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NUMERICAL MODELLING OF EFFECTS OF THE DRYING RATE ON KAOLIN FRACTURING

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Abstract

Non-uniform distributions of moisture inside the porous materials during drying results in compressive stresses inside the material and tensional ones close to the surface. The tensional stresses together with brittleness of dry material are the reasons of fracturing of the material. In the paper the model describing the fracturing is used to examine the influence of the drying rate on fracturing. It is shown that slow drying does not involve any cracks. The quicker drying generates higher risk of fracturing, and the final fracture pattern is more complicated.
Keywords: Cracking by drying, Spring network model, Mass transfer, Mathematical model, Numerical solution

MODELOWANIE NUMERYCZNE WPŁYWU SZYBKOŚCI SUSZENIA NA PĘKANIE KAOLINU

Niejednorodny rozkład wilgoci wewnątrz porowatych materiałów podczas suszenia wywołuje naprężenia ściskające wewnątrz materiału i rozciągające w pobliżu powierzchni. Naprężenia rozciągające wraz z kruchością suchego materiału są przyczyną jego pękania. W artykule wykorzystano model opisujący pękanie do zbadania wpływu szybkości suszenia na pękanie. Wykazano, że powolne suszenie nie pościąga za sobą powstawania pęknięć. Szybsze suszenie powoduje większe ryzyko pękania, a końcowy obraz przebiegu pęknięć jest bardziej skomplikowany.
Słowa kluczowe: pękanie wywołane suszenie, model sieci strunowej, transport masy, model matematyczny, rozwiązanie numeryczne

1. Introduction

During a drying process, the non-uniform distributions of both the temperature and the moisture content appear. That is why the temperature expansion and moisture shrinkage are also non-uniform. It causes drying induced stresses. The magnitude of the stresses depends mainly on the rate of the drying process. The problem of the shrinkage and stresses induced by drying has been discussed in literature for many years. The extensive review of these works could be found in [1]. Most of them are devoted to the influence of shrinkage on heat and mass transport. Some of them investigate the drying induced strains and stresses, that are very important from the product quality point of view. They are the reason of the all permanent deformations, *e.g.* warping and fracturing. These phenomena were experimentally investigated and reported in many papers [2, 3]. Clays at the low state of the moisture content are usually brittle-elastic. The tensional stresses together with brittleness of dry material are the reasons of the generation of cracks. The cracks start if the drying induced stress exceeds locally the material strength usually at the material surface. Then the cracks rise, change direction, bifurcate, joint and generate more or less complicated fracture inside the material. The exemplary fracture pattern obtained by drying of kaolin clay is shown in Fig. 1.

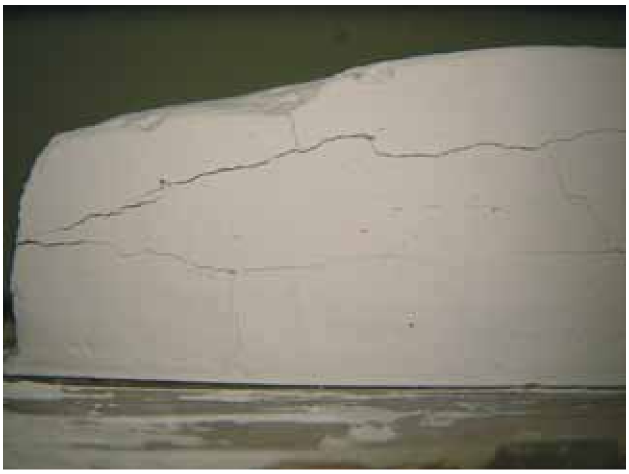

Fig. 1. Exemplary fracture pattern obtained by convective drying of kaolin clay.

To describe the fracturing by drying Peron *et al.* [4] used a discrete modelling approach to the problem. In the case of free shrinkage drying simulations no fracturing was obtained. The discrete modelling approach was also used by Kharaghani *et al.* [5]. The dried body was the cube $2\cdot10^{-6}$ m in size. Therefore the work could model the reason of microcracks occurring but could not describe the fracture pattern. Aoki *et al.* [6] used spring model for visualization of the crack generation by drying. The main fault of this approach is the limit condition which is connected with the geometry (extension) instead of strength or energy.

The model combining continuous diffusion equation (mass transfer) with the spring-network model (mechanical behaviour) was proposed in [7, 8]. The model is used in the presented paper to study the influence of convective drying rate on the fracturing of kaolin clay.

2. Mathematical model

The model used in the paper is thoroughly described in [7, 8]. Hence, short model recapitulation in two-dimensions is given now. In the paper drying of a brick made of kaolin clay (the section of the brick) is considered.

2.1. Mass transport description

It is assumed that the problem is isothermal and mass transfer is independent of the body deformation. Then the well known moisture diffusion equation is used:

$$\frac{\partial X}{\partial t} = D\left(\frac{\partial^2 X}{\partial x^2} + \frac{\partial^2 X}{\partial z^2}\right) \tag{1}$$

The diffusion coefficient is equal $D = 1.5\cdot10^{-7}\ \mathrm{m^2\cdot s^{-1}}$ [9] The uniform initial condition $X(t{=}0) = X_0 = 0.4$ is assumed. The convective drying at the upper, left and right sides:

$$-D\left.\frac{\partial X}{\partial z}\right|_{z=h} = \alpha\left(X|_{z=h} - X_e\right) \tag{2}$$

$$-D\left.\frac{\partial X}{\partial x}\right|_{x=0,x=l} = \alpha\left(X|_{x=0,x=l} - X_e\right) \tag{3}$$

and symmetry at the down side:

$$\left.\frac{\partial X}{\partial z}\right|_{z=0} = 0 \tag{4}$$

conditions are assumed. The equilibrium moisture contents equals $X_e = 0.0079$.

The rate of drying depends on the moisture exchange coefficient α. In the work initially very slow drying was considered with $\alpha = 0.000001\ \mathrm{m\cdot s^{-1}}$. Then the drying was accelerated by an increase of α coefficient up to $\alpha = 0.00005\ \mathrm{m\cdot s^{-1}}$. In Fig. 2, there is shown the exemplary moisture content distribution after 300 s of drying ($\alpha = 0.00001\ \mathrm{m\cdot s^{-1}}$).

2.2. Mechanical behaviour

The mechanical behaviour of material is described by the network model. It is assumed that the material could be divided into small particles interconnected via springs. In the presented two-dimensional model, each particle is connected with the eight neighbouring particles (Fig. 3).

All springs in the model are described by two parameters: (i) spring constant k, (ii) critical force F_{cr} (tensile force of breaking of the spring). Geometrical relations give that these parameters are the functions of the Young modulus E and the material strength σ_{cr} (both moisture content dependent, see [10]):

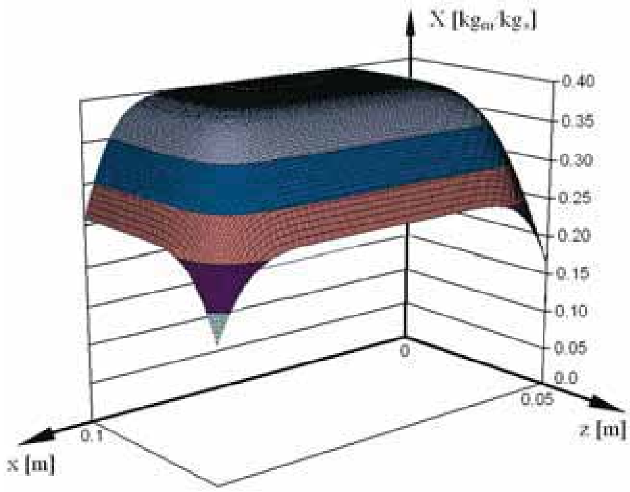

Fig. 2. Distribution of the moisture content X in the bar section after 300 s of drying (α = 0.00001 m·s⁻¹).

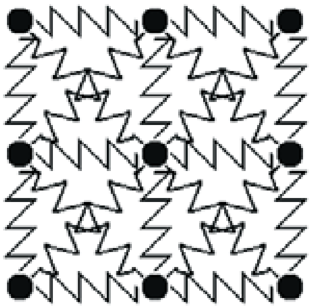

Fig. 3. Scheme of connections between particles.

$$k = \frac{\delta}{2}E(X) \tag{6}$$

$$F_{cr} = \delta^2\sigma_{cr}(X) \tag{7}$$

The formulas (6) and (7) are smooth functions of the moisture contents. In real clay, the local strength and local stiffness of the material has the random character. Therefore the normal dispersion of the spring constants and the critical forces for all springs are applied to obtain better description of real material behaviour.

The forces acting in the springs are calculated from the equations:

$$F_x = \frac{x_2 - x_1}{L}k(L - L_f) = (x_2 - x_1)k\tfrac{\Delta L}{L} \tag{8}$$

$$F_z = \frac{z_2 - z_1}{L}k(L - L_f) = (z_2 - z_1)k\tfrac{\Delta L}{L} \tag{9}$$

where (x_1,z_1), (x_2,z_2) are the positions of the spring ends, L is the actual length of the spring and ΔL is the spring elongation due to the inner force [8]. Because of the quasi-static behaviour of the particles the Newton's first principle of the force equilibrium is valid: the sum of the all forces acting at the particle is equal to zero:

$$\sum_{j=1}^{8} F_{ij} = 0 \tag{10}$$

where $i = 1...n$ is the number of particle and $j = 1...8$ is the number of neighbouring, linked via spring, particle.

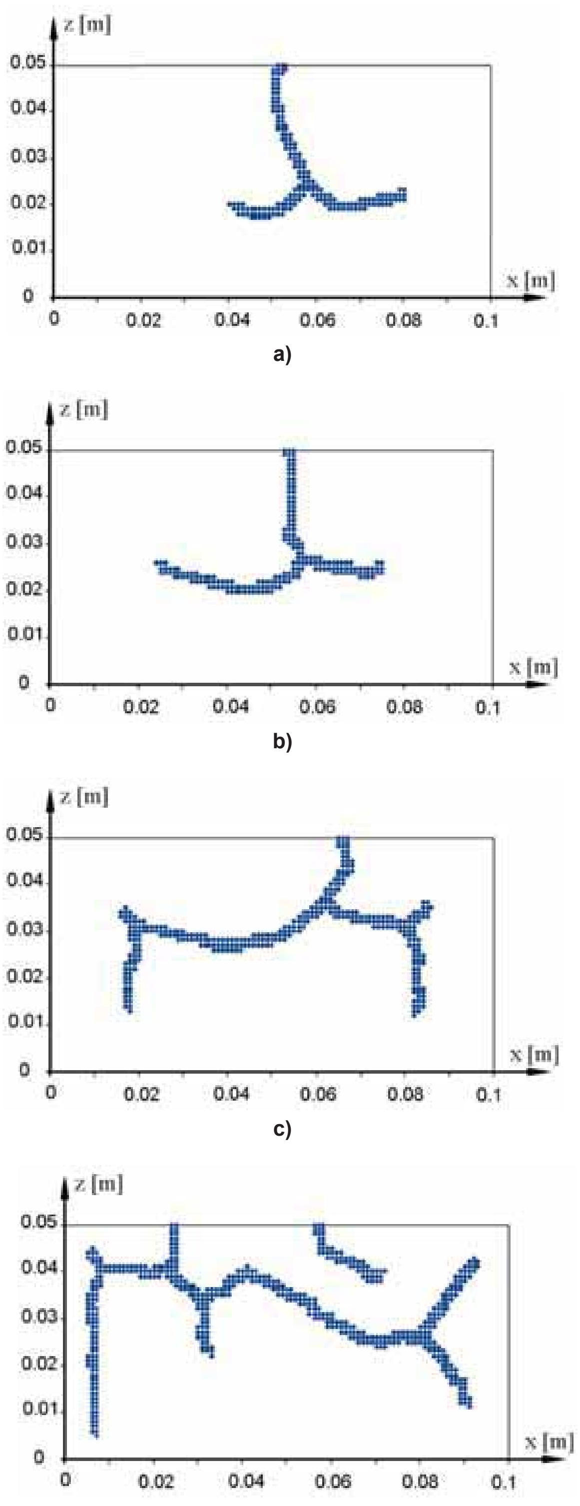

Fig. 4. Fracture patterns after drying: a) α = 0.000004; b) α = 0.000005; c) α = 0.00001; d) α = 0.00005 m·s^{-1}.

It is assumed that the bottom side of the bar is fixed in *z* direction (vertically), the left and the right hand sides and also the upper side are free of forces. Introducing (8) and (9) into (10) give two non-linear equations with unknown positions of particles locations. Then if the number of particles is *n*, the 2*n* non-linear equations are obtained. Solution of these equations gives the locations of the particles in actual moment. Knowing the positions of the springs ends, one can calculate spring forces using equations (8) and (9).

If the tensional force in any spring exceeds its critical force, the spring breaks. This is the way of the description of microcracks generation. Due to the linking of the microcracks, the less or more complicated fractures are expected. Of course every microcrack causes the network change. Small crack is a kind of notch in the material. It is the reason of the stress concentration which could cause the fracture growth.

3. Results of simulations

The drying with the small moisture exchange coefficient *α* = 0.000001-0.000003 m·s^{-1} causes no cracks. Acceleration of the process (α = 0.000004 m·s^{-1}) results in the sudden appearance of big bifurcate fracture (Fig. 4a). In the case of *α* = 0.000005 m·s^{-1} the obtained fracture is a little bigger than the previous one (Fig. 4b). Still faster drying (*α* = 0.00001 m·s^{-1}) causes that the initial big fracture rises during the process, and could bifurcate once again (Fig. 4c). The fastest considered drying process (*α* = 0.00005 m·s^{-1}) results in the quick appearance of some (2-4) initial cracks on the material surface. Usually one or two of them rise in jerks during the process. In these cases, the most complicated fracture patterns are obtained (Fig. 4d).

In Fig. 5, there is shown the number of springs broken during the considered processes. It illustrates the rate of fracturing. If the drying is slow the fractures appear in one step. Acceleration of the process causes the increase of the number of broken springs, the growth of the fracture during process, and the increase of the number of initial cracks. The fracturing is the random phenomenon therefore the results are also random, and different fracturing are obtained as the result of the same drying conditions.

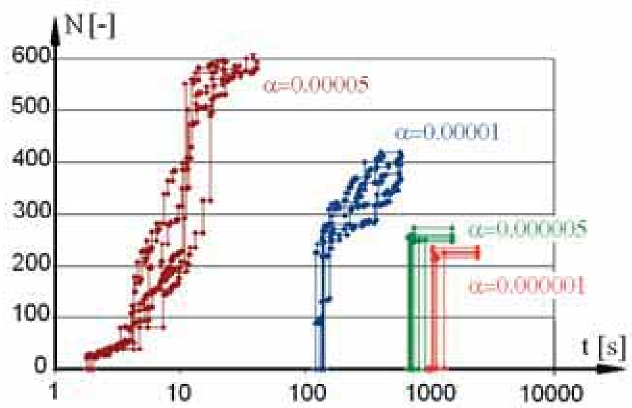

Fig. 5. Evolution of number of broken springs

4. Conclusions

The simulations shown that slow drying does not involve any cracks. The increase of drying rate results in fracturing, and the faster drying the more complicated final fractures.

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