A-2-2 Silane treatment on the salt frost durability of concrete: Its effect and implications

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ABSTRACT: Silane treatment is a common technique to minimize water penetration into concrete and reduce the risk of moisture induced damage. This paper aims to evaluate the effect of freeze-thaw (F-T) action on the silane treated air-entrained concrete including moisture uptake, internal bulk cracking, surface scaling. It is found that moisture uptake, although substantially decreased under room-temperature exposure, is accelerated immediately after F-T test begins. This is accompanied by gradual reduction in relative dynamic modulus of elasticity (RDM) and ultimately results in the disintegration of the bulk specimen. This is because the hydrophobic effect is cancelled by the enhanced absorption associated with the F-T pumping effect. However, the exposed surface shows limited scaling until the disintegration occurs which results in the removal of coarse aggregate particles on the surface. The decoupling of surface scaling and internal damage demonstrates that the major mechanisms governing the two durability problems are different, the former being dominated by the cryogenic suction while the latter being controlled by the universal saturation of the pore structure.

KEY-WORDS: Silane treatment, frost durability, moisture uptake, surface scaling.

INTRODUCTION

Concrete is intrinsically a hydrophilic material and spontaneous moisture ingress occurs when an unsaturated concrete specimen is exposed to moisture. This has caused an array of durability-related deterioration problems in concrete structures [1]: water saturation of concrete leading to frost damage; migration of chloride ions causing the corrosion of reinforcements; ingress of sulfate inducing detrimental expansion, in correlation with the alkali-aggregate reaction (AAR), carbonation, etc.

When concrete is subjected to a freeze-thaw (F-T) condition, two distinctive deterioration problems can occur [2-4]: (1) internal damage with loss of strength and structural integrity due to freezing of internal moisture; (2) surface scaling with progressive removal of superficial mortar particles or flakes. Surface scaling only occurs when moisture is present on concrete surface and it is substantially exacerbated when exposed to a moderate salt solution [5].

Hydrophobic surface treatment has been proven to be an effective technique to minimize moisture transport into concrete and its effect on durability improvement and service life extension is well-documented [6-9]. Silanes are one of the most common surface treatment agents for concrete structures. They fall into the category of pore liners and can easily penetrate capillary pores due to their small molecular size (1-2 nm) [8], which substantially reduces capillary suction.

In this paper, the effect of hydrophobic surface treatment by silanes is evaluated in concrete specimens prepared in the laboratory and obtained from the field. The deterioration mechanism is explained by measuring mass loss, moisture absorption and internal damage in a salt scaling test, along with simultaneous measurement of sub-freezing length change on small-scale concrete specimens.

EXPERIMENTAL

Commercially available Type I portland cement and grade 120 slag cement were used as cementitious materials. Fine aggregate was silica sand with a fineness modulus of 2.43. Coarse aggregate was limestone with a 25 mm nominal maximum size. A 40% silane-based water repellent agent was used for surface treatment of concrete specimens. It is has a specific gravity of 0.947-0.957 and its application will not alter the appearance of concrete surface. Field concrete samples were used for F-T test with a total air content of 2.80% and a Powers' spacing factor of 207.

Resistance of concrete to the combined attack of de-icing salt and frost is evaluated by CIF (Capillary suction, Internal damage and Freeze-thaw) test [10], where the moisture uptake by isothermal suction, surface scaling and the internal damage are measured simultaneously. For untreated specimens (~10×10×7cm), the lateral surfaces were sealed by aluminum foil lined with butyl rubber. This was followed by one-week water presaturation, the test surface immersed in 5 mm demineralized water. 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 involved two-time brush coating with an interval of 6 hours. For regime 2, specimens with the lateral surface tape-sealed were presaturated for 7 days. Then only the test surface was exposed to air drying at 20 °C and 60±5% RH for ~6 hours before silane application. The moisture loss during drying was registered. Sufficient curing period was followed after silane application for both regimes. Preconditioned specimens were placed in an environmental chamber exposed to demineralized water or 3% NaCl solution.

RESULTS AND DISCUSSION

Bulk moisture uptake in silane treated concrete under F-T exposure

Fig. 1 shows the bulk moisture uptake regularly measured during both the 20 °C isothermal pre-saturation stage and the F-T stage for specimens with and without silane treatment under two exposure conditions (water and a 3% salt solution). In the case of control specimens with no surface treatment, there is initially a rapid increase in moisture uptake showing linear pattern with the square-root of time, which is a clear sign of capillary suction. This is followed by a well-defined transition point indicating the saturation of the connected pores [4]. Moisture uptake then levels off even during the initial stage of the F-T test. When silane is applied on the exposed surface, moisture absorption is substantially suppressed in the presaturation stage with the sorptivity reduced from 0.73-0.94 mm/hour$^{0.5}$ to 0.06 mm/hour$^{0.5}$. This hydrophobic effect is illustrated by the evolution of a water droplet on a treated surface which maintains its shape with time while the other one on an untreated surface gradually disappears by penetrating into the concrete (Fig. 2). This can be attributed to an increase in the contact angle that reduces the negative capillary force and can be modelled by the cumulative moisture uptake curves using Eq. (1). As shown in Fig. 3, the absorption rate is reduced at a higher contact angle.

$$\mathrm{Q}(\mathrm{t}_j) = \mathrm{P}_{\mathrm{paste}} \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{V}(\mathrm{r_i})\mathrm{x_i}$$

where, $\mathrm{x_i} = ((\sigma r_i \cos\theta)/2\eta)^{0.5} \cdot t_j^{0.5}\ (when\ \mathrm{x_i} < h)$ and $\mathrm{x_i} = h\ (\text{when } \mathrm{x_i} \geq h)$, $\mathrm{Q}(\mathrm{t}_j)$ is the cumulative moisture uptake at time t_j, $\mathrm{P}_{\mathrm{paste}}$ is the paste content, $\mathrm{V}(\mathrm{r_i})$ is the pore volume fraction of the pore size $\mathrm{r_i}$.

Once F-T test commences, moisture uptake is accelerated regardless of the exposure condition, which suggests the barrier created by silane is overcome. This is consistent with other studies [7, 12]. This acceleration may be attributed to a "pumping" effect [13] that the expulsion during the initial freezing and the enhanced suction during thawing is able to overcome the reversed pressure difference from the hydrophobic effect.

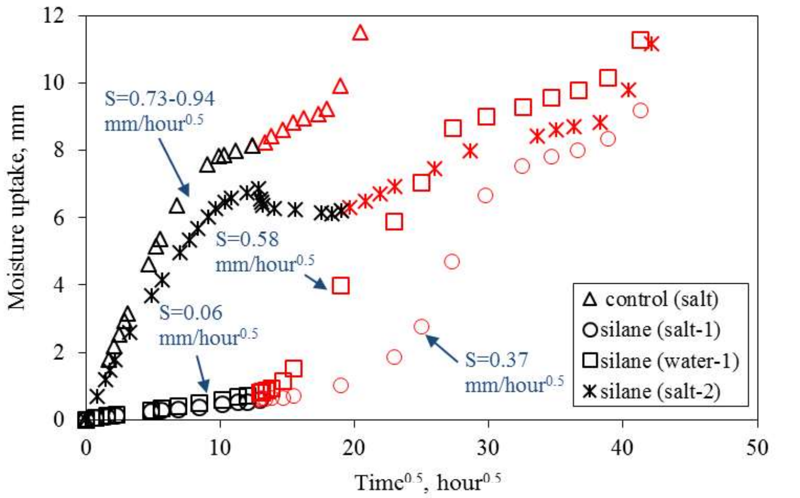

Fig.1. Moisture uptake in concrete with and without silane treatment under water and salt exposure (black curves are the presaturation and drying stages while red curves are F-T stage).

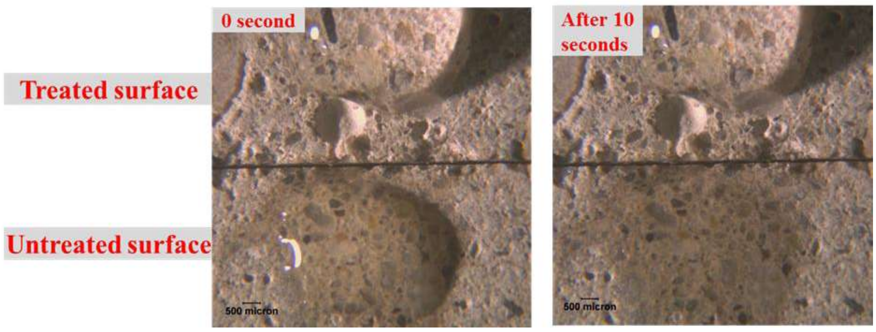

Fig.2. Hydrophobic effect from silane treatment

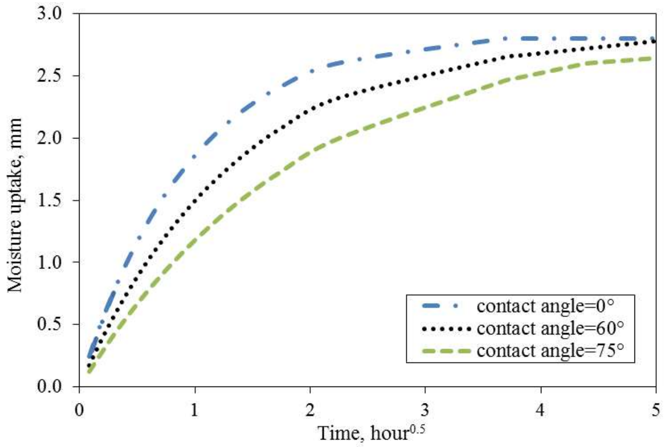

Fig.3. Modelled moisture uptake in concrete affected by the contact angle parameter.

Effect of silane on salt frost durability of concrete under F-T exposure

The mass loss and changes in the relative dynamic modulus of elasticity (RDM) with F-T cycles were measured concurrently with moisture uptake, as shown in Fig. 4. Untreated specimens are characterized by a significant increase in mass loss. When the critical saturation point is reached, internal bulk cracking sets in, evidenced by the sharp decrease in RDM and the presence of cracks propagating to the top unexposed surface (Fig. 5(a)). This leads to an increase in moisture uptake (Fig. 1) and the removal of a chunk concrete piece on the exposed surface (Fig. 5(b)). Thus a sharp rise in mass loss is noted. Silane application almost completely eliminates mass loss up to 100 F-T cycles. The gradual increase after 100 F-T cycles is a result of the localized spalling associated with pore over-saturation, as demonstrated by the corresponding decrease in RDM.

It has been suggested that salt scaling and internal frost damage are governed by different mechanisms [10, 14]. Salt scaling is caused by the excessive ice growth in the surface region promoted by the cryogenic suction of unfrozen surface liquid [11] while internal bulk damage is a result of oversaturation in the universal pore system. This is further supported by the fact that specimens of the same degree of saturation (silane (salt-2) and control (salt)) show very different performance in mass loss (Fig. 1 and 4).

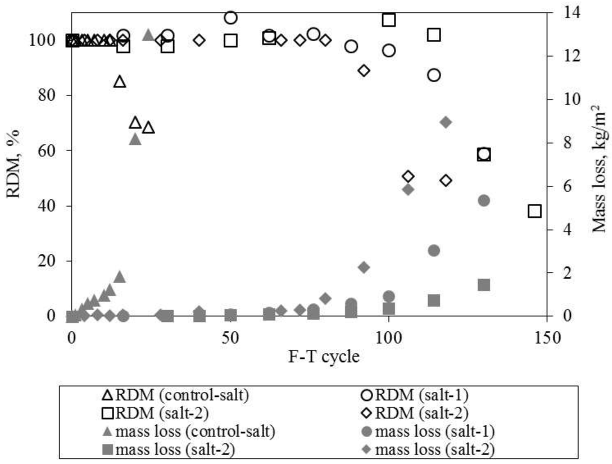

Fig.4. Relative dynamic modulus of elasticity (RDM) and mass loss development in concrete with and without silane treatment under water and salt exposure.

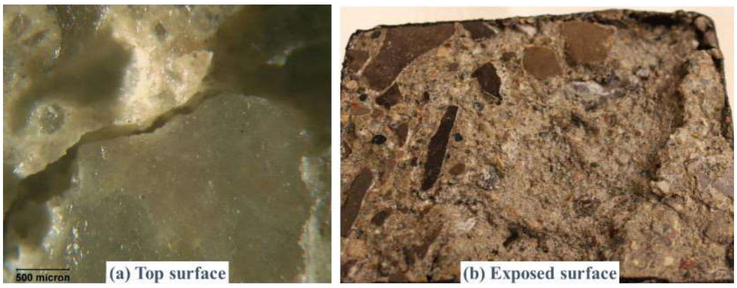

Fig.5. (a) Exposed surface showing the removal of a chunk concrete and (b) top surface showing the propagation of cracks

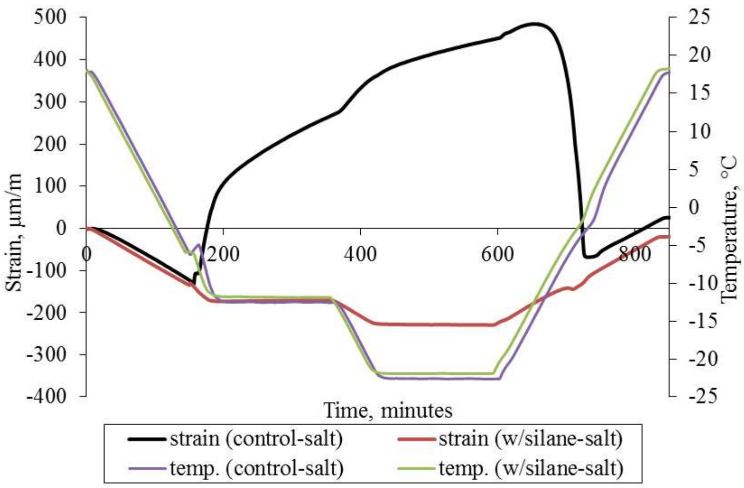

Fig.6. Length-change result on the lab concrete specimen surface treatment and two exposure conditions.

The decoupling of the two deterioration problems stems from the associated sequence of events during F-T exposure. Cryogenic suction occurs once ice forms in the pores, indicated by the continuous dilation in the LTD test after the freezing point (Fig. 6). This process extends throughout the sub-freezing stage until thawing commences. Thus salt scaling is a slowly-occurring process, consistent with the finding that a lower freezing rate causes more severe scaling [14]. Silane remains effective in the sub-freezing stage to prevent the cryogenic suction as illustrated by the suppressed specimen dilation in Fig. 6. Thus mass loss is reduced. Nevertheless, internal bulk cracking is controlled by the hydraulic pressure associated with the instant freezing of pore water which is more of a transient phenomenon. The pumping effect during instant freezing and thawing negated the hydrophobic effect, causing the gradual pore saturation and ultimately leading to cracking. It is worth noting in Fig. 1 that the critical saturation point as indicated by the rapid moisture uptake is very close between four different scenarios.

CONCLUSIONS

The present study investigates the bulk moisture absorption, mass loss and internal bulk damage of concrete mixes with and without silane treatment. Hydrophobic surface treatment by silanes is effective in practically eliminating over 90% of the surface scaling in a highly deicer scaling susceptible concrete (i.e. high water/cement ratio) while the cumulative bulk moisture absorption during the F-T exposure is not related to how much scaling occurs, but is related to the internal bulk damage. This elucidates the decoupling of salt scaling and internal frost damage which are governed by different mechanisms.

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