Modeling the Freeze-Thaw Damage Mechanism in Cement

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PROBLEM

Freeze-thaw (FT) damage is a significant threat to roads and pavement, yet the underlying mechanism is still unclear. Conventional thinking attributes the damage to pressure generated by expansion of water upon freezing. However, this idea fails to explain three phenomena: 1) only above a critical degree of water saturation will FT damage occur; 2) the use of de-icing salt aggravates FT damage; 3) cement mortars loaded with benzene, a fluid that shrinks upon freezing, also experience FT damage. While salt crystallization, which occurrs during freezing, is correlated with damage in some instances, its role still remains unclear.

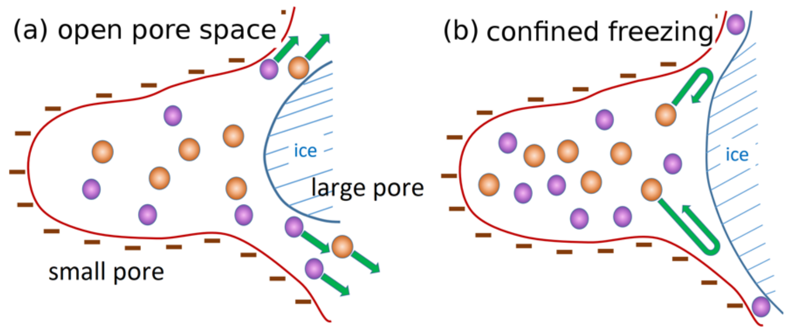

Fig. 1: A schematic drawing of an open pore and possible salt trapping mechanisms. The small spheres represent ions immersed in water. When the surface of a porous network is charged and the channels are narrow, the timescale for transport of salt ions through them can be prolonged, effectively trapping the ions. This concentration of ions lowers the freezing point which, in turn, inhibits the release of pressure.

APPROACH

Our approach to this problem is derived from nano-fluidic devices (ionic diodes, bipolar transistors, etc.) and the theory of electrokinetics. Inspired by these devices, we propose that FT damage is not caused by the expansion of water in the pores at freezing, but rather due to the pressures created by salt ions within the pore water when they are trapped (Fig.1). We further consider how the concentration and crystallization of ions impact the freezing point and pressures exerted.

WHY DOES THIS RESEARCH MATTER?

- Our research corrects common misconceptions about FT damage and proposes a possible mechanism. This theory consistently explains current observations in experiments and fields.
- A better understanding of FT mechanisms can lead to improved mitigation practices, thereby reducing damage due to FT and saving transportation agencies valuable maintenance and rehabilitation dollars.

FINDINGS

Our proposed theory explains the three phenomena mentioned above. 1) If water saturation level is low, the large pores are empty. When freezing occurs salt ions will simply escape with unfrozen water into the larger pores (Fig.1 (a)). 2) Adding de-icing salts increases the salt ion concentration, and larger pressures are generated. 3) If mortar is loaded with benzene instead of water, FT damage still occurs. When either of these fluids occupy the large capillary pores upon freezing, only a narrow lubricant liquid layer remains between the benzene or ice solid and the pore surface. This turns the large open pores into bottlenecks for ions that generate pressures that can easily damage the structure (Fig.1 (b)). There also is generally a belief that salt crystals generate pressure. However, we found that salt crystallization actually releases pressure. During freezing or oversaturation, salt ions crystalize within the pores and the pressure exerted on the pores by the water diminishes. This is illustrated in Fig. 2.

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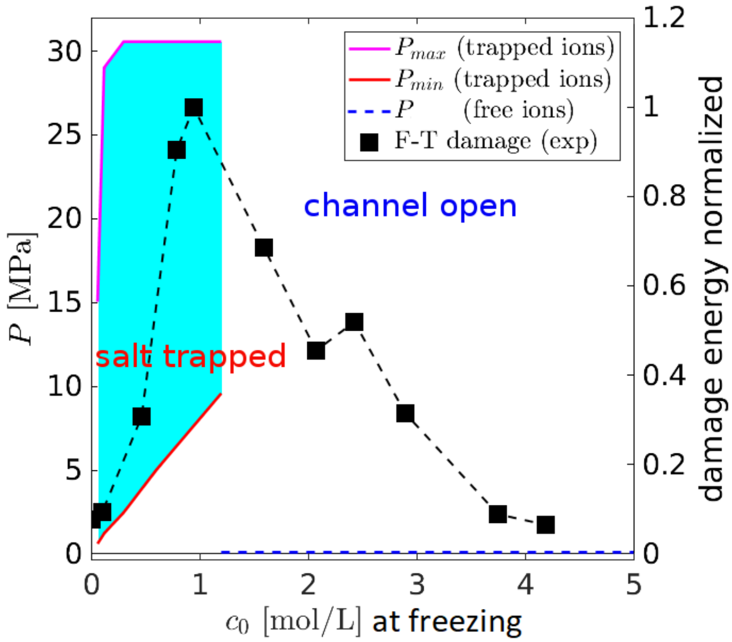

Fig. 2: Salt ion concentration predicts the pressure and damage generated. At a lower salt concentration, trapped salt ions lead to greater pressure and damage. However, as freezing occurs, the ionic concentration can reach a critical point in which the trapping mechanism fails. This reduces the pressure and lessens the subsequent damage.

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