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BASIC PROBLEMS OF ENERGY AND RENEWABLE ENERGY

STUDY OF THE MECHANICAL BEHAVIOUR OF CLAY, A NATURAL MATERIAL FOR HOUSE CONSTRUCTION

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Experimental results were obtained on four types of clays from various sites in Togo, West Africa (where they are traditionally used in house construction), to understand the rheological behaviour of these materials and the effects of the heat treatment on them, in order to optimize the process of structures manufacture. Four types of clays show very different behaviours, and the observed origin of sample cracking is compatible with the stress distribution in the structures.

Keywords: structural materials

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Main range of scientific interests: PLD, ferroelectrics (mainly Tungsten Bronzes), electrical and dielectric properties, material science, alternative energies for third world countries.
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Introduction

Clay-based materials compete today with composite materials and find important applications in various fields of modern industry including civil engineering for the construction of big monuments and buildings, dams, ports, bridges, tarmacs, roads, etc [1, 2, 3]. Clay is also used in industry refractory materials for the manufacture of enameled earthenware, porcelain, and ceramics.

The mechanical behaviour of a clay-based structure depends not only on the chemical composition of the original raw material, i.e. the deposit site and its constituent minerals, but also on experimental conditions of formatting (consistency of the clay paste, external mechanical stresses and drying conditions).

Theoretical frame

Rheological behaviour

Clay pastes studied in this work were modeled by the classical law (see for instance references [4, 5]): $\sigma = k\dot{\varepsilon}^m \varepsilon^n$, where σ is the stress applied on the sample, k the consistency of the dough, $\dot{\varepsilon}$ the rate of deformation, ε – the generalized strain, m – the coefficient of sensitivity on the velocity, n – the coefficient of hardening.

By fitting the experimental curves by the above law, the obtained parameters are consistent with those typically obtained in the literature, namely: $0.02 < k < 0.5$ MPa·S^{-m}; $0.05 < m < 0.8$ and $0.03 < n < 0.60$.

This law is based on the properties of the class of so-called viscometric flows. In this case, for these flows, the stress tensor can be written in the form below, considering the axes in cylindrical coordinates [6, 7].

Besides, the measurement of the strain time rate permits to define three functions: $\tau(\gamma) = \sigma_{12}$, $N_1(\gamma) = \sigma_{11} - \sigma_{22}$, $N_2(\gamma) = \sigma_{22} - \sigma_{33}$, called viscometric functions, which define the behaviour of the fluid (here the clay paste).

As we noted in the preceding paragraph, the problem is treated in cylindrical coordinates. Fig. 1 illustrates the geometrical considerations used. The (cylindrical) symmetry imposes that the non-zero stress components are: σ_{rr}, $\sigma_{\theta\theta}$, σ_{zz}, τ_{rz}.

Modeling of flow

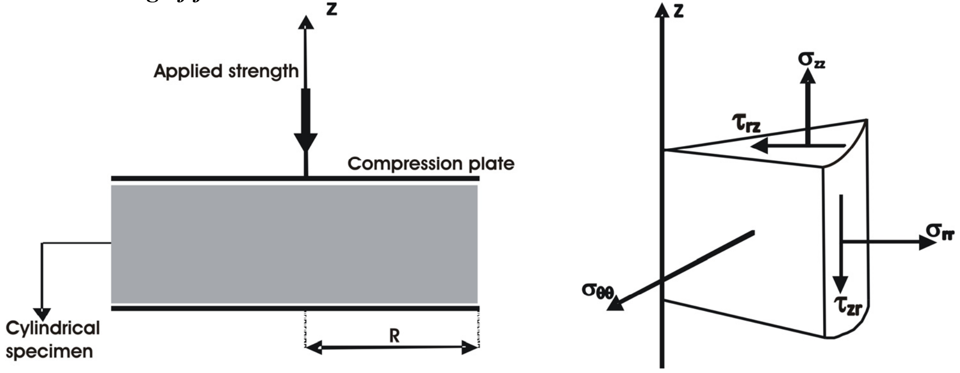

Fig. 1. *Plastometer with parallel plate and the stresses on a cylindrical element*

In our analysis of clay pastes, we neglect the terms related to gravity, because of the high rigidity of the paste, completely filling the inner cylinder.

In the same way we consider only the case of sufficiently slow flows to be able to neglect the inertial terms.

Under these conditions, the balance equations are written as [8, 9, 10]:

$$\begin{cases} \rho \dfrac{\partial u_r}{\partial t} = -\dfrac{\partial p}{\partial r} + \left[\dfrac{1}{r} \dfrac{\partial}{\partial r} \left(r\sigma_{rr}^{(d)} - \dfrac{\sigma_{\theta\theta}^{(d)}}{r} + \dfrac{\partial \tau_{rz}^{(d)}}{\partial z} \right) \right] \\ \rho \dfrac{\partial u_\theta}{\partial t} = -\dfrac{1}{r} \left[\dfrac{\partial p}{\partial \theta} - \dfrac{\partial \sigma_{\theta\theta}^{(d)}}{\partial \theta} \right] \\ \rho \dfrac{\partial u_z}{\partial t} = -\dfrac{\partial p}{\partial z} + \left[\dfrac{1}{r} \dfrac{\partial}{\partial r} \left(r\tau_{rz}^{(d)} \right) + \dfrac{\partial \sigma_{zz}^{(d)}}{\partial z} \right] \end{cases} \quad (1)$$

where u_r, u_θ, u_z are the components of velocity in the radial directions, tangential and axial, respectively, and p is the uniaxial pressure of the piston.

With the approximation that the material is assumed to be incompressible, the continuity equation writes:

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r u_r \right) + \frac{1}{r} \frac{\partial u_\theta}{\partial \theta} + \frac{u_r}{\partial z} = 0. \quad (2)$$

It is assumed that the law governing the fluid behaviour may be written as:

$$\sigma_{ij}^{(d)} = \Psi \varepsilon_{ij}^{(d)}. \quad (3)$$

Ψ is a function of invariants of the strain time rate tensor that is independent of the deformation (strain) history.

The compression tests were also carried out on specimens submitted to drying, in the condition of a low rate of deformation (~ 0.5 mm/min, to avoid an abrupt fracture of the sample) in order to locate and follow the cracking of the material.

Experimental study

Experimental devices

The mold we used is a duralumin block with a cylindrical cavity of diameter 30 mm, with a well polished boundary. It is equipped with a plunger that is used to compress the clay paste manually in the cavity. This equipment is presented in Fig. 2. The set mold and the plunger are placed between two plates of the compression machine that allows to apply a controlled force during the formatting. The removal from the mold is done by slowly moving the plunger across one end of the mold. A plate absorbing shocks allows to retrieve the sample out.

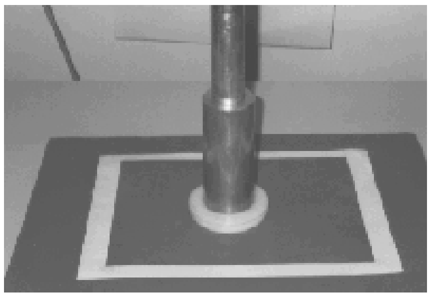

Fig. 2. *Plunger in place in the mold*

The universal tension/compression machine (INSTRON type), consists of a set of two columns equipped with a cross piece whose motion is performed by two ball screws of 1000 mm long with a pitch of 0.01 mm. It offers the possibility of displacements with a rate between 0.5 and 500 mm/min by steps of 0.01 mm/min. It is equipped with two parallel plates for the traction/ compression and the maximum force to be applied is 50 kN. The machine is entirely controlled by computer for the acquisition and processing of experimental results.

Preparation of the clay paste

Clays used in industry are generally a natural mixture of the following three main constituents [11, 12, 13]: kaolin clay (aluminum oxide Al_2O_3, silica $2SiO_2$, water $2H_2O$), feldspar providing sodium (Na) and potassium (K) that allow the formation of the vitreous phase, a neutral constituent (“charge”) that reduces the shrinkage but does not act on the reactions during burning.
The different kinds of clays studied in this work are natural ones, coming from four different sites of Togo. They are labelled according to Table 1.

Table 1
The 4 studied clays from Togo (West Africa) and their notation

Clay variety	Notation
Green clay from Kouvé	AVK
Green clay from Togblékopé	AVTK
Red clay from Guérin-kouka	ARGK
White clay from Bandjéli	ABB

Clay powders were placed during 24 hours in an oven at 60 °C for a complete drying. The grading plays an important role in the mechanical properties of the obtained paste. A paste with smaller particles sizes has a more marked plasticity because the particles react more intensively between each other.
For the characterization of samples, we start from a quantity m_0 of anhydrous clay powder, which is then mixed with the quantity m_e of water to get a paste whose water content noted ω writes:

$$\omega = 100\frac{m_e}{m_0}, \text{ with } m_e = m - m_0,\ \omega = 100\frac{m - m_0}{m_0}.$$

The masses were measured using a METTLE PJ 360 Delta Range balance, with an accuracy of 0.01 g.
The water content $\omega \sim 18$ % was deduced from the assessment of fluidity, of the consistency of paste and the external appearance of specimens after removal. The water content of the four varieties of studied clays range from 15 % to 20 %. This region of plasticity for pastes prepared is consistent with the limits set by ATTERBERG [14, 15, 16].
To get a clay paste having satisfying plasticity properties, the powder-water mixture must be kneaded (for about 2 h) until getting a homogeneous paste. The paste is then stored in a hermetically climatic chamber for more than 24 hours, to insure a uniform moisture content while preventing evaporation and increasing the plasticity of the paste under the effect of microorganisms that play an important role in the process.

Preparation and drying test specimens

The conditions used for the preparation of specimens are similar to those used in industrial tile factories ($\omega \sim 20$ %, mass density $\rho \sim$ g/cm^3). All specimens were prepared in the same experimental conditions, from the powder of the 4 varieties of clay. The specimen size (diameter D = 30 mm, height h = 30 mm) is defined to ensure a uniform compaction within the thickness of the specimen.
Compaction is performed by imposing the plunger motion with a low rate of 3 mm/min to avoid resistance due to the viscosity of the paste.
Clay pastes, even though they have good characteristics of cohesion, are subject to adhesion to the metallic walls in industrial processes, and this is also the case for the mold we used. In most cases, friction is below the threshold at which shear occurs. Therefore, pastes slip instead of warping, which promotes good removal without special lubricants [17, 18, 19]. Several samples were elaborated as shown in Fig. 3 where 24 specimens having a cylindrical shape are presented.

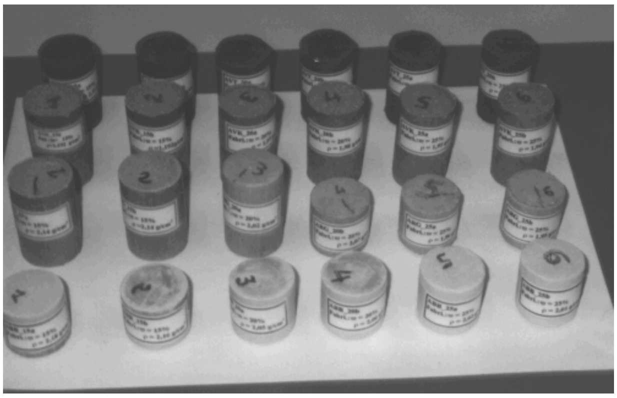

Fig. 3. *Clay specimens with cylindrical shape (from front to the back: ABB, ARGK, AVTK, AVK clays)*

In order to study the influence of the applied force, namely of the stress when compacting the paste, we divided the original clay paste in several samples, and we applied three levels of charge, one per sample: 5, 20 and 35 kN, for each kind of clay. It appears that the mass density $\rho \sim 2$ g/cm^3 is reached for the four varieties of clay we studied, already at 5 kN.

Experimental results on pastes

Fig. 4 shows the compaction curves for the four clay paste varieties with an applied force up to 35 kN. This representation follows the usual one found in literature, where the applied force is on the ordinate and the induced deformation is on the axis of abscissa (though deformation is a function of the force) because of the simple (parabolic) shape of the curve. We observe that, if all curves have the same general aspect, they differ clearly. The most flat curve corresponds to the AVK clay that presents also the most marked plasticity. We may introduce a parameter to characterize the curves, for instance the spreading W of the curve at a given value of the applied force. We observe that $W_{AVK} > W_{ARG} > > W_{AVTK} > W_{ABB}$, namely the W parameter decreases from the most resistant (in dried state) and more plastic (as paste) to the less resistant and less plastic paste.

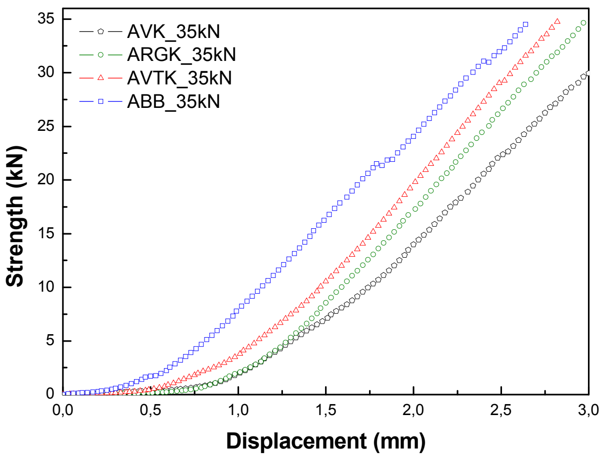

Fig. 4. Compaction curves of the four clay varieties pastes at a strength F = 35 kN

Fig. 5 gives the behaviour of each clay paste for three different levels of compaction. We observe that curves obtained at different force value during the pastes compaction, do not coincide: the reproducibility is difficult to obtain, and this expresses a strong sensitivity of experimental results on tiny experimental uncontrolled differences. We may invoke air bubbles in the bulk of the paste or at the interface with the boundaries, or an inhomogeneity in the original paste ball before its division into the different specimens and the existence of shear strength at the internal wall of the mould when dragging the clay paste.

In spite of this uncertainty as far as the reproducibility is concerned, we shall see in next paragraph that we may draw conclusions concerning the mechanical properties of the obtained dried specimens.

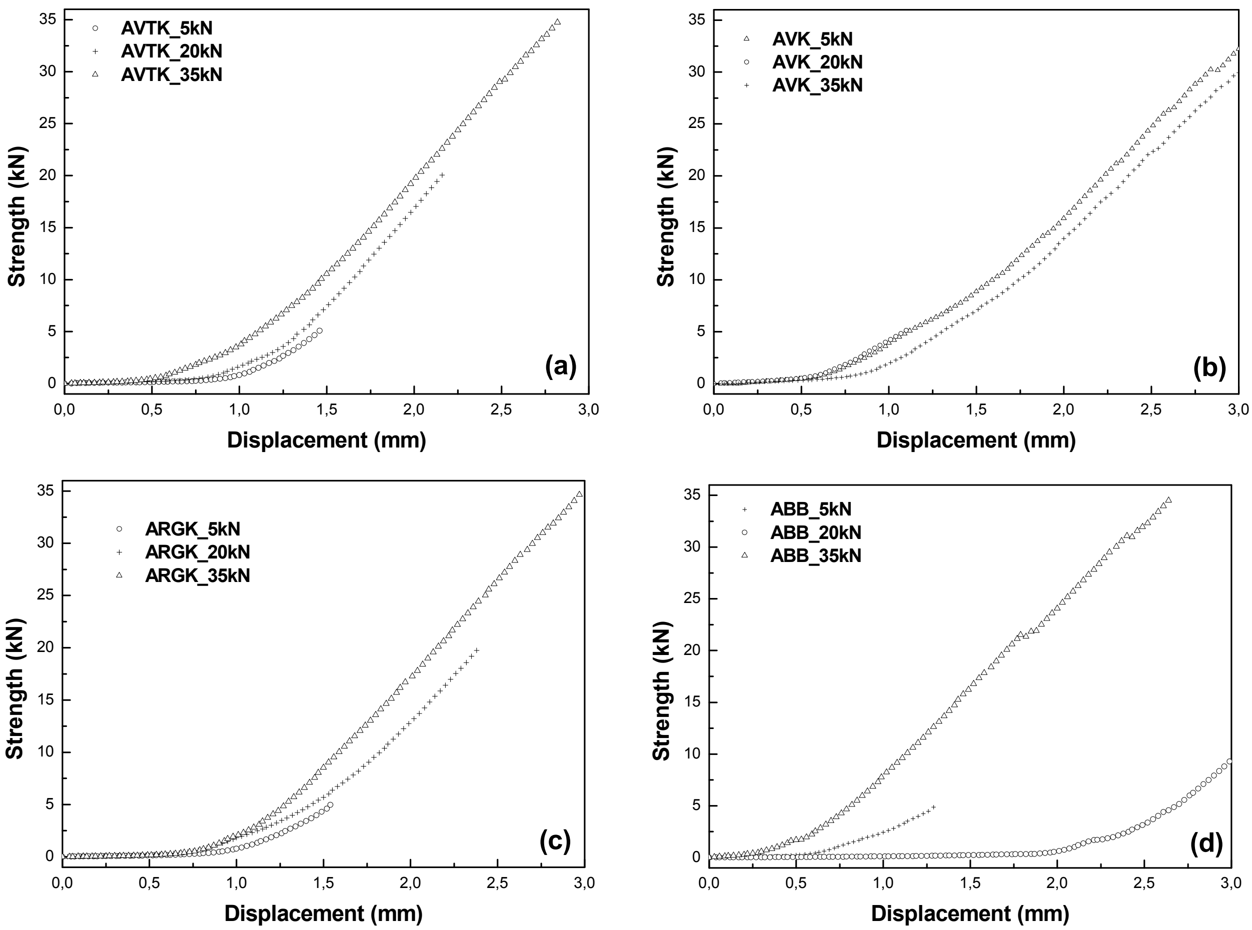

Fig. 5. Compaction curves of the four clay varieties pastes under three different strengths for each specimen (F = 5, 20 and 35 kN)

The characteristics and comments on pastes and prepared specimens are described in Table 2. After compression, the specimens are taken off from the cavity and then confined in a waterproof box at the room temperature. The moisture content of specimens is gradually reduced by a slow drying so as not to disrupt the normal removal of the matrix. Otherwise, it would create localized cracks. During the drying (and the accompanying consolidation of the structure) there always occurs a contraction of the size due to the evaporation of water and the reduction of pores.

Table 2

Characterization of clay pastes and visual observation of test samples

Clay varieties	Water content (%)	Consistency of the paste	External appearance of the wet specimen	Appearance of the dried specimen
Green clay from Kouvé (AVK)	18	Pasty and plastic	Smooth, moist cracks barely visible	Less visible porosity
Green clay Togblékopé (AVTK)	18	Pasty and very plastic	Very wet and deforms easily	Open porosity
Red clay from Guérin-kouka (ARGK)	18	Wet powder	Solid, with very smooth appearance	No cracks or pores
White clay from Bandjéli (ABB)	18	Pasty and less plastic	Smooth and less humid	Good appearance after drying

Experimental results on dried specimens: compression tests

The test results show that the specimens compacted to 20 kN are less subject to damaging than those compacted to 5 kN. Thus, the larger the strength of compaction, the better the dried specimen resists to compression, which is confirmed by a better resistance to damaging of the specimens compacted to 35 kN. Visual observations of dried specimens do not however allow us to mark a notable difference on cracks. Table 3 shows the values of the constraints at the fracture threshold, and resumes visual aspects of the samples tested in compression. These results confirm the key role of compaction in the preparation of clay based materials (removal of air bubbles in the paste, reduction of pore, density increase of the material).

Fig. 6 shows the compression test on the four dried specimens of the clay variety studied. One can observe different Young modulus for each specimen proving different mechanical behaviour of each variety.

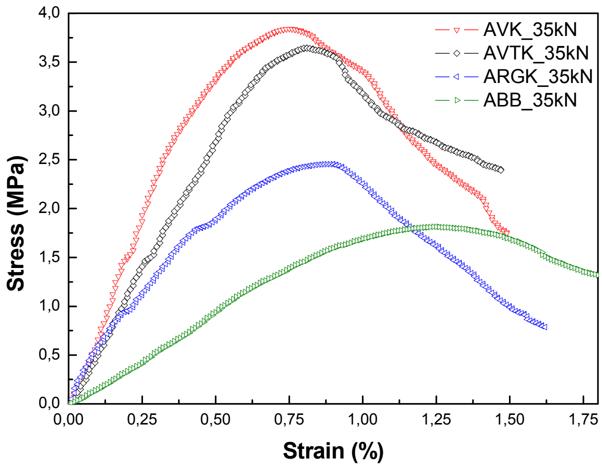

Fig. 6. *Comparative compression test curves for the four different dried specimens initially compacted at 35 kN*

Table 3

Dried specimens characterization

Compacting strengths						
	5 kN		20 kN		30 kN	
Clay varieties	Stress maxi (MPa)	Specimen external observations	Stress maxi (MPa)	Specimen external observations	Stress maxi (MPa)	Specimen external observations
AVTK	4.37	total fracture	6.06	mean fracture	6.35	important fracture
AVK	5.46	total fracture	5.66	lateral fracture	6.42	important fracture
ARGK	2.91	mean fracture	3.76	break less pronounced	3.85	several breaks
ABB	1.90	crash	2.06	erosion	2.72	partial erosion

Fig. 7 presents the compression tests curves on the dried specimens for the four varieties of clay and for three different loads related to the paste initial compacting. These curves show that the elastic modulus and constraints at the fracture threshold increases with the overall load applied during the molding of the paste. The maximum value of the constraint at fracture threshold is of the order of ~ 5 MPa.

Contrary to observations on the paste, we noted that the ABB clay is the least resistant after drying while it was the most reactive during kneading and resistant to compression. The explanation for this behaviour has to be found in the chemical composition of this clay, and in the atomic bonds in the structure. It is relevant at this stage to remember that the pastes are made up of clay particles electrically polarized sheets with opposite charges on both sides. These charges attract in the clay, water molecules which act as lubricants between sheets and confer plasticity properties to the paste. This may be accounted for by forces between particles of minerals themselves and water molecules: electrostatic forces between particles, dynamic forces between water flows and particles, Van der Waals forces, gravity, and capillary forces [19, 20, 21]. In the paste, the sheets can thus slide over one another, lubricated by water layers, and this so called hydroplasticity and the behaviour during kneading are strongly dependent on the structural configuration involving water whose influence is predominant. It may thus be understood that dried specimens properties that depend only on the structural arrangement in the mineral matter are not related with those of pastes.

The analysis of all data, shows that thermoplastic and less resistant clay is ABB (Young modulus E = 0.8 MPa, and rupture stress $\sigma_{r\text{-max}}$ = 1.90 MPa). The most elastic and resistant clay is AVK (Young modulus E = 2.8 MPa, and rupture stress $\sigma_{r\text{-max}}$ = 6.42 MPa).

The cracking of a structure after its formatting depends on several factors. The most common factors are the nature of the clay, the shrinkage during drying, and the constraints at removal. The samples studied here have the same shrinkage rate.

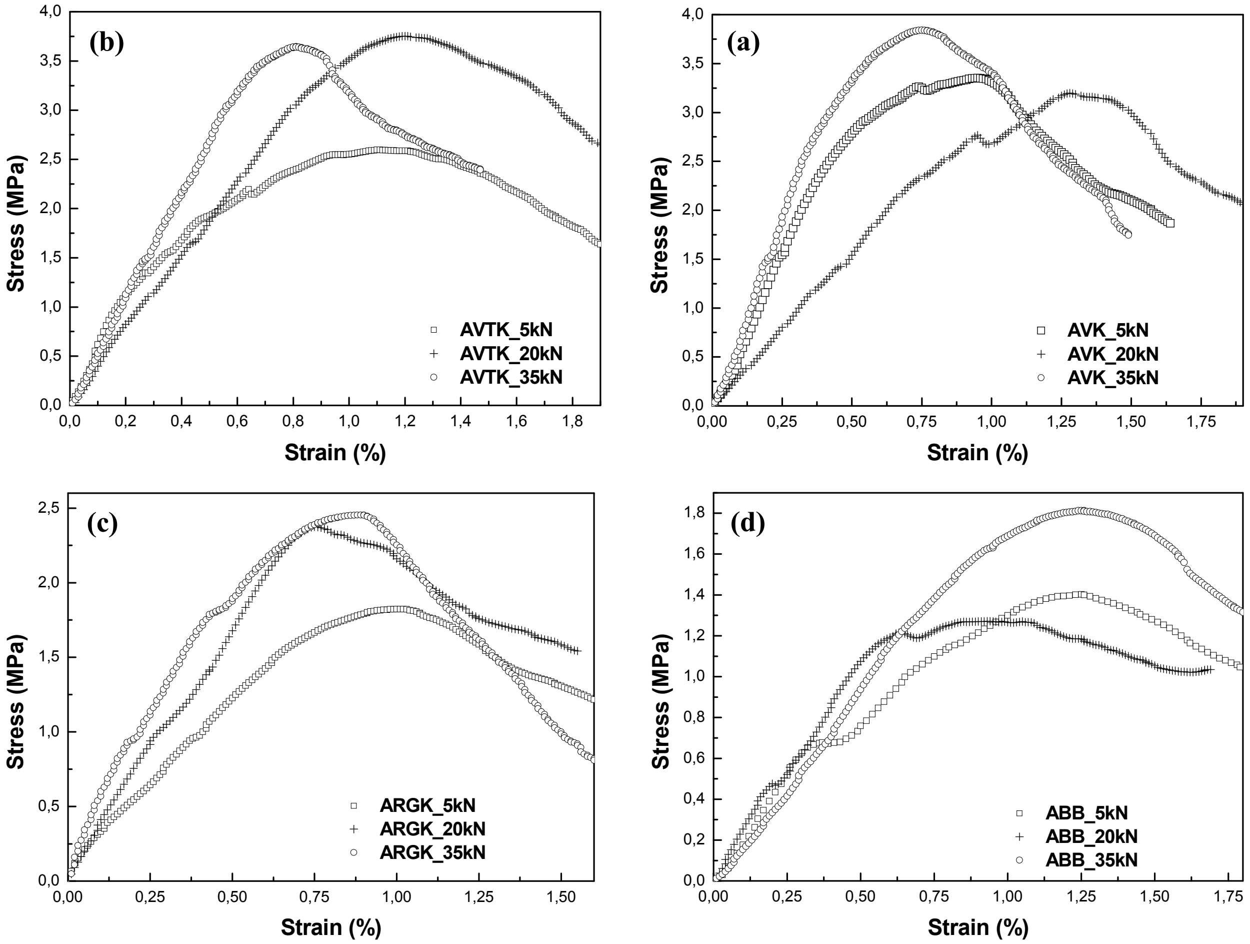

Fig. 7. *Compression test curves on dried specimens of the four clay varieties initially compacted as paste at three different strengths (F= 5, 20 and 35 kN)*

Conclusion

This work has enabled us to understand the problems of the clay paste rheological properties by comparing the behaviour of four varieties of clays, and to show the influence of the compaction load of the clay paste on the resistance of the dried material. The compression tests on the dried structures showed longitudinal cracks on the side faces that are more remarkable on less compacted specimens.

It is likely that the cracks found on the side faces of compressed dried specimens result at least partially from those initiated by the formatting. A numerical approach based on an elasto-viscoplastic model will allow us to better describe the distribution of the stress and displacement fields in the dried material. In addition, observations under microscope should allow us to quantify the problem of matrix cracking in order to deduce the influence of the formatting. Work is underway to clarify these issues. Finally, a more sophisticated model should take into account details on the microscopic structure of the materials studied, both in the hydrated form (paste) and in the dried one.

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