizer.

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 7, Issue 10 , October 2020

The curves on Figure 8 shows the evolution of the voluminal plastic deformation in the brick as a function of the evolution temperature, for mesh elements located respectively in the middle and on the edge of the brick. An overall low strain was observed in the brick. However, this low strain was representative on the edge of the brick and inside. This could be explained by the greater expansion of the particles at the edge due to a higher temperature.

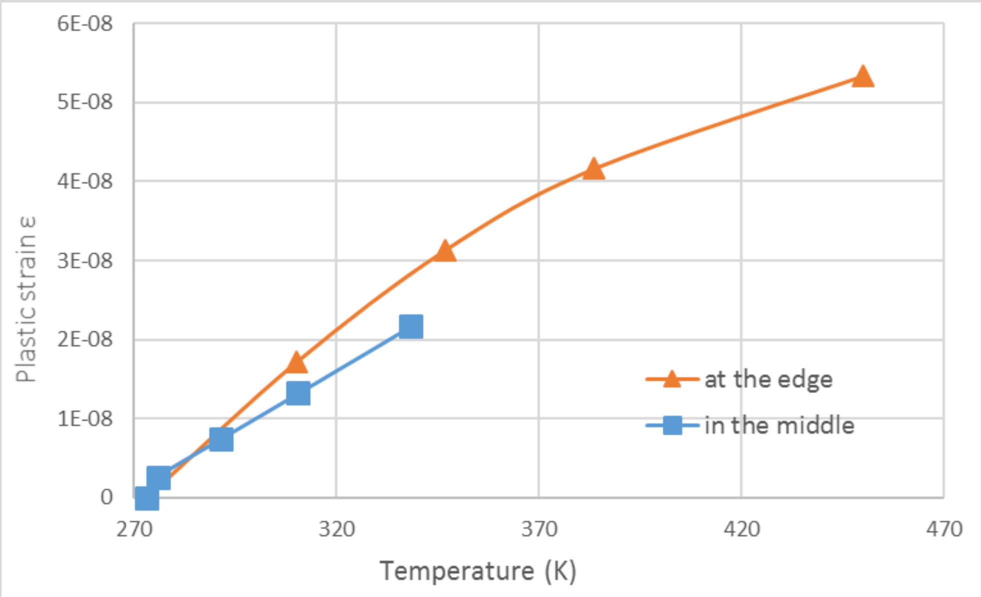


Figure 8: Evolution of the voluminal plastic deformation according to the temperature, in the middle (element 2501) and at the right edge (element 2700) for an earth brick with 0% stabilizer.

The curves on Figure 9 shows the evolution of voluminal plastic strain in the brick with respect to the evolution of the vertical stress with regard to the temperature, in the middle (element 2501) and at the right edge (element 2700) for a clay brick with 0% stabilizer. These curves are qualitatively in agreement with the works of [15, 16, 17] who showed that the stress in the material increases during firing following its densification, and that of [18, 19] who showed that the mechanical resistance to bending and compression increases with increased temperature, up to a limit value where the brick becomes brittle. The observed deviations can be justified by the thermal characteristics of the brick which remains constant during the simulation, and by the limited values of the temperature during the simulation.

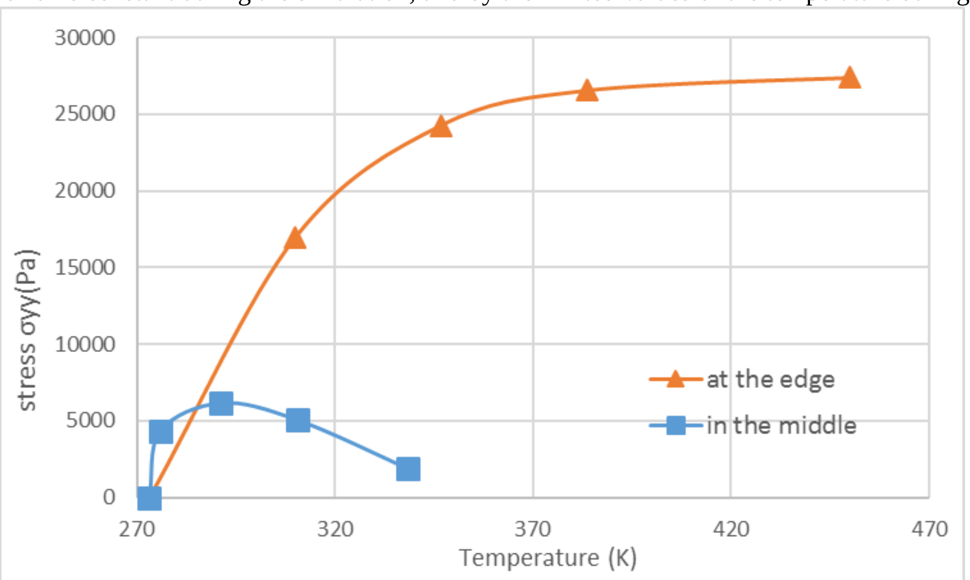


Figure 9: Evolution of the vertical stress as a function of temperature, in the middle (element 2501) and at the right edge (element 2700), for an earth brick with 0% stabilizer.

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 7, Issue 10 , October 2020

B. Influence of the variation of stabilizer fraction on the thermomechanical behaviour of earth bricks

The variation in the percentage of stabilizer influenced the Young's modulus of the brick, thus, varying the thermomechanical response of one stabilized earth brick to another during firing. To demonstrate this influence of the variation in the percentage of stabilizer on the thermomechanical behaviour of the earth brick, the curves on Figures 10 and 11 shows the changes in plastic deformation as a function of temperature, for various percentages of stabilizer: 0%, 5.56%, 6.25%, 7.14%, 8.33% and 9.17%.

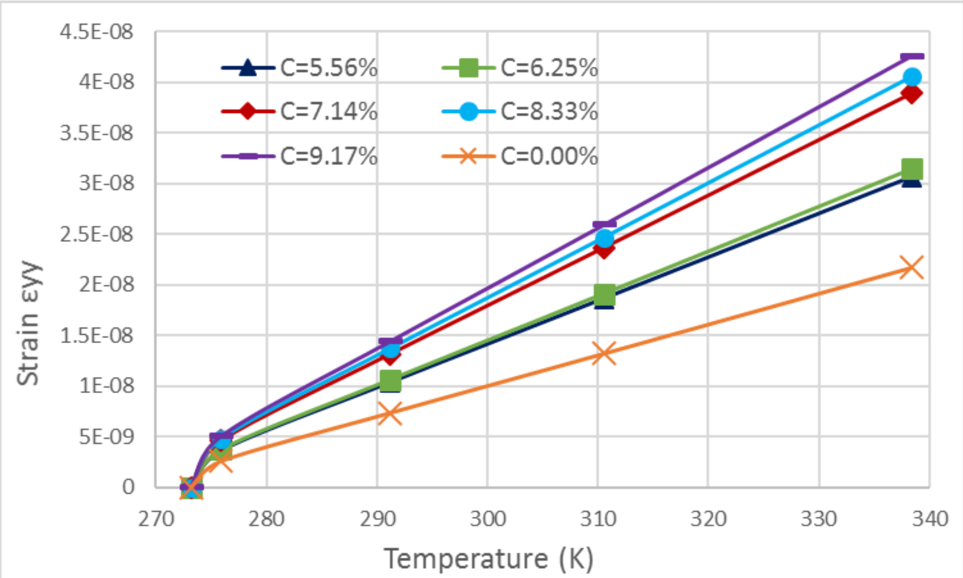


Figure 10: Evolution of the voluminal plastic deformation with respect to temperature, in the middle (element 2501) for various percentages of stabilizer.

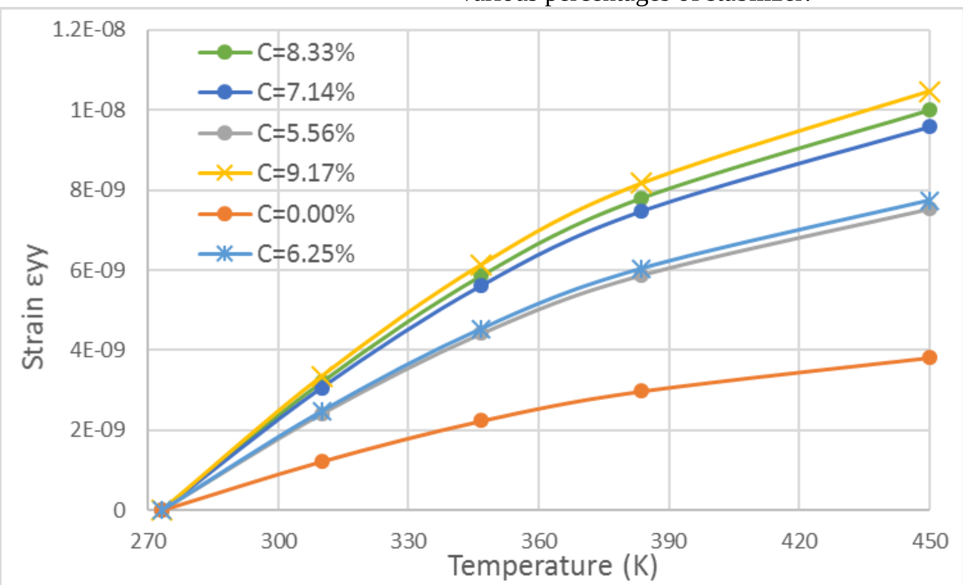


Figure 11: Evolution of the voluminal plastic deformation with respect to the temperature, at the right edge (element 2700) for various percentages of stabilizer.

Regardless of the position in the brick, the analysis of the curves on Figures 10 and 11 show deformations which are greater and faster under the effect of temperature during firing, as the percentage of stabilizer increases. The more the

ISSN: 2350-0328

International Journal of Advanced Research in Science, Engineering and Technology

Vol. 7, Issue 10 , October 2020

clay brick is enriched with stabilizer, the more it is likely to tolerate large deformations during firing. This could be explained by the higher level of fine particles introduced into the brick, and which would promote greater expansion (plasticization) thereof.
The curves on Figures 12, 13, and 14 respectively present the evolution of the stresses σ_{yy} and σ_{xx} respectively, according to the temperature, in the middle and on the edge of the brick and for the same percentages of stabilizer: 0%, 5.56%, 6.25%, 7.14%, 8.33% and 9.17%.

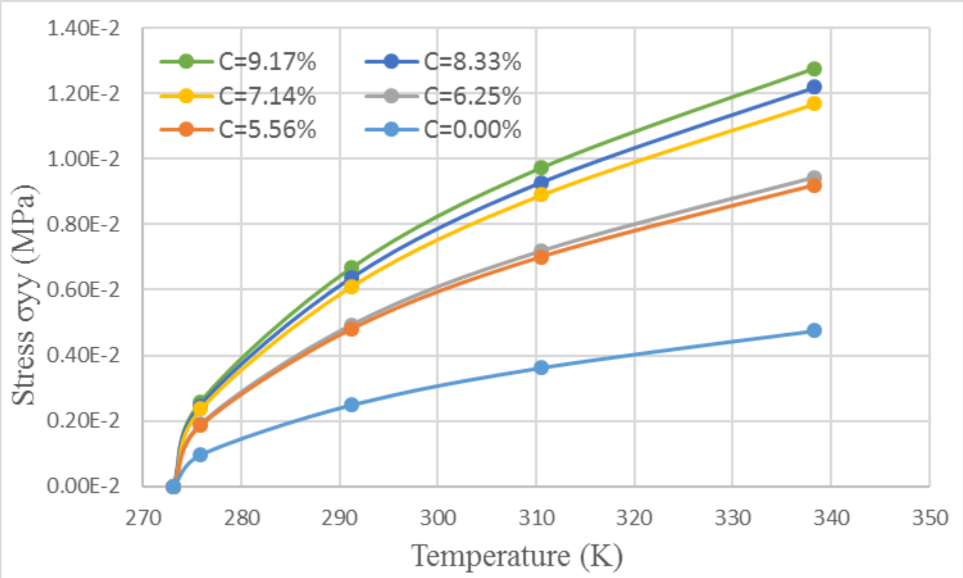


Figure 12: Evolution of the stress σ_{yy} according to the temperature, in the middle (element 2501) for various percentages of stabilizer

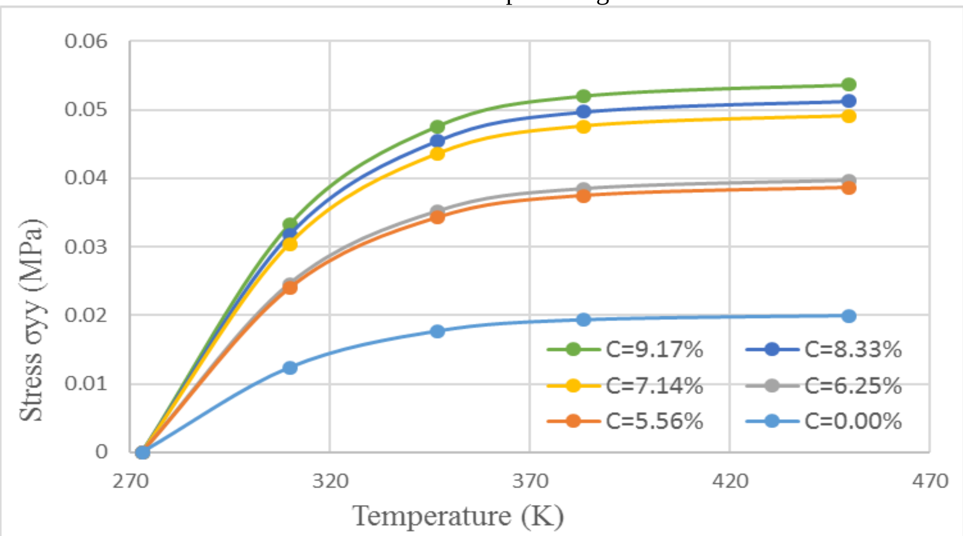


Figure 13: Evolution of the stress σ_{yy} according to the temperature, on the right edge (element 2700) for various percentages of stabilizer

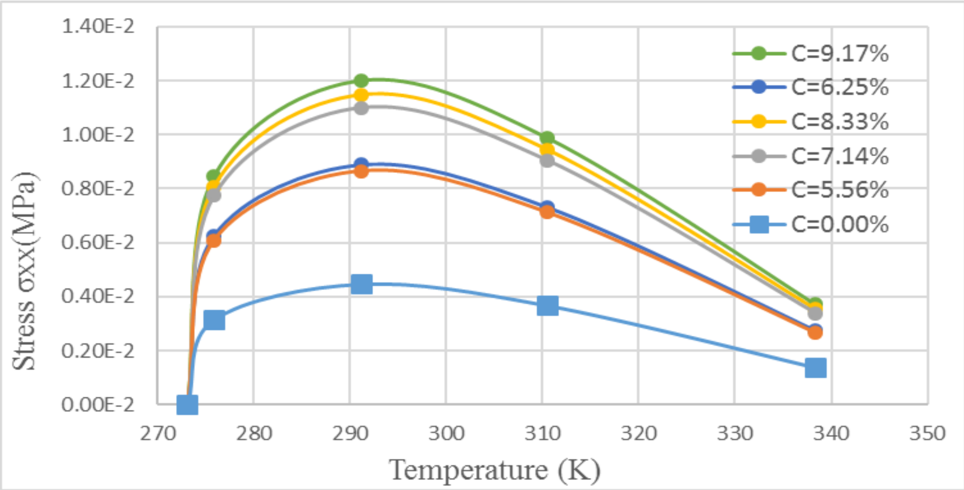


Figure 14: Evolution of the stress σ_{xx} according to the temperature, in the middle (element 2501) for various percentages of stabilizer

From the analysis of the above curves, it appeared that the stresses, σ_{yy}, in the middle of the brick remain in small proportions, and do not reach the plateau. However, these stresses change quickly at the edges, and then stabilizes at a plateau that increases in size with the addition of stabilizer. In addition, the stresses, σ_{xx}, in the middle of the brick evolved until the stress peak, then gradually decreased, tending towards a zero value. These stress peaks, just as in the case of σ_{yy} stress levels, increased with increase in the percentage of stabilizer introduced into the brick. These observations could be explained by the increase in the cohesion of the earth brick with increase in the percentage of stabilizer, thus making it possible to mobilize greater stress levels and peaks during firing [20].

IV. CONCLUSION

A study was carried out to examine the evolution of thermomechanical properties of a stabilized clay brick subjected to heat transfer during firing. The numerical resolution was carried out by the finite element method, and the numerical simulations via the Cast3M calculation code. On the basis of the numerical results, the following observations were made: the mechanical resistance to bending and compression increased with increase in temperature, up to a limit value where the brick became brittle; during firing the Young's modulus of the brick, and the thermomechanical response of the clay brick varied with the stabilizing rate. The more the clay brick was enriched with stabilizer, the more it was likely to tolerate large deformations during firing. The stresses in the middle of the unstabilized brick remain in small proportions, and did not reach the plateau. However, these stresses changed quickly at the edges, and then stabilized to a stage that its magnitude increased with the addition of stabilizer. In addition, the stresses in the middle of the stabilized bricks evolved up to the stress peak, then gradually decreased, tending towards a zero value. The use of stabilizers in the manufacture of earth bricks was found to be more effective and can be more sustainable compared to unstabilized earth bricks.

Acknowledgements
We are grateful to the technicians of the Material and Geotechnical Laboratories of BEGL, GTHS Bamenda and MIPROMALO Yaounde-Cameroon for assisting in laboratory analyses and the anonymous reviewers of this manuscript.

Conflicts of Interest
The authors declare that there are no conflicts of interest regarding the publication of this article.

REFERENCES

[1] V. Kocí, L. Scheinherrová, J. Madera, M. Keppert, Z. Suchorab, G. Łagód, and R. Cerný. "Experimental and Computational Study of Thermal Processes in Red Clays Exposed to High Temperatures", *Energies* :13, 2211, 2020.

[2] M. Velasco, M. Ortiz, M. Giro, M. Velasco. "Fired clay bricks manufacturedby adding wastes as sustainable construction material—A review" *Construction and Building Materials*, 63:97–107, 2014.
[3] K. Rashid, E.U Haq, M.S. Kamran, N. Munir, A. Shahid, and I. Hanif, "Experimental and finite element analysison thermal conductivity of burnt clay bricks reinforced with fibers", *Construction and Building Materials,* 221:190–199, 2019.
[4] M.P. Deru and T. Kirkpatrickallan, "Ground-coupled moisture transfer from buildings", Part 1-Analysis and modeling. Transaction of the ASME 10, Vol. 124, 2002.
[5] M.K. Mbuh, D. Kagou, F. Ngapgue, N.A. Mofor, B.E. Manefouet. and E. Yamb, "Compressed Stabilized Earth Brick (CSEB) As Building Construction Elements", *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE):* 17(4):42-48, 2020.
[6] U. Rehman, M. Ahmad, and K. Rashid, "Influence of fluxing oxides from waste on the production and physico-mechanical properties of fired clay brick: A review", *J. Build. Eng.,* 27:17, 2020.
[7] M.S. El-Mahllawy, A.M. Kandeel, A.M. Latif, A.M Nagar, "The Feasibility of using Marble Cutting Waste in a Sustainable Building Clay Industry", *Recycling*, 3: 39, 2018.
[8] B. Reddy and P. Walker, "Stabilised mud blocks: problems, prospects", *In: Proceeding of international earth building conference **2005**, Sydney, Australia*, 63–75, 2005.
[9] H. Beshr, A.A. Almusallam and M. Maslehuddin, "Effect of coarse aggregate quality on the mechanical properties oh high strength concrete", *Construction and Building Materials*, 2: 97-103, 2003.
[10] V.R. Fetra, I.A. Rahman, and A.M.A. Zaidi, "A brief review of Compressed Stabilized Earth Brick (CSEB)", *2010 International Conference on Science and Social Research (CSSR)*, 2010.
[11] T. J. García, M.J. Orts, A. Saburit, G. Silva, "Thermal conductivity of traditional ceramics. Part I: Influence of bulk density and firing temperature", *Ceram Int* 36:1951–1959. 2010
[12] N. Phonphuak, "Effects of Additive on the Physical and Thermal Conductivity of 18 Fired Clay Brick", *J. Chem. Sci. Technol.,* 2:95–99, 2013
[13] P. Muñoz, M.C. Juárez, M.P. Morales, M.A. Mendívil, "Improving the thermal transmittance of single-brick walls built of clay bricks lightened with paper pulp", *Energy Build*ing, 59:171–180, 2014.
[14] E. Farah, "Modèle constitutive du comportement viscoplastique d'un matériau CTC'', Département de Mécanique Ecole Polytechnique de Montréal, 53-60, 2009.
[15] P. Meukam, "Valorisation des briques de terre stabilisées en vue de l'isolation thermique de bâtiment", Thèse de Doctorat de l'Université de Yaoundé I, 88-99, 2004.
[16] A. Abdelhak, S. Abdallah, R. Moussa, T. Remmal, M. Gomin, "Caractéristiques structurales et mécaniques de céramiques à base d'argiles : influence de la source de feldspath", *Comptes Rendus Chimie*, 2007.
[17] P. Pialy, "Etude de quelques matériaux argileux du site de Lembo (Cameroun): minéralogie, comportement au frittage et analyse des propriétés d'élasticité'', Thèse de Doctorat de l'Université de Limoges, 98-105, 2009.
[18] P.M. Nigay, "Etude des transformations microstructurales de mélanges argiles/biomasse lors de la cuisson et relations avec les propriétés mécaniques et thermiques'', Thèse de Doctorat de l'Université Fédérale de Toulouse Midi-Pyrénées, 193p, 2017.
[19] S. Rababe, "Etude des transformations microstructurales des mélanges argile/combustibles solides de récupération (CSR) lors de la cuisson : relations entre propriétés physico-chimiques, mécaniques et thermiques", Thèse de Doctorat de l'Université Fédérale de Toulouse Midi-Pyrénées, 88-99, 2018.
[20] D. Wetshondo, "Caractérisation et valorisation des matériaux argileux de la province de Kinshasa (RD Congo)'', Thèse de Doctorat de l'Université de Liège, 257-263, 2012.