Cryogenic Suction-A Major Salt Scaling Mechanism in Highway Concrete

Zhichao Liu[1], Youngjae Kang[2],Will Hansen[*], Claus Borgnakke[**]
Dept. of Civil and Environmental Engr., University of Michigan, Ann Arbor, MI.

Abstract

Combined salt and frost attack is a major durability problem in concrete highway pavements in the state of Michigan, USA, where road-salts are used extensively for ice melting purposes. Previous studies have shown that continuous measurement of length-change during a freeze-thaw cycle is an effective tool in indentifying frost mechanisms. In this study the focus was to evaluate the cryogenic suction effect on frost expansion. The net frost expansion (linear dilation) was determined by monitoring the change in length of air-entrained concrete specimens undergoing a freeze-thaw cycle between 20 °C and -20 °C. Two dilation processes were found during freezing, an initial dilation at the freezing point (independent of surface exposure liquid), and a subsequent dilation, which is only found when a salt solution is present on the surface. Specimen expansion continues during the entire freezing period, including a 3 hour ramp at constant temperature (-20 °C). This secondary dilation dominates when the surface is exposed to a deicer solution. At constant temperature below initial freezing point, cryogenic suction of surface liquid (i.e., 3% salt solution) was found to be a major factor in sub-zero liquid transport that causes frost expansion in concrete. During this process, air voids are being filled as well and air is being displaced. Some air near the surface can escape. This was observed at -20 °C where escaping air was trapped in the liquid surface layer.

Keywords: Salt scaling; Concrete frost dilation; Air void system; Cryogenic suction pump; Spacing factor.

Introduction

Salt scaling is the progressive tensile cracking of the porous surface paste in contact with a salt solution during freezing. The distress is characterized by mortar flaking of the surface layer. In this study, salt scaling was found to manifest itself as joint spalling, starting at the bottom of a saw-cut joint, where trapped liquid was prevalent in poorly drained pavements combined with low concrete resistance to frost attack due to low air content (Hansen and Kang 2010), as seen in Figure 1.

[*] Corresponding author Will Hansen (whansen@umich.edu), Professor, Dept. of Civil & Environmental Engr., University of Michigan, Ann Arbor, MI 48109
[**] Dept. of Mechanical Engr., University of Michigan, Ann Arbor, MI.

Figure 1. Typical joint deterioration associated with
deicer salt scaling (Hansen and Kang 2010)

Multiple studies have demonstrated that continuous measurement of length changes of concrete during frost cycles is an effective tool for determining the damage mechanisms due to frost action of internally saturated air-entrained paste and concrete (e.g., Buck 1988, Fridh 2005, Kaufmann 2004, Penttala and Al-Neshawy 2002, Powers and Helmuth 1953), while only few studies have investigated frost dilation in the presence of a surface liquid (e.g., Kaufmann 2004, Setzer 1993). In this paper, a high-resolution dilatometer is employed to monitor the continuous length change of concrete prisms subjected to a specified temperature profile between 20 °C and -20 °C.

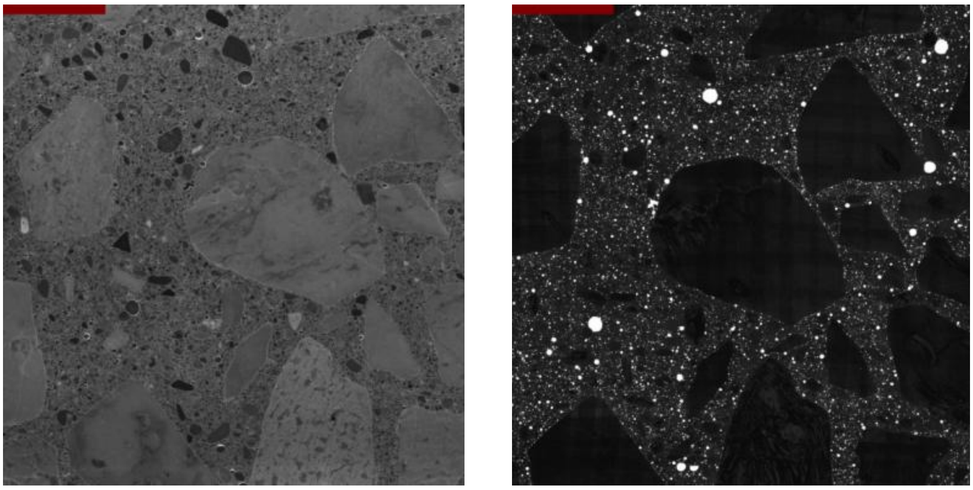
Research Significance

Other studies have shown that the driving force of liquid towards ice front is the Gibbs free energy difference effect, which creates liquid transport from surrounding pore water. Pore drying starts a suction pump, here called cryogenic suction, which attracts liquid from surrounding pores and the surface. The effectiveness of air entrainment in mitigating frost expansion due to cryogenic suction is the main focus of this study.

Experimental

Air void analysis (ASTM C457 2009). Square specimens of 100 mm by 100 mm are cut from the mid-depth portion of 150 mm diameter cores with the testing surface parallel to the pavement surface. Specimens are then carefully polished with silicon carbide abrasives to obtain a smooth surface with undamaged paste and clearly defined air voids. The polished surface is pretreated by filling all the air voids with a white powder and the rest of the surface is darkened by a permanent marker to produce a sharp contrast. Pictures of a prepared sample are shown in Figure 2 and the RapidAir 457 (Jakobsen et al. 2006), an automatic image analysis system, is used to perform the air void analysis.

Air voids in concrete are classified into entrained air and entrapped air (the sum of which is total air). Entrained air voids are usually fine spherical voids compared to more irregular and larger entrapped air voids. There is no agreed criterion to distinguish the two types of air, so in this study, air voids smaller than 500 µm in chord-size are defined as entrained air.



a) Polished surface (b) Coated surface
Figure 2. Specimens treated for air void analysis

Low temperature dilatometer (LTD) test. The preparation and treatment procedures of test specimens are as follows: A 10 mm×10 mm×90 mm prism is cut from a 150 mm×300 mm concrete cylinder. Cutting section is away from the two ends of the cylinder to avoid any in-homogeneity. The prism is dried in the oven at 50 $^{\circ}$C until a constant weight is achieved and then it is pre-saturated with a test solution for about 2 hours, until the rapid rise in moisture uptake has ended and it progresses linearly with the square root of time, indicating a stage of capillary saturation (Fagerlund 2004). To retain a liquid reservoir on the test surface, several sponge segments are pre-saturated with the desired liquid (either de-mineralized water or 3% NaCl solution, which are abbreviated as W or 3%S hereafter) and placed on the surface, then the prism is wrapped to minimize moisture loss. The temperature profile of a LTD cycle is shown in Figure 3.

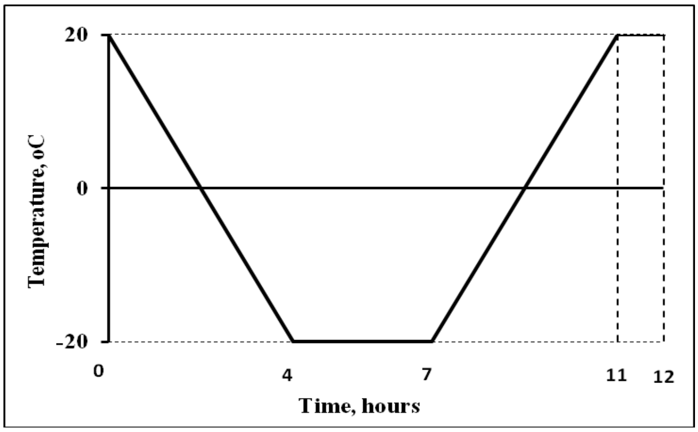


Figure 3. Temperature profile of one LTD cycle

Materials and mix design. A low cement mix is used for the preparation of lab concrete. Several field concretes obtained from a previous project (Hansen and Kang 2010) are also used in this study. The mix design, air void analysis results are listed in Tables 1-3.

Table 1 Mix design of lab concrete

Mix design (kg/m^3)			
Cement	Fine aggregate	Coarse aggregate	Water
222	593	853	100

Table 2 Air void results of field concretes (Hansen and Kang 2010)

Field performance	Paste content (%)	Air content (%)		Specific surface* (mm^{-1})		Spacing factor (μm)	
		Total	Entrained	Total	Entrained	Total	Entrained
Joint distress	21.8	3.86	1.47	16.7	38.3	294	197
	28.6	4.23	2.42	24.7	40.2	215	170
	23.0	3.76	2.49	23.1	32.9	220	212
No distress	24.4	5.72	3.19	23.6	39.5	181	142
	27.1	6.93	4.29	31.5	48.4	124	106
	22.0	8.14	6.5	40.6	49.7	67	68

*The surface area of air voids per unit volume of air.

Table 3 Air void results of lab concretes

Paste content (%)	Air content (%)		Specific surface (mm^{-1})		Spacing factor (μm)	
	Total	Entrained	Total	Entrained	Total	Entrained
25.8	3.02	2.49	33.2	45.9	192	162
24.2	5.07	4.37	45.3	52.5	104	96
26.1	8.08	7.16	53.5	59.9	75	67

Results and Discussions

Continuous length change and temperature measurement. When specimens are exposed to different surface conditions, the characteristics of dilation (positive or negative) are different to various degrees and the profiles of length change of a 3.0% air lab concrete versus both temperature (Figure 4) and time (Figure 5) are plotted in order to provide a more complete view of this process (in the legend, the first letter or word identifies the type of pre-saturation liquid, the second letter or word is the type of surface liquid, if any). In the case of either dry surface or water on surface, only a single dilation is noted, followed by a contraction more than the thermal contraction of the dry specimen. However, a quite different scenario is found in the presence of 3% salt on the surface. In addition to the initial dilation, which now happens at a lower temperature due to surface tension and osmotic effects, a continuous expansion occurs and extends to the end of the constant temperature period. If the total frost dilation causes internal cracking, then a permanent expansion is found at the end of each freeze-thaw cycle.

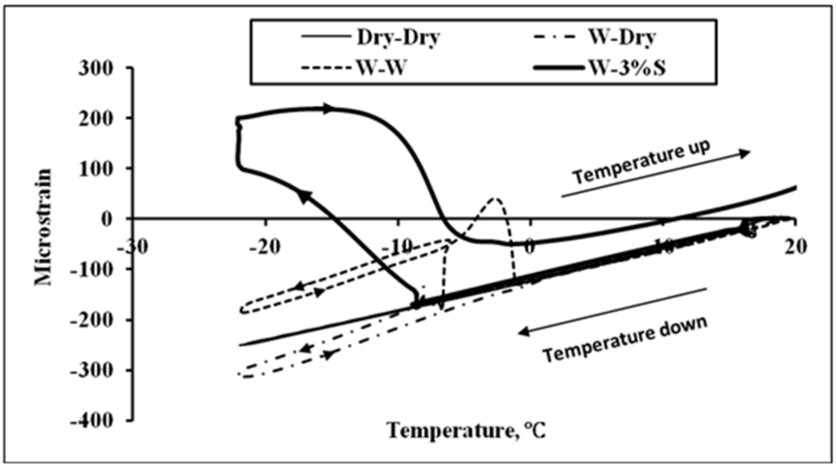


Figure 4. Length change versus temperature of specimens

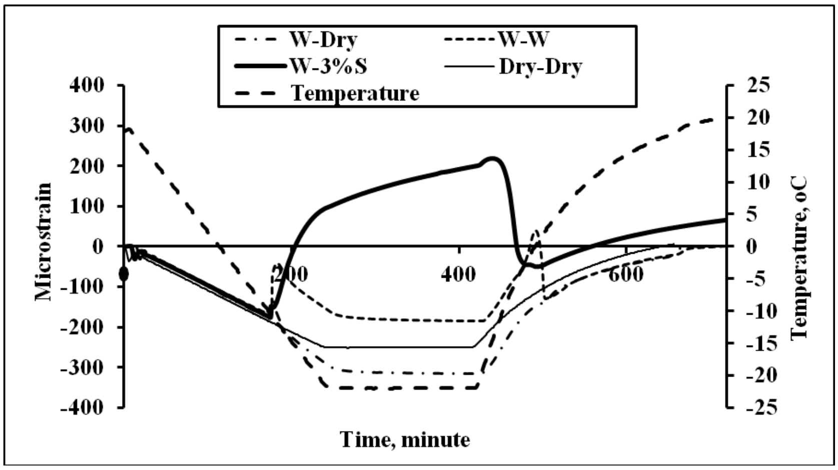


Figure 5. Length change and temperature versus time of specimens

Fridh characterized three types of dilations occurring in one F-T cycle (Fridh 2005), but her work was restricted to moisture-isolated specimens only. Here, we extend this concept to incorporate the significant contribution of external liquid, which is schematically shown in Figure 6. The possible mechanisms behind these dilations are explained below.

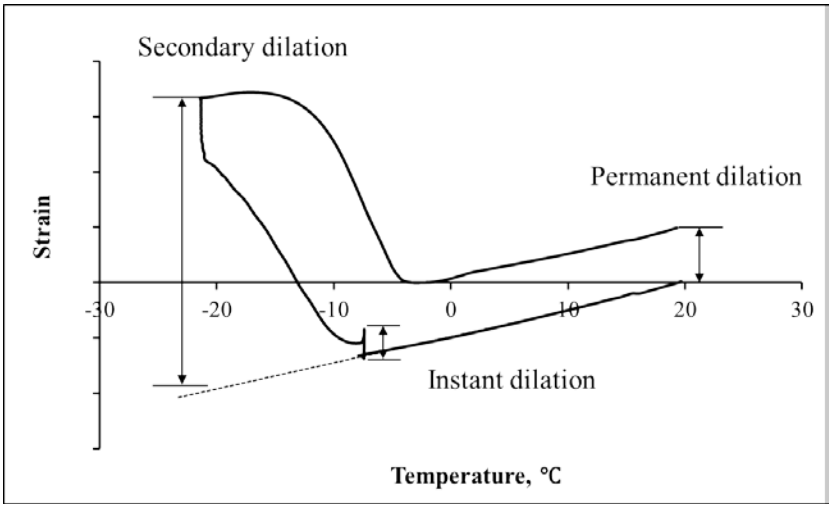


Figure 6. Schematic definition of dilations

(1) Instant dilation. Instant dilation occurs when ice-nucleation starts.
(2) Secondary dilation. A continuous frost expansion due to cryogenic suction develops at temperatures below ice-nucleation point.
(3) Permanent dilation. The permanent dilation is a measure of the magnitude of the irreversible strain, which indicates the cumulative internal damage in concrete.

With salt on the surface, a big secondary dilation is noted at intermediate air contents (e.g., 3.0% total air), and the maximum value usually occurs at -20 °C, the lowest test temperature. Recent theories (Coussy 2005, Coussy and Monteiro 2008, Setzer 2004) for a closed system without a surface liquid suggest that a cryogenic suction pump drives internal pore liquid towards the already frozen pores and this effect is discussed in more details later. The Gibbs free energy of bulk ice is lower than water, which means that the diffusion of moisture towards ice is a spontaneous process; the attainment of equilibrium requires partial drainage in pores neighboring the ice formation sites (Powers 1945), which accounts for a larger shrinkage following the instant dilation in the case of either dry surface or water on surface, where concrete is essentially moisture isolated. When water is present on the surface, it will freeze completely, preceding the internal ice formation, thus no liquid is available from the outside. However, a unique feature of freezing with 3% salt on the concrete surface is that there is always a certain amount of liquid existing in the salt solution as long as the temperature is between the freezing point and the eutectic temperature. As a result, the outside liquid will keep being sucked in and “the drainage required for equilibrium will never be reached” (Lindmark 1998), the ice body can grow continuously.

Effect of air void system on dilation. In concrete, the “shelter spots” are typically entrained air voids and the spacing factor is a measure of the travelling path. The effect of entrained air is well explained by (Lindmark 1998) as that upon cooling, thermal contraction of air can suck liquid into the pores and when the water freezes, it will attract the moisture flow, resulting in water accumulation in the air voids. On melting, the air will expand and expel the water out of the air voids. If the air content is adequate, all the secondary expansion can be absorbed. Otherwise, secondary expansion of varying magnitudes will occur. This is shown in Figures 7 and 8. Both the secondary and permanent dilations are decreased with increasing air contents and a slight shrinkage is even noted in the case of 8.0% air, which is consistent with the explanations.

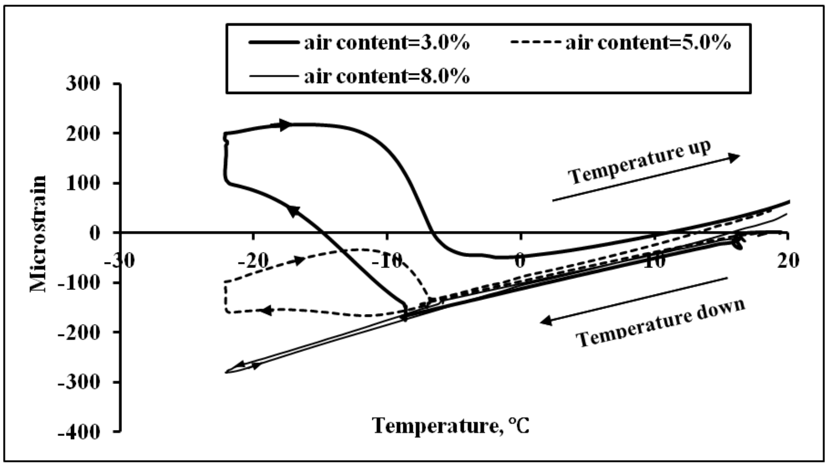


Figure 7. Length change versus temperature of specimens with varying air contents

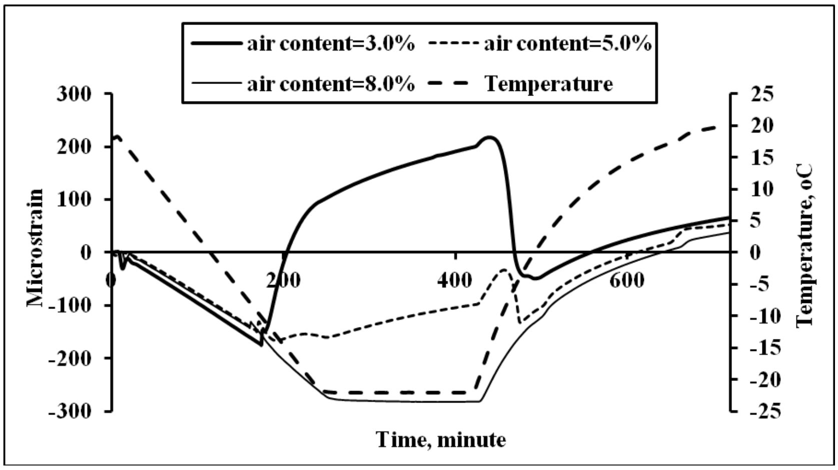
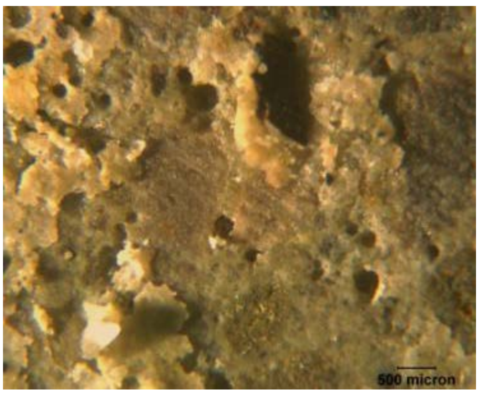
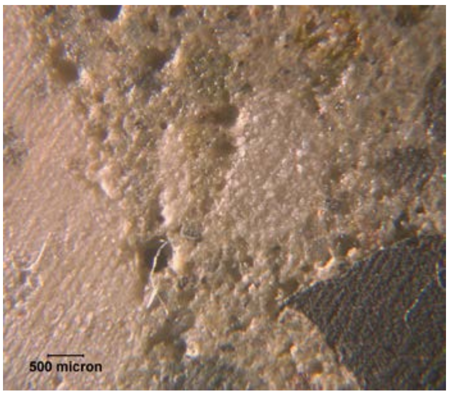


Figure 8. Length and temperature change versus time of specimens with varying air contents

For the low air concrete (3.0% air), surface damage is noted after five LTD cycles. This is because the expansion exceeds the tensile capacity of concrete. As seen from the microscopic pictures (Figure 9a), some of the cement paste is spalled from the surface. However, no visible damage is observed in the case of high air content specimen (Figure 9b).

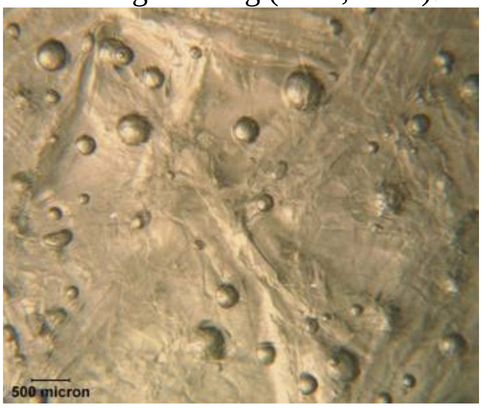




(a). 3.0% air content (b). 8.0% air content

Figure 9. Microscopic pictures of specimens after LTD test

Lindmark hypothesized (Lindmark 1998) that the contracting air-bubbles inside the air-voids create a suction pressure between the bubble and the pore-walls as the temperature is lowered. This in turn accelerates cryogenic suction and ice development inside the air-voids. At a sufficiently low temperature air-bubbles escape through buoyancy. With additional freeze-thaw cycles, an increasing number of air voids will be permanently filled with liquid when the compressed air is pressed out due to severe exposure conditions (Lindmark 1998). This phenomenon is confirmed in our test when specimens are exposed to 3% salt solution, as shown in Figure 10, many air bubbles are trapped below the upper layer ice. Thus the protective effectiveness of air voids is reduced gradually, which is consistent with field experience that more air is needed for frost durability in the presence of a deicer solution during freezing (PCA, 2003).



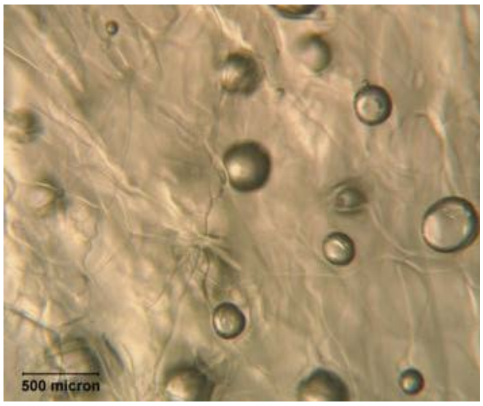
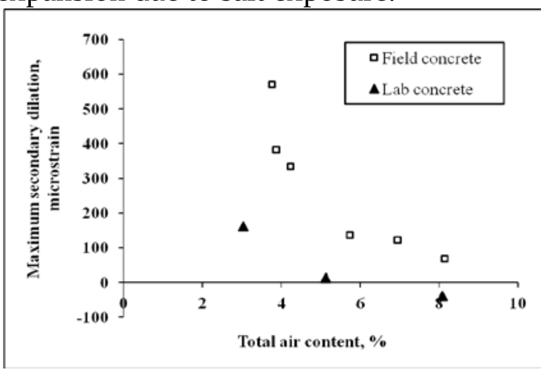
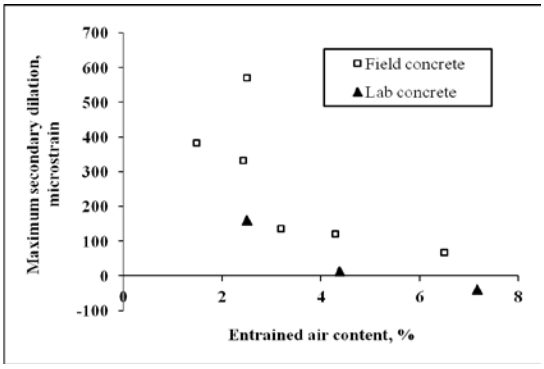


Figure 10. Expelled air bubbles due to the filling of air voids

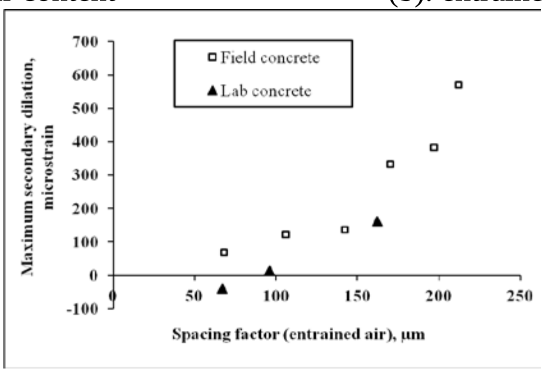
As seen in Figure 11 (a-c) air entrainment is effective in controlling frost expansion due to salt exposure.



(a). total air content



(b). entrained air content



(c). spacing factor (based on entrained air)

Figure 11. Relation between maximum secondary dilation and air content, Powers spacing factor

Cryogenic Suction. Cryogenic suction is the liquid transport within the closed pore system as well as the added liquid transport from a surface liquid (i.e., salt solution) which is occurring once ice formation starts. If only internal transport develops when sufficient air entrainment is present (e.g., 3.0% total air), no secondary expansion develops. If however external liquid is present, then a 3.0% air content is inadequate in curtailing rapid ice-growth resulting in substantial additional specimen dilation. This is seen in Figure 12 for the lab concrete system presented in Figures 4 and 5 when plotting the dilation versus time held at -20 °C. Liquid transport develops once initial freezing occurs and it is driven by differences in Gibbs free energy between the pore liquid, the ice, and surface liquid. If pore liquid is present in small air voids, freezing is spontaneous there as well. This in turn accelerates cryogenic suction and the expulsion of air reaches the maximum at the lowest temperature since the air void has contracted the most. The process slows down as the temperature no longer drops and becomes diffusive in nature as illustrated in Figure 12. In the limit the process approaches thermodynamic equilibrium with only the smallest pores containing liquid and the largest ones containing ice while in the middle range, there is water vapor and air. It is thus hypothesized that the smallest air voids become filled with ice, which aggravates expansion and paste destruction. It is therefore of vital importance that concrete in the joint area of a pavement system is well-drained so that a salt solution is not trapped during freezing.

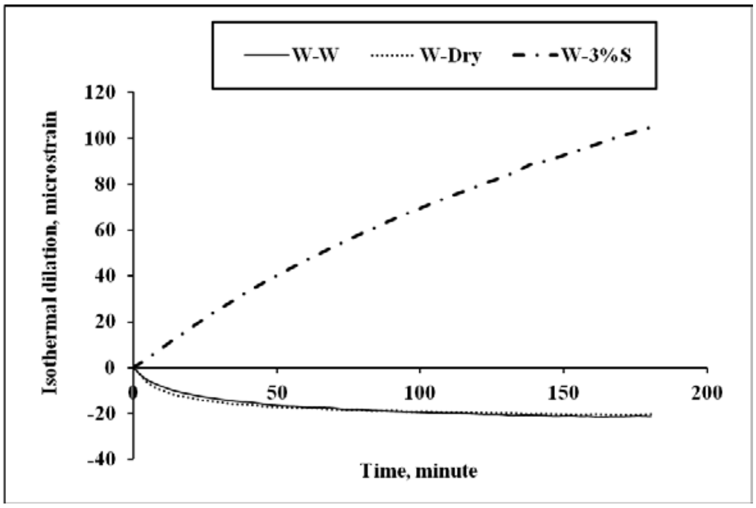


Figure 12. Cryogenic suction effect on specimen dilation in the presence of a surface salt solution

Conclusions

The following conclusions can be made from this paper:

Cryogenic suction associated with surface liquid (3% NaCl solution) at temperatures below initial freezing is a major factor in sub-zero liquid transport that causes frost expansion in concrete.

During this process, air voids are being filled as well and air is being displaced. Some air near the surface can escape. This was observed at -20 °C where air-bubbles were trapped by ice present at the top portion of the salt solution.

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