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DAMAGE TO MASONRY CONSTRUCTIONS BY THE ICE-LENSING MECHANISM

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Field studies of failures in the cladding of buildings have provided conclusive evidence that ice-lensing occurs in masonry materials and that its excessive expansion accounts for the displacements and deterioration observed. It should have been possible from a knowledge of the ice-lensing mechanism in soils to predict the occurrence of ice lenses in building constructions. Although suggested by some writers, the possibility has not been widely recognized. This paper discusses the conditions required for ice-lens growth, presents evidence of its occurrence in building constructions, and considers some of the implications of these observations. Although not discussed in this paper, ice-lensing in the soil under building foundations is frequently responsible for structural movements producing masonry failures.

Extensive investigation of the mechanism of ice-lensing with respect to frost heaving in soils has shown that it can occur in wet, fine-grained soils subjected to unidirectional freezing. Freezing of water, in causing a decrease in potential, induces water to migrate to the freezing plane. The release of the heat of crystallization, upon freezing of the water which migrated to the freezing plane, acts to retard its rate of advance. So long as the advance of the freezing plane is retarded by this means, water migrates between the ice and soil particles to freeze onto the ice, producing expansion far in excess of the normal expansion of water on freezing with the accompanying heaving pressure.

Ice-lensing in a wet, frost-susceptible soil subjected to freezing can be resisted by a load or tensile strength, by suction [1] at the freezing plane, or a combination of both. The load or tensile strength required to prevent its occurrence is proportional to the heaving pressure attainable. The maximum heaving pressure in a material varies inversely with pore size but can only be developed when the

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suction is essentially zero. With an increase in suction the rate of ice-lens growth and the heaving pressure are both reduced with no ice-lensing occurring when the suction is sufficiently high. When the potential rate of desiccation due to freezing exceeds the rate of moisture migration through the unfrozen material, even though saturated, the suction at the freezing plane increases, resisting ice-lensing.

It should be emphasized that ice-lensing does not require that conditions conducive to ice-lens growth be maintained over a long period of time for damage to occur. It has been shown by Penner [2] that a heave of 0.04 in. (0.1 cm) can occur in less than half an hour in several different frost-susceptible soil samples only 3 in. (7.5 cm) deep, with a total expansion of from 0.3 to 1.5 in. (0.75 to 3.25 cm) in two days. It is also important to note that, although sizable expansions in soil under roads can be tolerated, even small expansions in masonry can be quite serious since a strain of only 0.01 per cent can cause failure.

The conditions required to cause ice-lensing in soils - freezing, fine-pore structure, and moisture supply - frequently occur in building materials. In walls of heated buildings the thermal balance required to retard the advance of the freezing plane is not dependent upon the rate of moisture migration as it generally is for frost heaving in the ground. When this balance is essentially independent of the heat of crystallization of water on freezing a reduced rate of moisture migration may be of little significance in resisting ice-lensing. Furthermore, freeze-thaw cycling tends to produce a moisture accumulation in the zone of freezing despite low permeance or periodic fluctuations of the moisture content of the unfrozen materials. Under these conditions a low suction can occur and the tensile strength of the material may then be the only condition resisting ice-lens growth. If the exterior surface of a wall is highly permeable and drying can occur by evaporation, a high suction may be maintained and ice-lensing seldom occurs. When the exterior surface has a low permeability, however, the risk of low suction and ice-lensing is increased. Stone facings, flashings, and impermeable coatings are instrumental in many cases in producing accumulations of water which lead to severe ice lens damage to masonry materials. When the moisture supply to the freezing zone is very great, however, ice-lensing can occur even with a highly permeable surface on the cold side.

Although most of the conditions required for ice-lens growth frequently occur, damage to materials may not result. It has been proposed that for ice-lensing to occur in a sound porous material its structure must first be damaged by freezing while in a highly saturated state. This would appear to be of importance when the tensile strength of the material exceeds the potential heaving pressure but not necessary for the mechanism to operate in a material with low tensile strength, such as mortar. There is not enough evidence, however, to say that the failures to be discussed were not influenced in any way by prior history of freezing.

The following examples, chosen from many such cases, are included to show how ice-lensing is instrumental in cases of severe deterioration of masonry materials and constructions. Granite facing stones on a row of exterior columns, rising out

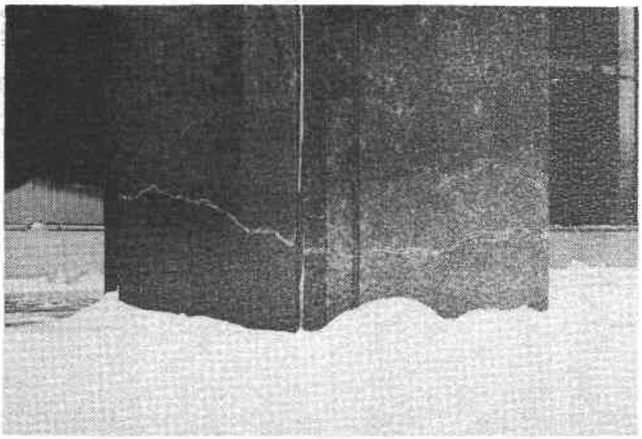

Figure 1. Granite facing broken because of ice-lensing in the back-up mortar.

of a poorly drained roof terrace, were displaced during the first winter after construction. The steel columns had been infilled to provide a square masonry column and the space between masonry and facing stones was filled with an over-watered mortar. The stones were installed in such a manner that the back-up mortar connected with the mortar bed of the terrace topping materials. The heat loss from the space below prevented the freezing of water in the terrace mortar bed and in the base of the columns. Water from the terrace could migrate through the mortar behind the column cladding stones to a freezing plane a short distance above the base. The appearance of the mortar, its low strength and fine pore structure, the existence of an ample supply of water and unidirectional freezing led to the assumption that ice-lensing was responsible for the failure. The following summer, displaced stones were removed and relaid, using new mortar throughout, and the space behind facing stones was again filled with mortar. Early the following winter similar displacement occurred and some stones 4 in. (10 cm) thick were broken by the force (Figure 1). Some stones were immediately removed and examination of the mortar back-up showed many ice lenses between wafers of solid material, typical of ice-lensing damage (Figure 2), confirming the assumption made the previous year.

On the same terrace there were low walls of a highly absorptive brick, faced with large stone slabs, the space between being filled with mortar. These walls were built on the roof membrane in contact with the terrace topping materials. The same displacement of stones occurred but, in addition to the ice-lensing in the mortar, a laminar break-up of the brick occurred.

Air leakage outward at the top of a humidified building caused excessive condensation [3]. The condensate was absorbed by the bricks and mortar in the 8-in.

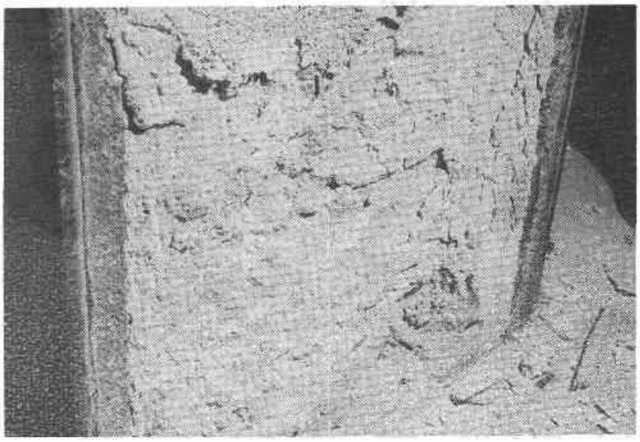

Figure 2. Ice lenses in mortar behind granite facing stones of Figure 1.

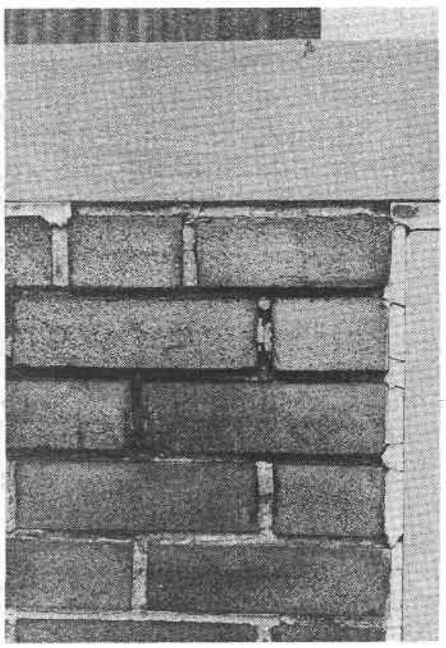

Figure 3. Masonry deterioration due to ice-lensing in the mortar joints.

Figure 4. Laminar break-up of masonry units which were covered by a metal flashing.

(20 cm) high parapet and several courses of brick below. Ice-lensing occurred, causing expansion in the mortar joint and disruption of the brickwork (Figure 3). The bricks at the back of the parapet were covered by the roof membrane and flashing and suffered a laminar break-up typical of ice-lensing damage. This break-up did not occur in the exposed face bricks because of drying to the atmosphere. Similar mortar failures and masonry disruption also occurred at window sills in the upper part of the building where condensation due to air leakage had been occurring.

On a building where roof leaks were permitting water to enter the wall, ice-lensing caused laminar failure of the bricks behind a base flashing. Above the flashing the bricks were not damaged because the partial drying and their tensile strength were sufficient to resist ice-lensing but the mortar joints were damaged. Figure 4 shows the wall with the flashing removed.

A high humidity was produced by plastering and finishing operations in a building under construction which was closed in by the permanent exterior walls and heated [4]. During freezing weather the exfiltration of air with a high moisture content through spaces between the windows and the inner wythe and through the wall cavity resulted in excessive condensation on the back of the glazed brick exterior wythe. Within a few weeks ice-lensing in the mortar joints had caused severe disruption of the face brick (Figure 5) with the expansion causing breakage of many panes of window glass.

Examinations were made of a window assembly in a residence where a large pane of glass had broken early in the winter, in both the first and second years after construction. The pattern of fracture indicated edge loading and it was observed that the wooden sill had been forced upward at the middle. Examination

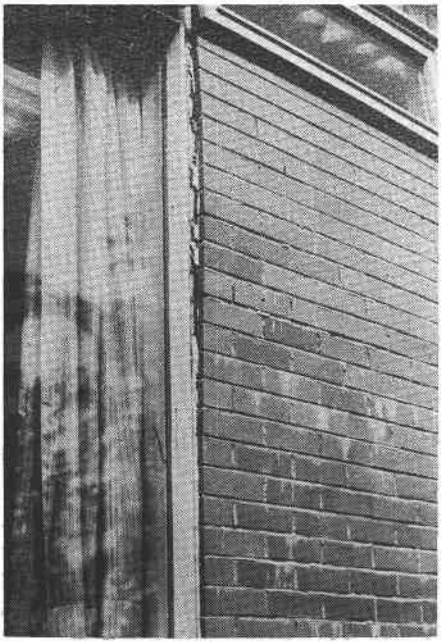

Figure 5. Damage to masonry and windows from ice-lensing in mortar joints. High moisture condition was due to condensation from air leakage.

of the brickwork below the window sill disclosed evidence of ice-lensing in the mortar joints. As the relative humidity in the house was being held at 50 per cent, the air leakage under the window sill produced continual condensation in cold weather. With this high moisture supply neither drying to the exterior nor the tensile strength of the mortar were sufficient to resist ice-lensing, at least for some period of time.

Ice-lensing, although responsible for many cases of severe deterioration of masonry materials and constructions, can be controlled. Since the four basic conditions - fine pore structure, low tensile strength, freezing, and high moisture content - are required simultaneously, sufficient modification of any one can prevent the growth of ice lenses. If economy in building is a factor, as it generally is, available materials must be used as they are. Consequently it is not reasonable to consider modification of the pore structure or tensile strength if the problem can be controlled in other more economical ways. Coating all the interior surface of a porous material with a compound to reduce the surface energy might reduce the potential heaving force but sufficient information is not yet available upon which to base a positive statement and furthermore the cost of such an operation could be prohibitive. Since the required tensile strength and the reduction of strength due to freezing in a saturated state are both indeterminate it may be unwise to rely on strength alone to prevent the occurrence of ice-lensing. By positioning the insulation as far to the cold side as possible, the temperature in most materials of a wall can be kept above freezing. With such a wall, only the exterior facing materials will be subjected to freezing and the risk of ice-lensing considerably reduced. Ice-lensing cannot occur in dry materials and the control of the moisture content of materials exposed to freezing can also be employed to prevent its occurrence.

The best way to prevent ice-lensing damage to masonry construction is by designing so as to minimize the quantity of materials subjected to freezing and to maintain the moisture content of these as low as possible. A cavity-type wall with insulation applied to the outside surface of the inner wythe has great possibility for success. With the insulation as far to the outside as practical, most of the wall can be kept from freezing. The moisture content of the exterior wythe can be kept low if the mechanisms producing rain penetration have been properly controlled and adequate ventilation of the cavity to outside has been provided. Ventilation of the cavity, in addition to aiding in control of rain penetration, permits drying of the outer wythe from both sides. It also acts to transport water vapour out of the wall, promoting a dry condition. Air leakage through the inner wythe must, however, be kept small and water entry to the face materials by contact with the ground or by faulty flashings should not be permitted.

Although ice-lensing has been found to be responsible for many cases of masonry deterioration, the mechanism can be controlled to a high degree by good wall design. As in many building problems the control of water is of vital importance.

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