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Pumping effect to accelerate liquid uptake in concrete and its implications on salt frost durability

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HIGHLIGHTS

- Characteristics associated with pumping effect is demonstrated.
- A major pumping mechanism to accelerate liquid uptake in concrete is proposed.
- Implications of pumping effect on salt frost scaling are elucidated.

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ABSTRACT

Pumping effect is studied by means of bulk moisture uptake in low water-binder (w/b) ratio concrete mixes under freezing-thawing (F-T) exposure. The added absorption is clearly demonstrated under either water or salt exposure with no appreciable difference noted. Air void degassing and subsequent saturation accelerated by the pumping effect is shown to cause void infillings commonly observed in concrete pavement exposed to prevalent freezing weather and deicing procedures in winter. Measured moisture uptake at two different minimum temperatures (−10 °C and −20 °C) indicates equally significant absorption suggesting external moisture forced into the concrete interior upon freezing is a major pumping effect. Concurrent investigation on the cumulative mass loss and internal damage reveals the decoupling of salt scaling and internal frost damage governed by different mechanisms. This is enhanced by the silane and temperature effects on the mass loss and relative dynamic modulus (RDM) change. Silane treatment and a higher minimum temperature (−10 °C) are found to create much less scaling attributed to the restricted ice growth. However, the hydrophobic effect is neutralized by the hydraulic pressure at instant freezing, which maintains the universal pore saturation in concrete and eventually causes cracking.

1. Introduction

Concrete is intrinsically a hydrophilic material and spontaneous moisture uptake occurs when an unsaturated concrete is exposed to a wet environment. Liquid transport has been related to an array of durability-related deterioration issues in concrete structures [1], among which frost damage is a result of the phase transformation and associated moisture movement [2,3]. This degradation problem exists in two distinct forms: the internal bulk damage and the superficial surface scaling [4,5]. Characteristic of the latter is the gradual removal of small pieces of paste/mortar within the surface region less than 300 μm in thickness when exposed to repeated freezing-thawing (F-T) cycles. The severity of damage is exacerbated with the presence of a salt solution on the surface. One prominent feature associated with salt frost scaling is the "pessimum" effect that a low-to-medium salt concentration causes the most severe damage regardless of the type of deicer used for the test (organic or inorganic) [6–10], which suggests the mechanism behind this durability issue is physical, not chemical [9,11,12].

Salt frost deterioration has been recognized as one of the major concerns in concrete structures for a few decades in North America and Northern Europe where freezing temperature is prevalent and widespread use of deicing salts is common in winter [13]. Typical mitigation techniques for this material-related distress include entrainment of sufficient air bubbles [3,4], the re-configuration of the pore structure by lowering the water-binder (w/b) ratio and utilizing supplementary cementitious materials [14,15] or the application of surface treatment to form a barrier against moisture

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ingress [16,17]. However, special caution should be executed when slag is partially incorporated in the mix in that slag has been shown to undermine the carbonation resistance and thus the superficial scaling by coarsening the pore structure [18].

F-T action has been shown to cause additional liquid transport in concrete beyond the isothermal room-temperature condition [8,10,19,20], which is known as the pumping effect. Jacobsen [21] reviewed different mechanisms such as the gradient expulsion of unfrozen liquid by the external ice nucleation upon freezing and strengthened suction associated with thawing. However, most of the results are only based on the weight gain measurement [10,19], with the assumption that internal bulk cracking, another contributor to moisture absorption, is not an issue. There has also been many reports on the added absorption under salt exposure which may account for the role of salt in aggravating the surface scaling [7,22–25] with conflicting conclusions, though.

This paper investigates the pumping effect by bulk moisture absorption, the surface scaling by cumulative mass loss and the internal frost damage by RDM change in sufficiently air-entrained laboratory concrete mixes and one field mix with poor F-T performance in the field. Results will hopefully cast more light into the major mechanism of pumping effect and its effect and implications on salt frost durability.

2. Experimental

Type I Portland cement and grade 120 slag cement were used as cementitious materials and their chemical compositions can be found in [12]. Fine aggregate was silica sand with a fineness modulus of 2.43. Coarse aggregate was lime stone with a 25 mm nominal maximum size. Concrete mixes used for this study had a w/b ratio of 0.33 and a cementitious weight of 390 kg/m^3 and two replacement levels of portland cement with slag cement by weight (25% and 50%), as listed in Table 1. Two commercially available admixtures (superplasticizer and air entrainer) were used. The superplasticizer dosage was maintained at 4.0 ml/kg cementitious material to achieve a slump between 80 and 100 mm. Air entrainer was used at a constant dosage of 1.2 ml/kg cementitious material. One type of silane at a 40% concentration was used as the water repellent agent.

For the mix denotation (e.g. 033-0S-9.3%), the first two parts were the w/b ratio and slag cement replacement level respectively while the last part was the measured total air content on hardened concrete.

The 033-0S-9.3% specimens were beams of 150 mm × 150 mm × 510 mm made in a ready mix plant and delivered to the laboratory after one day, while the other two mixes were prepared in the laboratory. All the specimens were removed from the mould after one day and then submerged in tap water at 20 °C for another 27 days. One field sample obtained from a highway section in Michigan was also tested. Tests started after 28 days. Air void results in the hardened concrete based on the linear traverse procedure in ASTM C 457 [26] and the 28-d compressive strength results based on ASTM C 39 [27] are listed in Table 2.

Resistance of concrete to the combined attack of de-icing salt and frost is evaluated by a modified CIF (Capillary suction, Internal damage and Freeze-thaw) method [12] with both water and 3% NaCl solution as the test liquid, where the moisture uptake by weight gain, surface scaling by cumulative mass loss and the internal damage by relative dynamic modulus (RDM) were measured simultaneously. Specimens with a dimension of 100 × 100 × 70 mm were cut from the beam using a wet cutting saw and were then dried in the oven at 50 °C for 3–4 weeks until near constant weight was achieved. For untreated specimens, the lateral surfaces were sealed by the aluminum foil with butyl rubber. This was followed by one-week presaturation with the test surface immersed in demineralized water by 5 mm in a stainless container. For silane treated specimens, two different regimes were adopted. For regime 1, the silane was first applied to the test surface of the pre-dried specimens before the presaturation test. Silane application involves two-time brush coating with an interval of 6 h. For regime 2, tape-sealed specimens were presaturated for 7 days. Then only the test surface was exposed to air drying at 20 °C and 60 ± 5% RH for ∼6 h before silane application. The moisture loss during drying was registered. Sufficient curing period was followed after silane application for both regimes.

The preconditioned specimens were then positioned the same way as the presaturation procedure with the test surface exposed to water or 3% NaCl solution. The containers were placed in the environmental chamber subjected to a specific F-T cycle. After a certain number of F-T cycles, measurement commenced during the one-hour isothermal stage, involving the collection of scaled-off materials, the weighing of test specimen and the transit time measurement at two directions. Mass loss was represented as the normalized weight of dried scaled-off materials at 105 °C with respect to the test surface area. Moisture uptake was calculated from the weight measurement of the specimen and the scaled-off materials. The moisture content of the scaled-off materials was assumed to be the same as that of the bulk. Detailed computation procedure was listed in [28]. RDM was calculated from the ultrasonic transit time in the coupling medium (typically water at 20 °C) by a Pundit Plus ultrasonic digital indicating tester with 54 kHz transducers.

3. Results and discussion

3.1. Pumping effect in concrete under F-T exposure

Weight gain in tested specimen under F-T exposure is a reliable and commonly used method to register the pumping effect. Fig. 1 presents the moisture uptake profile against the square-root of time based on weight gain measurement during the isothermal presaturation stage (20 °C) and the F-T cycling stage. The isothermal presaturation profile starts with a rapid and linear development followed by a smooth transition into a polynomial pattern, the first part being attributed to the rapid capillary absorption in well-connected pores while the latter part being a result of the slow uptake in the poorly-connected pores [5,20]. Once F-T test commences, pumping effect manifests itself in the immediate

Table 1
Mix design of concrete.

Mix	Mix proportion (kg/m^3)				
	Portland cement	Slag cement	Fine aggregate	Coarse aggregate	Water
033-0S-9.3%	390	0	672	1068	129
033-25S-7.1%	262	129	691	1106	129
033-50S-8.4%	195	195	690	1103	129
Field concrete	290	0	775	1116	122