Stresses and Fractures in Capillary-Porous Materials under Drying

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Extended Summary

Introduction. Fracture of materials during drying processes is a well-known phenomenon in industry drying, as for example, in ceramics industry, wood industry, etc. Efforts are made to minimize this negative effect. This paper is a contribution to this issue. Main aim of this paper is a theoretical and experimental analysis of fracture risk in saturated capillary-porous materials under drying. In particular, we want to show that the acoustic emission method (AE) may serve for identification of fracture intensity accruing in such materials and in this way to prevent the material against its destruction.

The reason for fracture is the shrinkage phenomenon and the drying induced stresses. In this paper, the drying induced stresses are detected theoretically on the basis of mechanistic model of drying. The boundary-value problem for cylindrically shaped kaolin sample is solved under the assumption that the saturated kaolin is visco-elastic and obeys Maxwell model. The distribution of the stresses in the cross-section of the cylindrical sample and the time evolution of the stresses on the cylinder surface (maximal) are presented for different temperatures of the drying medium (air).

The cylindrical kaolin sample of the same dimensions as that analyzed theoretically was dried convectively in different temperatures in the chamber drier. The AE set-up installed in the drier was used for measurement *on line* of the number of AE events rate (the number of AE occurrences per 30 s time intervals) as well as the energy of the individual occurrences and the total energy emitted by the material under drying. Parallel, the so-called drying curves illustrating the time-change of moisture content in the sample were appointed by making use of the electronic balance and software, which registered and drawn the curves automatically. The drying curves allowed us to identify at which periods of the drying the fracture phenomenon became the most intensive.

Comparing the history of AE energy emitted from the material during drying with the theoretically appointed curves of stress evolution allowed to state that the most intensive fracture of the material occurred at those moments at which the stresses reached maximal values. As the most amount of energy is released due to micro- and macro cracking of the material structure, it denotes an immediate correlation between the growth of stresses and the intensification of fracture phenomena.

Mechanistic model of drying. The thermomechanical model of drying used for analysis of the drying induced stresses was developed on the basis of mechanics of continua (Kowalski, 2003). The differential equation describing the alteration of moisture content in dried body follows from the mass balance and the rate equation of mass transport for moisture. The latter relates the moisture flux with the gradient of moisture potential $\mu(T, \varepsilon, \theta)$, which is a function of temperature T, the body volume deformation ε, and the moisture content θ (mass of water referred to mass of dry body).

The distribution and evolution of temperature in the body under drying follows from balance of energy, The energy equation reduces to the balance of entropy $s(T, \varepsilon, \theta)$ after application of Gibbs identity. The heat flux supplied to the body consists of two parts: conductive and convective. The later expresses the transport of heat by moisture flux. In our considerations concerning kaolin, however, we applied the empirical observation that the most shrinkage of this material and the maximal stresses occur during the so called constant drying rate period, during which the temperature of the body is constant in natural way. Therefore, we have confined our theoretical analysis to this period and assumed constant but different in various drying processes temperature of the body.

The stresses $\sigma_{ij}(T, \varepsilon, \theta)$ in the body under drying are determined from the condition of mechanical equilibrium of internal forces, $\sigma_{ij,j} = 0$, and the Maxwell physical relation

$$\dot{\sigma}_{ij} + \frac{M}{\eta}\sigma_{ij} = 2M\dot{\varepsilon}_{ij} + \left(\frac{A}{K}\dot{\sigma} + \frac{\xi}{\chi}\frac{M}{\eta}\sigma\right) - \frac{2}{3}M\dot{\varepsilon}^{TX}\delta_{ij}, \qquad \text{where} \qquad \varepsilon^{TX} = 3\left(\alpha_T\vartheta + \alpha_X\theta\right),$$

with $\vartheta = T - T_r$ and $\theta = X - X_r$ denote the relative temperature and the moisture content. The former is assumed constant in this paper and the latter is determined from the differential equation mentioned above. In the Maxwell relation ε_{ij} denotes the total strain tensor and ε^{TX} is the volumetric strain caused by the temperature and moisture content alterations, α_T and α_X are the coefficients of thermal and humid expansion, $K = 2M/3 + A$,

$\chi = 2\eta/3 + \xi$, and M and A are the elastic and η and ξ the viscous counterparts of Lame constants for dried material.

The moisture content distribution in the cylindrical sample and its time evolution were calculated by making use of the finite difference method (Crank-Nicholson scheme) with taking into account the initial and boundary conditions. The stresses in viscoelastic cylinder were determined analytically due to correspondence principle between elastic end viscoelastic behavior of materials, and by making use of the Laplace transforms and the Borel's convolution formula. The stresses in elastic cylinder were determined by the assumption that the cylindrical sample is long enough (problem of axial symmetry).

Experimental studies. In order to test the stress generation in kaolin under drying, the drying processes were carried out in five temperatures of the drying medium: 120^{o}C, 100^{o}C, 85^{o}C, 75^{o}C and 45^{o}C and of the relative humidity 3.9%, 4.2%, 4.6%, 4.9% and 7.9% respectively. The samples were made of the composite consisting of kaolin (70%) and sand (30%), and were molded into cylinders of external radius 0.025 m and height 0.09 m (Fig. 1). The samples were dried convectively in the chamber drier, in which the acoustic emission transducer, the balance, the temperature and humidity sensors were installed. The kaolin sample placed in the drier constituted the generator of AE signals during drying. These signals were transported as elastic waves to the boundary of the sample where they were detected by the piezoelectric transducer. The transducer transformed the AE signals into electric impulses, which after suitable filtration and amplifying were registered by the computer thanks to software compatible with the canvassing card GPIB, and observed and the oscilloscope as well. The balance registered the moisture removal in prescribed time periods with accuracy of 0.01 g.

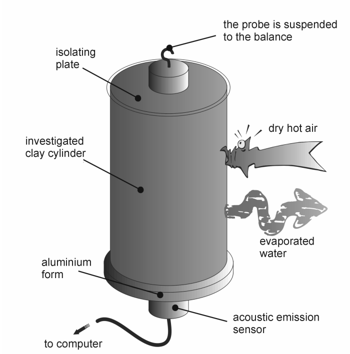

Fig. 1. The clay sample

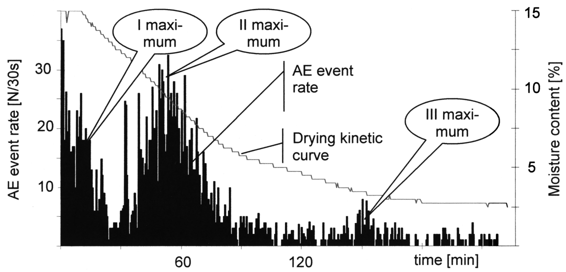

Fig. 2. AE signals and the curve of drying

Fig. 2 presents the registered AE signals and the removal of moisture content in time for drying at temperature 100 ^{o}C and 4.2% humidity of the air.

Fig.3a presents the rate of AE events and Fig.3b the evolution of circumferential stresses at the cylinder surface for drying in different temperatures

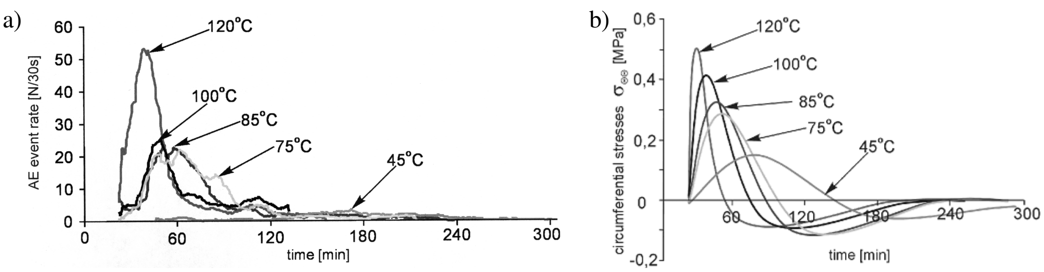

Fig. 3.Drying of clay cylinders in different temperatures a) the rate of AE events during drying b) evolution of circumferential stresses at the cylinder surface

Conclusions. The AE event rate descriptor illustrates the evolution of the drying induced stresses. The maximal values of the AE event rates depend on the drying temperature and coincide with the maximal stresses. Their peaks are greater and appear quicker in time for higher temperatures.

The AE energy descriptor can be used for the statement whether or not the dried product suffer the fracture. In those moments when the macrocracks occur, sometimes visible with the naked eye, the total AE energy curves manifest a rapid increase. The macrocracks were observed, particularly on the cylinder surface, when the drying conditions were very hard.

References

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