A COMPARISON OF THE THERMAL CONDUCTIVITY OF MOIST CAPILLARY-POROUS MATERIALS AT TEMPERATURES BELOW AND ABOVE 0° C

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The thermal conductivity of moist materials at temperatures below 0° C is examined. It is shown that the thermal conductivity of a material below 0° C can be either higher or lower than at positive temperatures and depends on the moisture content of the material.

Investigations [1, 2] have shown that the thermal conductivity of some dispersed materials in the frozen state can be either higher or lower than in the unfrozen state. When the moisture content is high the thermal conductivity of a frozen material is usually much higher than that of the unfrozen material. This can be attributed to the effect of the ice, which has a much higher thermal conductivity than water. When the moisture content is low, however, the thermal conductivity of some clays, sands, and other dispersed materials below 0° C is lower than at positive temperatures.

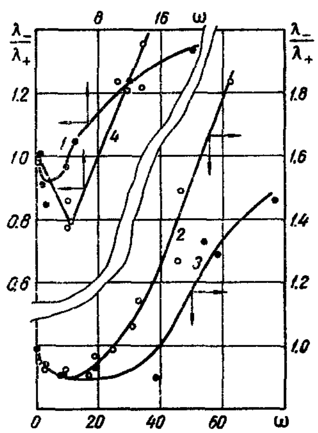

Fig. 1. Ratio of thermal conductivities at −18° C and +25° C in relation to weight moisture content ω, %: 1) Red brick; 2) gas-cinder concrete; 3) gas concrete; 4) sand (according to Kersten).

We have not found any data indicating the existence of conditions in which the thermal conductivity of frozen capillary-porous materials is less than that of the unfrozen material. To clarify this question we determined the thermal conductivity of some structural materials at temperatures above and below 0° C. The determinations were made by the steady-state method, which excludes the effect of the heat of phase transformations of water on the results of the tests.

The tests were carried out on a one-way instrument in which the temperature of the guard heaters was controlled to within ±0.01° C by means of 100 differential junction thermocouples in conjunction with EPV-2 regulating electronic potentiometers. The thermal conductivity at negative temperature was determined in a refrigerator providing a constant temperature of −25° C. The mean temperature in the experiment was −18° C and the temperature gradient in the sample was 1–1.5 deg/cm.

The sample was placed in the instrument and installed in the refrigerator for 12–16 hr. The heaters were then switched on, and when the steady state was attained in 10–12 hr, the required readings were made.

Leaving the sample in the refrigerator at the same temperature for up to one week and prolongation of the steady-state period to three days had no significant effect on the results of the tests. This confirmed that no phase transformations occurred during the tests. For comparison we also determined the thermal conductivity of the material at room temperature; in this case the experimental temperature was +25° C. The temperature gradient in the sample was the same as in the refrigerator. Figure 1 gives the results of the tests.

As the figure shows, the thermal conductivity of the investigated materials in the frozen state was higher than in the unfrozen state when the moisture content was high. When the moisture content was low the ratio of these two values was less than 1. For comparison the graph shows the corresponding curve obtained by Kersten [2] for sand at 25° F (−3.9° C) and 45° F (+7.2° C). The relative reduction of the thermal conductivity at negative temperature for different materials occurred at different moisture contents; in brick it occurred at 4%, in gas concrete at 40%, and so on.

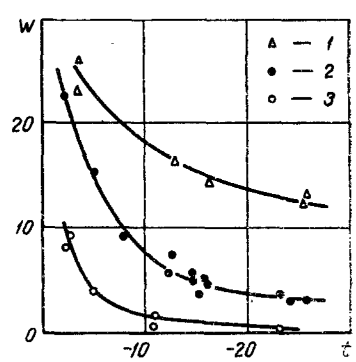

Fig. 2. Amount of unfrozen water W, % in relation to temperature t, °C: 1) Gas-cinder concrete, γ = 900 kg/m^3; 2) gas concrete, γ = 400 kg/m^3; 3) red brick, γ = 1800 kg/m^3.

Thus, depending on the moisture content the thermal conductivity of a frozen material may be higher or lower than that of the unfrozen material.

The physical explanation of the obtained results could be as follows. Below 0° C some of the water in the material remains unfrozen [3, 4]. Figure 2 gives the results of determinations of the amount of unfrozen water in some materials by the calorimetric method. As these data show, the amount of unfrozen water depends on the temperature and is different for different materials. The rate of phase transformation still takes place down to −30° C, i.e., any change of temperature in this region causes a change in the phase composition of the water, and this must be taken into consideration in the choice of the testing method.

As the experiments showed, the amount of unfrozen water at a given temperature is independent of the moisture content of the material, a result first reported for soils [6]. When materials with a low moisture content (less than the amount of unfrozen water at the given temperature) are frozen, the ice content of the material is practically zero. This suggests that the thermal conductivity of a material with low moisture content at negative temperature will be less than at positive temperature due to the reduction of the average temperature, as is confirmed by the data given in Figs. 1 and 2.

However, a relative reduction in thermal conductivity at temperatures below 0° C is also observed in materials with a high moisture content. For instance, the amount of unfrozen water in brick at −18° C is 0.3% and its thermal conductivity is lower when the moisture content is below about 4%; the corresponding figures for cinder concrete are 15% and 30%, and so on.

This can obviously be attributed to the fact that the freezing point of water in the pores depends on their size. Porous materials have pores of different sizes. When the material is cooled the water begins to freeze first in the large pores. The ice formed on the wall of the pore has an absorbing effect and draws the water out of the smaller pores, which thus lose some of their water. If there is not enough water the ice formed in the large pore does not reach the opposite wall of the pore and does not form an "ice bridge." When the small pores are depleted of water and there are no "ice bridges" in the large pores the thermal conductivity of the material may be reduced.

An idea of the structure of ice in the pores of materials can be obtained from the photomicrographs shown in Fig. 3. These are photographs of fragments of gas concrete ($\gamma = 400$ kg/m^3) under a microscope at a magnification of 50 ×. The samples were first saturated with water and then kept at −25° C for a day.

Thus, the thermal conductivity of some capillary-porous materials below 0° C can be higher or lower than at positive temperature. It is lower in material of low moisture content because the water is not converted to ice. The thermal conductivity of a frozen material at the next stage of moisture content is again lower owing to the difference in the freezing point of water in pores of different size.

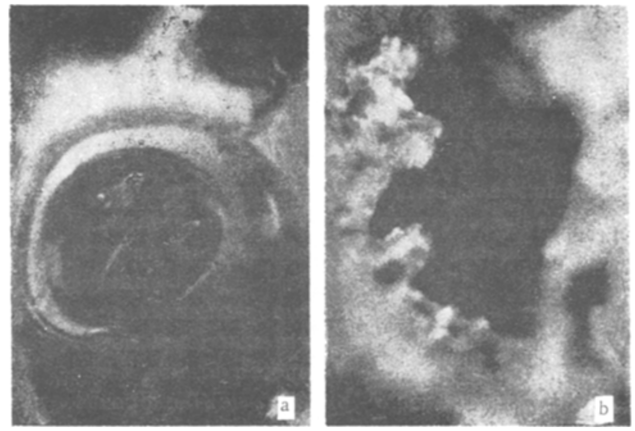

Fig. 3. Photomicrographs of ice in pores of gas concrete: a) Pore completely closed by ice; b) the ice formed on the wall of the pore does not reach the opposite wall.

With further increase in moisture content the ice begins to take effect and the thermal conductivity of the material rises sharply and becomes higher than at positive temperature. The moisture content at which the thermal conductivity of a material at negative temperature becomes higher than at positive temperature can be called the "critical" moisture content. The critical moisture content is different for different materials.

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