A METHOD OF DETERMINING LIQUID WATER AND ICE IN THERMOPHYSICAL TESTS ON POROUS MATERIALS

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A method is described for quantitative determination of liquid water and ice based on the sharp difference between the time characteristics of water and heat transport.

Measurement of the water conditions in wall structures under test in climatic chambers provides detailed data for thermophysical calculations and for forecasting the working life. Under any test conditions, one side of the structure is exposed to a positive temperature and the other to a negative one. These conditions simulate natural ones to a first approximation, but it is difficult to obtain data on the local water contents by layers because some of the layers contain liquid water and also ice.

There are traditional methods of determining liquid water in building materials (dilatometric and calorimetric), which give results for small specimens of material and are not suitable for use directly with a wall without sampling [1].

Electrical (conductometric) determination of liquid water in building constructions [2] requires the preliminary recording of numerous auxiliary relationships and does not provide satisfactory accuracy when there is any change in the salt content of the pore water.

In recent years, experiments have been performed on building thermophysics at the Building Physics Research Institute and various other organizations, where extensive use has been made of the layerwise determination of water content directly in walls [3]. The method is implemented by means of capacitance transducers for the local water content, which are built in during construction. The capacitance of a transducer is determined with a measuring instrument using the method of [4], which is free from effects from the conductivity of the material, which enables one to eliminate errors related to the migration of water-soluble components.

We give below a method of directly determining the amounts of liquid water and ice in a wall during such tests [5]. The following physical assumptions are involved: the dielectric constant of ice at 10^6-10^8 Hz is ε = 2-3, whereas the value for liquid water is ε = 78-83 [6]; and the water transport in the material is very much slower than the heat transport [7].

The essence of the method is that the capacitances are measured initially under nonisothermal conditions directly before the end of the tests (when the refrigerator is switched off), and then a second measurement is made 2 days later.

One of the stages in this method is calibration on a particular material [3], which provides a correlation between the capacitance and the water content. This relationship is recorded at positive temperatures, i.e., in the absence of ice.

As ε for ice is less than ε for liquid water by almost two orders of magnitude, the capacitance of a transducer in the material at a negative temperature is proportional only to the amount of liquid water. Therefore, the capacitances may be measured before the refrigerator is switched off, which gives information on the amount of liquid water in a given layer. Two days later, the temperature has become positive everywhere and the ice will have melted. Under practical test conditions (temperature differences up to 60°C) the temperature differences will have been virtually eliminated in this period of two days (temperature difference not more than 10°C). At the same time, the water will not have been substantially redistributed. To a first approximation one can assume that the water content in any local volume will have remained constant. Therefore, two measurements on each transducer are made: before the end of the tests (in the presence of ice) and two days later (after the ice has melted),

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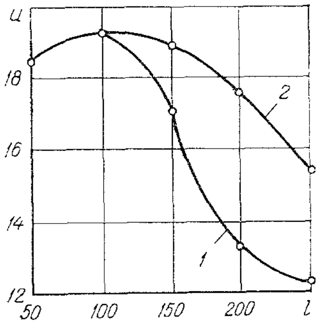

Fig. 1. Distribution of water content over a construction at the end of tests: 1) liquid water; 2) total water content (with ice); u%, l mm.

TABLE 1. Numerical Values of the Layerwise Water Content

Layer depth, mm	Water content u, %			δ_1, %	δ_2, %
	before switching off refrigerator, from specimens	2 days after switching off refrigerator			
		from specimens	from transducers		
50	20,5	20,3	18,5	9,0	1,0
100	20,5	20,0	19,1	4,5	2,5
150	18,9	18,7	19,1	2,1	1,1
200	16,7	17,0	17,5	3,0	1,7
250	15,6	15,1	15,5	2,7	3,5

which makes it possible to determine directly the amount of liquid water and the total water content in the same volume, the difference giving the amount of ice.

The method was checked out on a portion of wall panel made of ceramzite-pearlite concrete with γ_0 = 700 kg/m^3 of dimensions 1200 × 2000 mm and thickness 300 mm. Five capacitance transducers had been mounted in the panel during manufacture at various positions in the cross section. In the climatic chamber, the warmer surface was at +13°C and the cold one was at −22°C (difference 35°C). When the refrigerator had been switched on and a steady state had been reached, three of the transducers out of the five were in the negative-temperature zone.

Figure 1 shows the distribution of water content over the thickness and the boundary between ice and water as derived from the measurements.

The systematic component of the error in this method can be determined by comparing results with the transducers with data obtained in parallel on samples taken from the same layers. The water content in that case is determined by drying to constant weight.

The random component of the error may be determined by comparing the water contents in given layers before switching off the refrigerator and 2 days later.

Table 1 gives the results.

The effects of ice on the capacitance for various values of the ice content can be estimated from the following: the capacitance is directly proportional to the dielectric constant of the material, which is a heterogeneous multiphase system. The overall dielectric constant of such a system is given to a first approximation by the following formula [8]:

$$\sum_{i=1}^{n} \frac{\varepsilon_i - \varepsilon}{\varepsilon_i + 2\varepsilon} v_i = 0. \quad (1)$$

We consider the limiting (theoretical) case from the viewpoint of the effects of ice on the overall dielectric constant. This limiting case is when all the water is frozen in a water-saturated material. Here, as in the absence of water, we have a two-phase system ($v_1 + v_2 = 1$), for which (1) becomes

$$\varepsilon = A + \sqrt{A^2 + \frac{\varepsilon_1 \varepsilon_2}{2}}; \quad A = \frac{(3v_1 - 1)\varepsilon_1 + (3v_2 - 1)\varepsilon_2}{4}. \tag{2}$$

Typical values for ceramzite concrete are $\varepsilon_1 = 7$ and $v_1 = 0.7$ (in fractional terms), while $\varepsilon_2 = 1$ for air and $\varepsilon_2 = 2.2$ for ice, which on substitution into (2) gives $\varepsilon = 4.6$ for the dry material, while for the water-saturated material with 100% we get $\varepsilon = 5.2$, i.e., the limiting relative change in ε is 13%.

When one tests parts of wall constructions made of light concrete in climatic chambers, the real values of the ice content are not more than 30-40% of the total water, and therefore we assume to a first approximation that the dependence of ε on the ice content is linear, so the relative error due to the effects of the ice is $\delta_3 = 5\%$.

The overall relative error of this method is therefore [9]

$$\delta = \sqrt{\delta_{1\text{w}}^2 + \delta_{2\text{w}}^2 + \delta_3^2} = 7\%,$$

which is satisfactory for engineering purposes.

This method of determining liquid water and ice is rapid and simple, and it therefore differs favorably from existing ways of obtaining information directly without sampling.

NOTATION

ε, dielectric constant; γ_0, density of dry material; u, moisture content; l, thickness; δ, relative error; v_i, volume proportion of phase i.

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