EFFECT OF PORE PRESSURE ON THE STRUCTURE FORMATION IN HEATED CAPILLARY-POROUS MATERIALS

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Analyzed are the conditions of equilibrium and of breakdown in pore walls due to internal pore pressure in moderately heated concrete.

The shrinkage and the bursting of capillary-porous materials during drying are attributed to tensile or shear stresses in the pore walls produced by capillary forces and by a nonuniform moisture distribution over a section [1]. In order to establish the optimum heating mode, one uses methods based on the theory of elasticity and on the concept of linear expansivity. In the case of capillary-porous materials, however, and especially in the case of curing concrete, which is semiplastic, such assumptions are not valid.

The presence of a vapor–air mixture in the pores has an appreciable effect on the thermal expansion characteristics and is a source of internal pressure. The first attempt to theoretically analyze the effects of a vapor–air medium in concrete was made assuming the water vapor in pores to be saturated, the liquid water to contain no dissolved impurities, and the pores to be cylindrical capillaries [2]. These assumptions have led to higher calculated values of internal pressure and volume of air and water displaced by heating. The water vapor within the pores was not accounted for by some authors. This has resulted in lower values for the internal pressure and the expansion of bubble volume during heating [3].

The peculiar feature of a capillary-porous colloidal material, such as concrete, is that it always contains air-filled pores resulting from contraction, air entrapment during sealing, and air removal from solution in water (deaeration). The presence of free water causes its vapor in pores to be not saturated but saturating, i.e., in equilibrium with the water. This, and also the pressure relaxation through openings, cause the pore pressure to be usually lower than theoretically calculated [4].

Sometimes the bubble pressure in a capillary is assumed equal to the sum of the hydrostatic and the capillary pressure [5]. It is well known, however, that the skeleton structure of concrete and cement mortar during setting consists of a crystalline and a gel component which may not transmit the hydrostatic pressure to a bubble (pore). This is further compounded by the presence of the filler material and by the ability of the viscous mix to take up the shear forces. For this reason, the hydrostatic pressure decreases.

Attempts were made to calculate the hydraulic pressure in heated concrete, taking into account the porosity of this material as well as the viscosity and the thermal expansivity of water [6]. The hydraulic pressure was assumed there directly proportional to the porosity of concrete and to the specimen thickness (height) squared. This is not confirmed by tests. The pressure in concrete is lower than hydrostatic and in a pore (bubble) there may be none until vacuum has developed. A calculation of pore pressure is difficult, because the actual composition of the vapor–air mixture is usually unknown.

The total pressure in a pore, with relaxation disregarded, consists of air pressure and saturated-vapor pressure:

$$P_0 = P_A + P_V. \tag{1}$$

In engineering calculations, the air pressure is taken as

$$P_A = 29.27\ \gamma T. \tag{2}$$

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The air density varies from 1.205 kg/m^3 at 20°C to 0.946 kg/m^3 at 100°C. Its values under normal pressure are found in tables. Under pore pressures other than normal, the air density varies proportionally with pressure. The pressure of saturated vapor is easier to determine, because it depends on the temperature only and it increases from 17.54 mm Hg at 20°C to 760 mm Hg at 100°C. Intermediate values can be found in tables.

The first attempt to measure the pressure in concrete was made by Veksler and Goryainov [7]. In their tests, however, they measured the external hydrostatic pressure rather than the pore pressure. Because of the small specimen size and the temperature drop from one end surface to the other, moreover, the pressure gradient was apparently produced by osmosis and not by vapor migration. The vapor–air pressure in an internal pore was studied and measured in standard concrete [8] and in light-weight concrete [9] heated electrically, also during pressurization of gas concrete [10]. Maksimov [11] and Lebedev [12] have established the existence of internal pressure during low-temperature drying of moist porous bodies. It was attributed to water vapor and its "injection" effect through pores. In practical calculations of heat and mass transfer along with internal stresses, however, the effect of pore pressure is still not taken into account [13] and this is incorrect.

In Fig. 1 are shown curves of internal excess pressure during electric heating of standard concrete according to the 1 + 2 + 1 time cycle. The temperature of the isothermal treatment was here 92-93°C. The probes were open-ended elastic rubber tubes filled with filter paper and protected with a nylon mesh [14]. The effects of hydrostatic water pressure and concrete-mix pressure were eliminated by connecting a probe to a U-tube manometer after the specimen had been formed, i.e., measurements were started before heating. The deeper was a probe located, the higher was the pressure because of the greater hydraulic resistance to the discharge of vapor–air mixture and of water with less pressure relaxation. These and other tests [14] have shown that under severe heating, at rates of 30 deg/h or higher, the excess air pressure is 180-200 mm H_2O in standard concrete and 350-400 mm H_2O in the dissolved phase of light-weight concrete, but up to 700 mm H_2O inside ceramsite grain. The pressure curves follow the heating curves. After the end of heating, the pressure drops immediately down to vacuum. However, the overall pore pressure is lower than calculated according to formula (1). Nevertheless, such a pressure is sufficient to crack the pore walls.

We will now examine the internal and the external section of a porous body shown in Fig. 2 with respective pore pressures P_1 and P_2 during heating. We will establish the equilibrium conditions for the pore walls, considering the internal pressure P_a and the pressure due to dead weight W. With the assumption that the porosity is accurately enough estimated on the basis of the average clear area, it is possible to determine the average wall thickness and pore diameter by well-known methods. This is necessary for classifying the structural porosity in terms of "thin-walled" or "thick-walled" vessels for subsequent calculations. In the case of standard concrete, the initial porosity prior to heating is determined by the porous coagulative structure of cement mortar, i.e., by the residual water-to-cement ratio. During hardening, in addition to water-filled pores there appear air-filled pores produced as a result of cement contraction and water evaporation. During heating, the air porosity increases also owing to expansion of the vapor–air mixture and release of air from the sealing water. In the wet phase of standard concrete the ratio $a/2r$ is greater than unity. Therefore, the analysis of a thin-walled vessel will apply here. For the purpose of calculations, cellular and loose concrete are treated as spherical thin-walled vessels.

Rupture of cracking due to internal pressure on section 2 can occur if

$$\sigma_t \geqslant \sigma_y + P_a. \tag{3}$$

Equilibrium at section 1 is defined as

$$\sigma_t' \leqslant \sigma_y + P_a' + W. \tag{4}$$

The external pressure on the pore wall surface can be defined as

$$P_a' = \frac{P_a S_o}{S_S}. \tag{5}$$

As has been mentioned already, pressure W due to the dead weight of cement mortar or concrete is lower than the hydrostatic pressure. According to the data by Akhverdov, this pressure is equal to

$$W = h\gamma_c - 4hF. \tag{6}$$

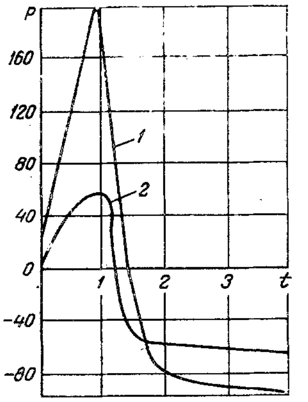

Fig. 1

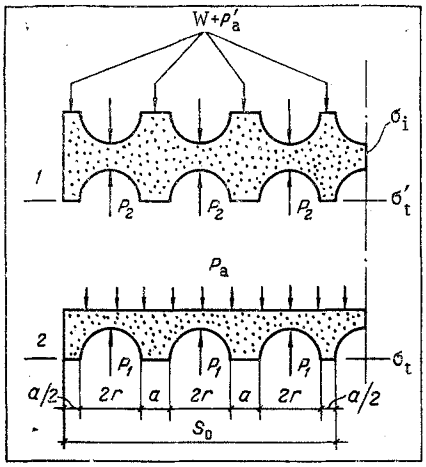

Fig. 2

Fig. 1. Kinetics of the internal excess pressure during heating of concrete: 1) at depth 7 cm; 2) 2 cm. Pressure P (mm H_2O); time t (h).

Fig. 2. Schematic diagram for calculating the stresses in pore walls: 1) inner zone; 2) surface layer.

According to our data, W is lower than calculated by formula (6), because of the several factors discussed earlier. Of course, we consider here the equilibrium state. As soon as the equilibrium is disturbed and cracking (swelling) occurs, the second term in Eq. (6) becomes positive. Even under such conditions, however, the internal pore pressure remains lower than hydrostatic. It is to be noted that, with probes as ours, the internal pore pressure is measured within a macrovolume on a surface at least 0.5 mm^2 area (medical syringe). Capillary forces and pressure in the gel pores remain unaccounted for, however. This does not matter as far as the conditions of pore and crack formation or satisfying the equilibrium conditions according to (3) and (4) is concerned, because the effect of capillary forces is included in the value of σ_y.

The actual stresses σ_t and σ_i in the pore walls due to internal pressure can be calculated by well-known formulas for single vessels. A correction is added for the superposition of stresses in adjacent single pores. This makes the stresses in a system of pores twice as high as in a single one. In a partially hardened material without cracks we then have

$$\sigma = P\frac{2r_i^3 + r_o^3}{r_o^3 - r_i^3} \leqslant \sigma_y. \tag{7}$$

Stress calculations for fresh concrete during the first stage of heating may be based on the theory of plasticity as, for example, according to the well-known Bezukhov formula. Transforming this formula to apply to two neighboring bubbles (pores), we obtain

$$\sigma = \frac{P}{\lg \frac{r_o}{r_i}} \leqslant \sigma_y. \tag{8}$$

It follows from expression (8) that the stresses become higher with increasing porosity (thinner pore walls). (The ratio r_0/r_i is, to the first approximation, equal to the reciprocal of the porosity.)

Formulas (3) and (4) bring out the role of internal and external pressure on the structure formation. For instance, the onset of scaling and peeling of surface layers during heating of the material is a result of internal pressure not compensated by additional loading or by the dead weight of the mix. In concrete this occurs during "severe" heating at a rate of 30 deg/h. Calculations show that, under an internal pore pressure above 100 mm H_2O, tensile stresses of the order of 0.2-1.2 kgf/cm^2 appear in the pore walls. This exceeds the ultimate tensile strength or the yield point considerably, the latter being of the order of 0.04-0.1 kgf/cm^2. As a consequence, there appear cracks. The orientation of these cracks is usually horizontal or, more precisely, perpendicular to the direction of air and water migration, i.e., parallel to the free surface of concrete. The size of cracks visible with a naked eye decreases gradually from the surface down deeper into the bulk. In cellular and loose concrete, where the ratio r_o/r_i approaches unity, this trend is even more pronounced.

On the whole, these experimental and theoretical studies have shown that, during moderate heating of concrete, the internal pressure must be one of the structure determining factors. It produces three-dimensional deformations and internal breakdown effects. For this reason, the optimum heating mode for hardening either concrete or other capillary-porous materials cannot be calculated from thermal stresses based on the theory of elasticity, as in the case of a homogeneous body. For the calculation of internal stresses we propose the use of the procedure described here, which takes into account the internal pore pressure and the thermodynamic state of the vapor–air mixture in pores.

NOTATION

P_0	is the total pressure;
P_V	is the saturated-vapor pressure;
P_A	is the air pressure;
γ	is the air density;
T	is the absolute temperature;
σ_t, σ'_t	are the tensile stress on outer and inner section of a pore wall, respectively;
σ_y	is the yield point or ultimate tensile strength of concrete;
S_0	is the total section area;
S_S	is the area of the solid phase (pore walls);
h	is the height of column from surface to given section;
γ_c	is the density of mix;
F	is the shear strength;
r_i	is the inner radius of a pore;
r_o	is the outside radius of a pore;
t	is the time, h.

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