INVESTIGATION OF THE EFFECT OF THE INTERFACIAL ZONE ON JOINT DETERIORATION OF CONCRETE PAVEMENTS

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Abstract

Some sawn joints in concrete pavements are deteriorating faster than desired in cold weather states. It is becoming clear that a significant factor causing the distress is the freezing and thawing of saturated concrete that contains a marginal air system and a high water to cement ratio, combined with the effects of non-NaCl deicing salts.

Typically, freeze-thaw damage is evidenced in the form of layers of small flakes, as water cyclically penetrates a few millimeters into the surface, then freezes, and expands. However, the distress in pavements is sometimes exhibited in the form of cracks that appear and grow about one inch from the free surface. These cracks are observed to go around the coarse aggregate leaving it clean with little or no cement paste adhering to it.

It is hypothesized that a mechanism for this observation is that when joints are saw cut, the cut aggregate face exposes the interfacial transition zone (ITZ) around the particle. If water is held in the saw-cuts, it can be wicked around the coarse aggregate particles through the ITZ. Subsequent freezing and dissolution of the soluble calcium hydroxide in the ITZ will cause cracking around the coarse aggregate particles until the stress field drives a vertical crack up to the surface about one inch from the sawn edge. Once the now-loose piece is removed by traffic loading, the cycle is repeated.

This paper describes an experimental program aimed at investigating this hypothesis. Factors influencing concrete ITZ evaluated in this study include w/cm, aggregate type, and addition of silica fume. A significant increase of both absorption and air permeability were observed with higher w/cm.

Introduction

Sawn joints in concrete pavements are deteriorating faster than expected in the middle region of the United States. The damage is typically observed in two different forms: one that looks like typical freeze thaw distress with small flakes being formed in the paste; and another in which vertical cracks form about an inch away and parallel to the joint face.

The freeze thaw mechanism is typically associated with pavements that contain marginal air-void systems and are exposed to abundant water – either through insufficient drainage in the base layer, or due to water being trapped in saw cavities. This mechanism has been thoroughly investigated by Weiss et.al. (Li, Pour-Ghar, Castro and Weiss 2011, and Spragg, Castro, Li, Pour-Ghaz, Huang and Weiss 2011). Their work has shown that saturated concrete is unable to resist cyclic freezing and thawing, regardless of the air content of the mixture. Entrained air helps to slow the rate of saturation, while the presence of some deicing salts will tend to attract water thus increasing saturation.

The other mechanism is less well understood because while a crack is forming remote from the joint face, the concrete in between is often in good condition. Typically the crack will form around the coarse aggregate leaving it unusually free of mortar. A possible explanation for this is that a saw cut through a piece of aggregate exposes the interfacial transition zone (ITZ) around the particle. Water or salt solution in the joint may absorb into the ITZ forming a thin layer around the aggregate. Subsequent freezing of water in the ITZ will cause expansion that will tend to separate the aggregate from the paste and drive a vertical crack up to the surface (Figure 1). Some field examples show evidence of water movement along cracks as shown in **Figure 2**.

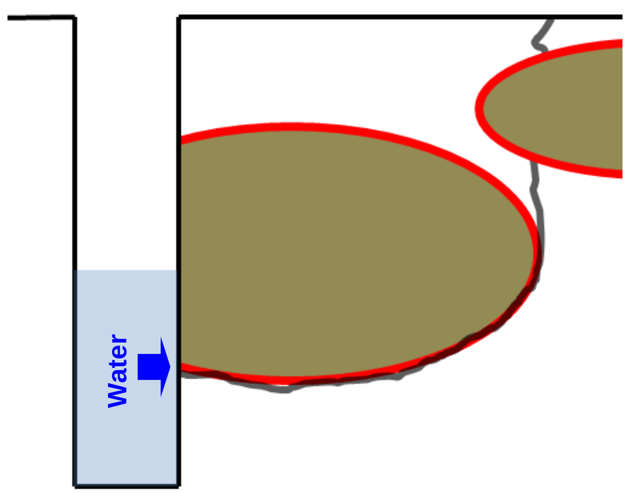

Figure 1. Crack developing out of a saturated ITZ

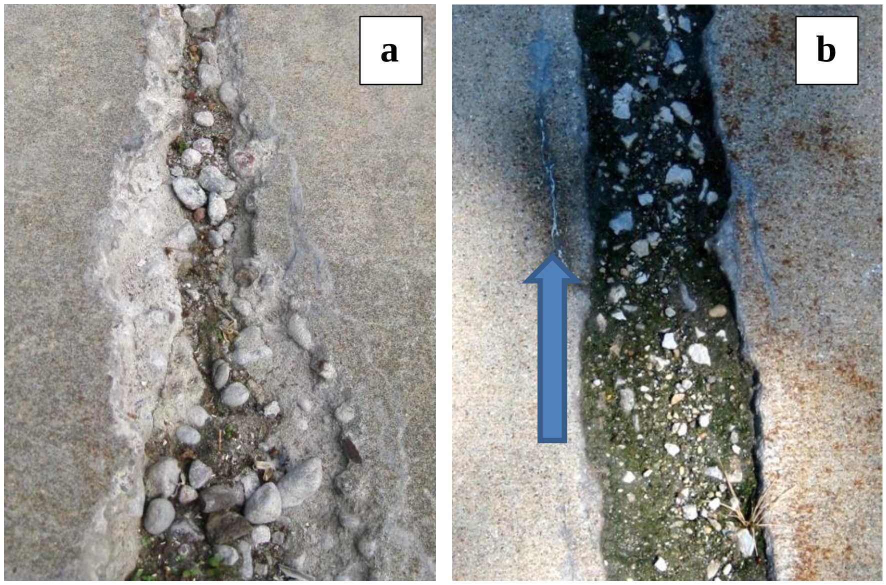

Figure 2. Field observations of joint deterioration (a: polished aggregates due to cyclic freeze thaw; b: water coming out of crack)

This paper discusses experimental work conducted to investigate the feasibility of this hypothesis.

Interfacial Transition Zone

The interfacial transition zone (ITZ) in concrete is a thin zone of paste around aggregate particles that has different characteristics from the bulk paste. According to Mehta (1986), the ITZ is typically 10 to 50 μm thick and is weaker than either of the two components of concrete. Under loading, micro-cracking will propagate more easily around the aggregate leading to reduce concrete strength. However, if the bonding between the aggregate and the paste is relatively strong, the failure surface may go through the aggregate rather than around the aggregate. The ITZ is also reportedly more permeable than the bulk paste, thus leading to reduce durability of the concrete, particularly if the aggregate is exposed to the environmental (Cwirzen and Penttala 2004).

The ITZ has a reportedly complex structure (Prokopski and Halbiniak 2000). Large flat $Ca(OH)_2$ crystals formed within this structure, perpendicular to the surface of aggregate grains, which results in the formation of a highly porous structure in the cement paste. The size and concentration of crystalline compounds such as calcium hydroxide and ettringite are larger in the ITZ than the bulk cement paste which leads to lower strength of the ITZ than the bulk cement paste in concrete (Mehta 1986). This information is consistent with the fact that the microcracks initiate within the ITZ and propagate to connect with each other when concrete is loaded.

Several factors influence the size of the ITZ. A common means of reducing the influence of the ITZ is to include silica fume in the mixture (Andrzej and Vesa, 2004). Use of 10% of silica fume in concrete reportedly results in a reduction of 36% in the thickness of the ITZ (Rossignolo, 2006). Silica fume particles strengthen the ITZ structure by consuming calcium hydroxide in a pozzolanic reaction (Vivekanandam and Patnaikuni 1997; Zhang, Lastra and Malhotra 1996). The mechanisms behind this reduction include:

- Reduced bleeding, leading to reduced water accumulation at the aggregate surface
- Presence of multiple nucleation sites for crystallization to start
- Accelerated pozzolanic reactions because of the extremely small particle sizes of silica fume.

Reducing water cementitious materials ratio will also reduce the width of the ITZ. Andrzej and Vesa (2004) reported that the width of the ITZ decreased from 40 μm to less than 5 μm as the w/cm was changed from 0.42 to 0.30.

A third factor that influences performance is the aggregate. The larger the size of aggregate in concrete and the higher the proportion of elongated and flat particles the weaker the ITZ (Mehta 1986). Elongated aggregate shapes resulted in lower aggregate contents being required for ITZ percolation than spherical ones, which decreases the ITZ volume and reduces the effects of ITZ connectivity on transport coefficients (Bentz et.al. 1995). It is also likely that the mineralogy of the aggregate will affect the ITZ due to variations in surface absorption and reactivity.

Experimental Design

An experimental program was conducted to investigate whether the ITZ is a contributing factor to the premature deterioration of joints in concrete pavements. The approach was to prepare a series of mixtures with differing amounts of silica fume, w/cm, and aggregate type, and subjects them to an ASTM C666 testing freeze thaw test environment followed by examination of the tested samples using optical and electron microscopy. The parameters that were fixed and varied are shown in Table 1.

Table 1. Design mix parameters

Variables	
w/cm	0.40 and 0.50
Binder	0, 3 and 5% silica fume
Coarse aggregate	Round gravel and crushed limestone
Fixed parameters	
Binder content	564 pcy
Air content	6±1%
Fine aggregate	River sand

Samples were wet cured for 14 days and then dried for 28 days prior to the start of testing.

The following tests were conducted:

- Sorption according to ASTM C1585 using two specimens prepared from one cylinder: one from the finished surface and another cut from deeper in the cylinder.
- Air permeability (API) testing was conducted using the University of Cape Town Method. Samples were similar to those used for sorption testing.
- Freeze thawing testing was conducted in accordance with ASTM C666 procedure A. Two beams were prepared from each mix. Two extra beams were prepared for the mixtures containing with gravel, high water cement ratio and non-silica fume and the mix with limestone, low water cement ratio and high silica fume content for testing in 3% sodium chloride solution.
- After testing the two beams cycled in NaCl were split and sprayed with silver nitrate to map the chlorides distribution in the cross section. Chloride distribution was also investigated using an SEM in previous research on concrete beam experienced 300 freezing and thawing cycles under calcium chloride solution.

Results and Discussion

The initial rate of absorption and secondary rate of absorption were obtained for each tested sample as shown in Figure 3 and Figure 4. Samples with higher w/cm show significant higher absorptions than those with lower w/cm. Concrete made using gravel has slightly higher absorption than the concrete with limestone, and there is no clear trend in the influence of the silica fume on the absorption of concrete.

The finished surface samples have higher initial and secondary rates of absorption than the sawn surface samples. This likely due to effects of

- Increased surface area of the rough finished surface
- Increased paste content at the surface
- Possible reduced hydration at the surface

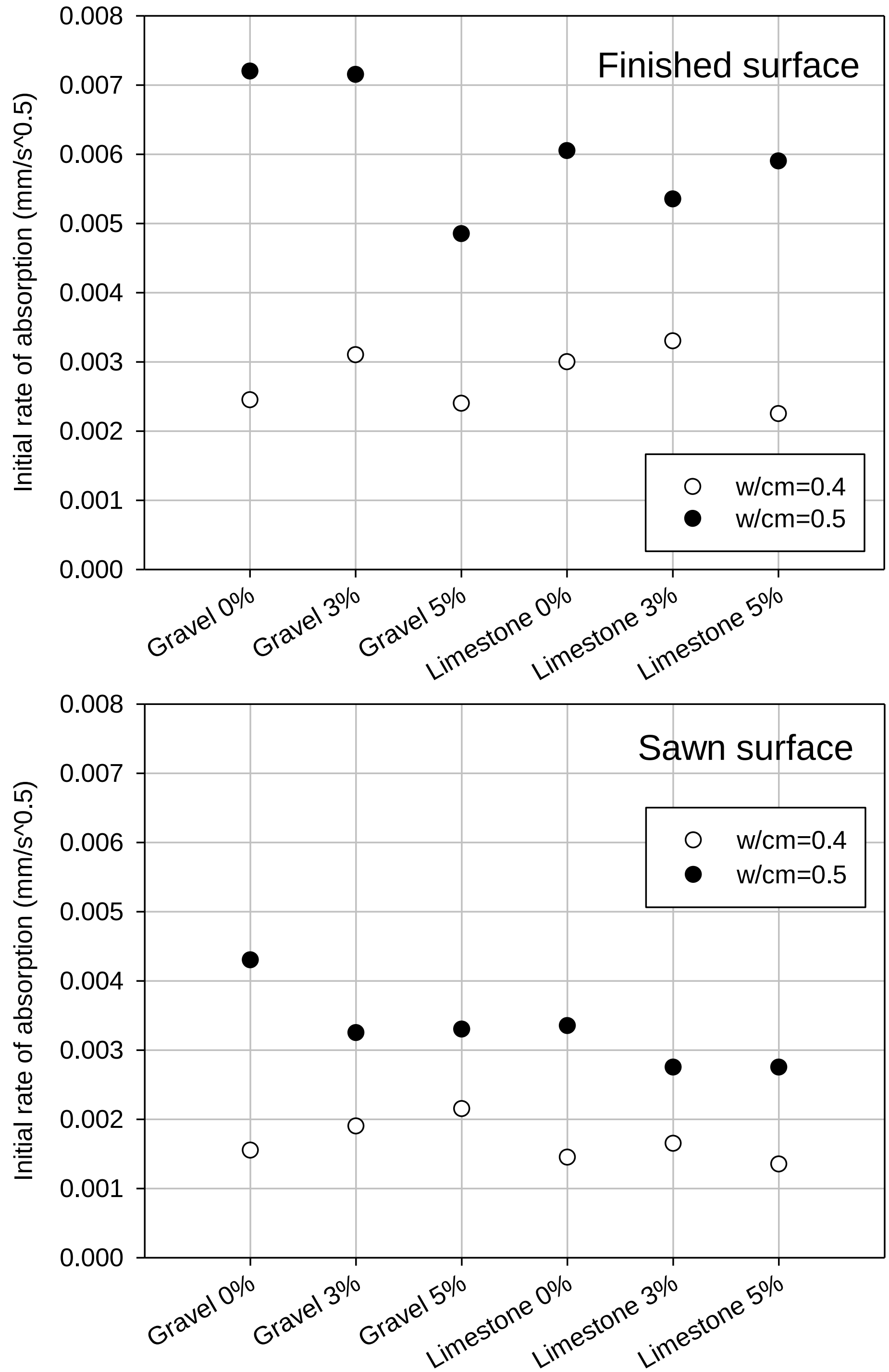

Figure 3. Initial rate of absorption for finished surface samples and sawn surface samples

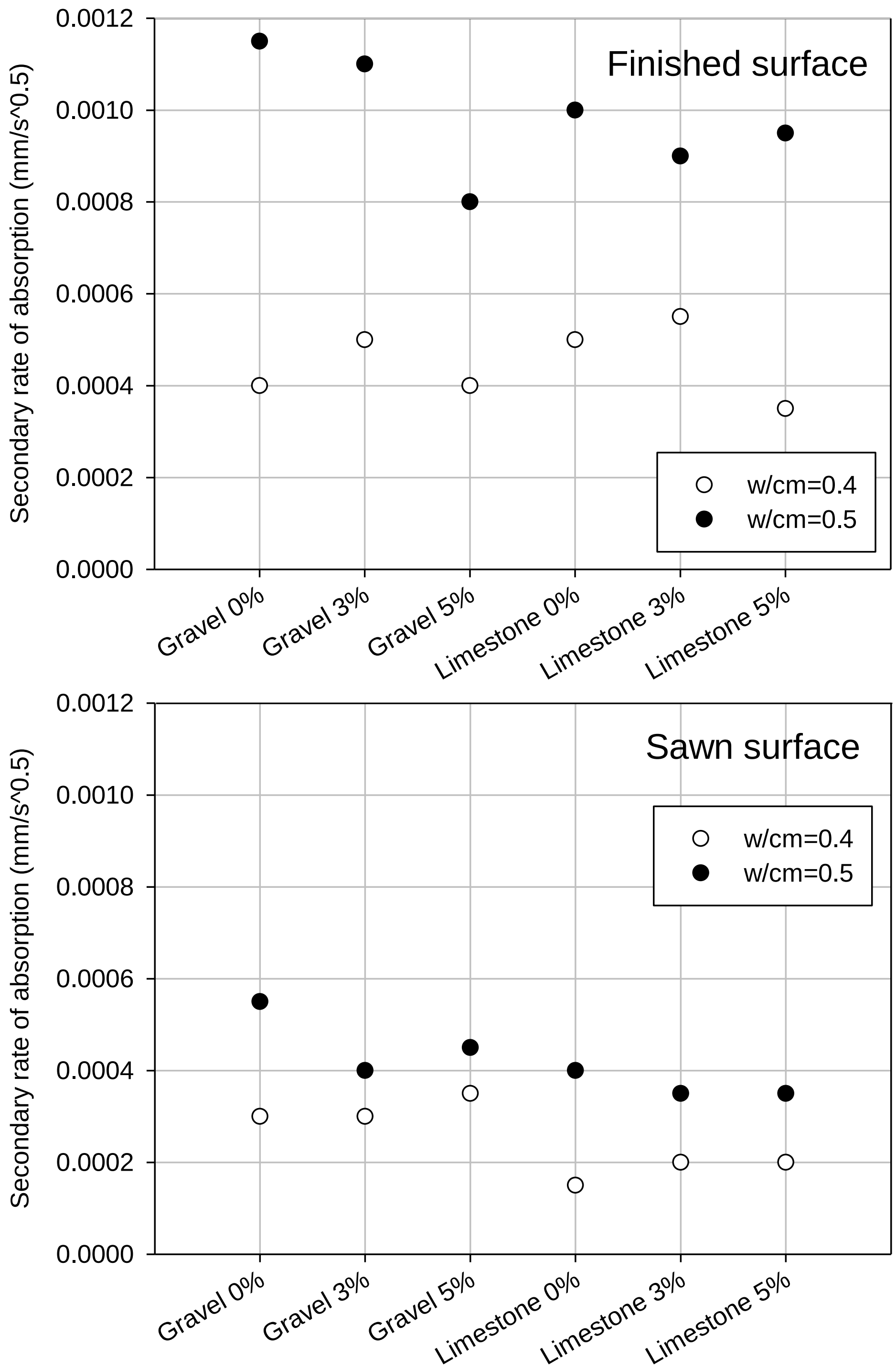

Figure 4. Secondary rate of absorption for finished surface samples and sawn surface samples

The air permeability tests results are shown below in Figure 5. Samples with lower w/cm have higher API indicating less permeable concrete. The API data does not show any significant differences with changing silica fume content. Samples using limestone have higher (better) API values than samples using gravel. Concrete with low w/cm using limestone leads to lower permeability than concrete with high w/cm using gravel. No significant differences were observed in terms of the different surface type of the evaluated samples.

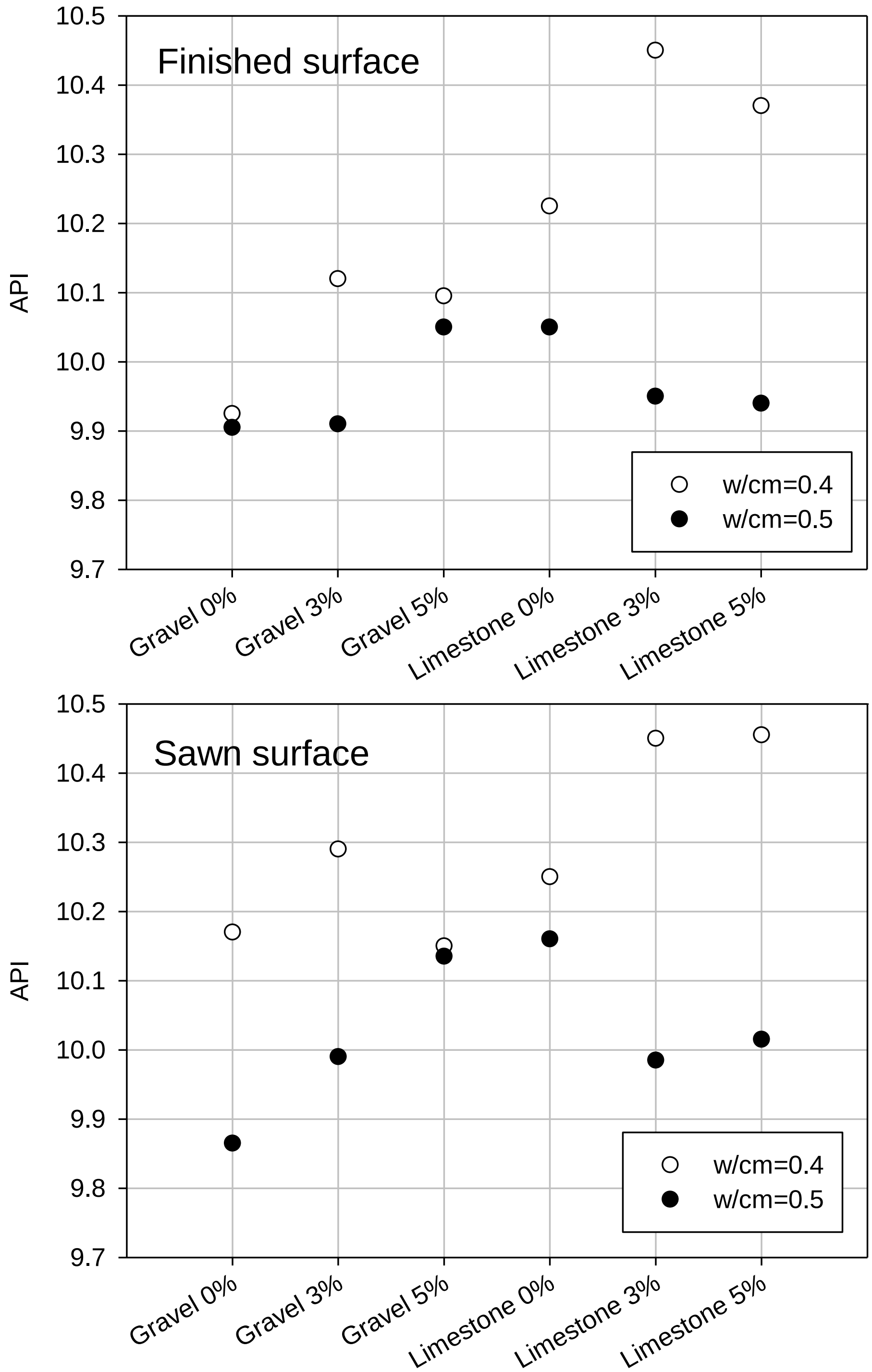

Figure 5. API of the finished surface samples and sawn surface samples

Freeze thaw tests were conducted for 300 cycles. Both weight and dynamic modulus were measured after every thirty freezing and thawing cycles. No significant differences, or distress, were observed except for the beams containing gravel tested under the salt solution which exhibited popouts. This is believed to be a function of the quality of the aggregates and not of the paste or ITZ.

Concrete beams tested under salt solution were further investigated using silver nitrate to map the distribution of chloride on a face perpendicular to the length of the beam. Two slices were cut from each beam. One slice was sprayed with silver nitrate after the surface dry out after cyclic testing was completed, and the other was vacuum saturated under salt solution prior spraying silver nitrate.

Some locations show a narrow “white ring” around the aggregate as shown in Figure 6, which indicated the salt solution preferentially penetrated into the ITZ. The sample limestone aggregate show fewer “white rings” than the sample mixed with gravel. The sample mixed with gravel had a higher w/cm without any silica fume, all factors likely leading to a more dominant ITZ.

Figure 6. Silver nitrate sprayed samples for mapping chloride (a: concrete mixture using gravel; b: concrete mixture using limestone)

If such porous ITZ zones were more saturated with water and/or salt solution than the bulk paste when the concrete was frozen, it is likely that the paste would separate from the aggregate, as is seen in the field. This is supported by examination of the fracture surfaces of slices broken in half. In the gravel, high w/cm case, the aggregate has debonded from the bulk paste, and the silver nitrate is showing some chloride presence in the cavity left behind (top slice in Figure 7). In the other low w/cm sample with silica fume, a similar fracture has propagated through the aggregate rather than around it.

Figure 7. Fracture surface of silver nitrate sprayed samples

SEM analysis was performed on a specimen obtained from a concrete beam which experienced 300 freezing and thawing cycles under calcium chloride solution from previous study. The SEM image is shown in Figure 8. The chloride map shows a concentration of chlorides around the aggregate particle.

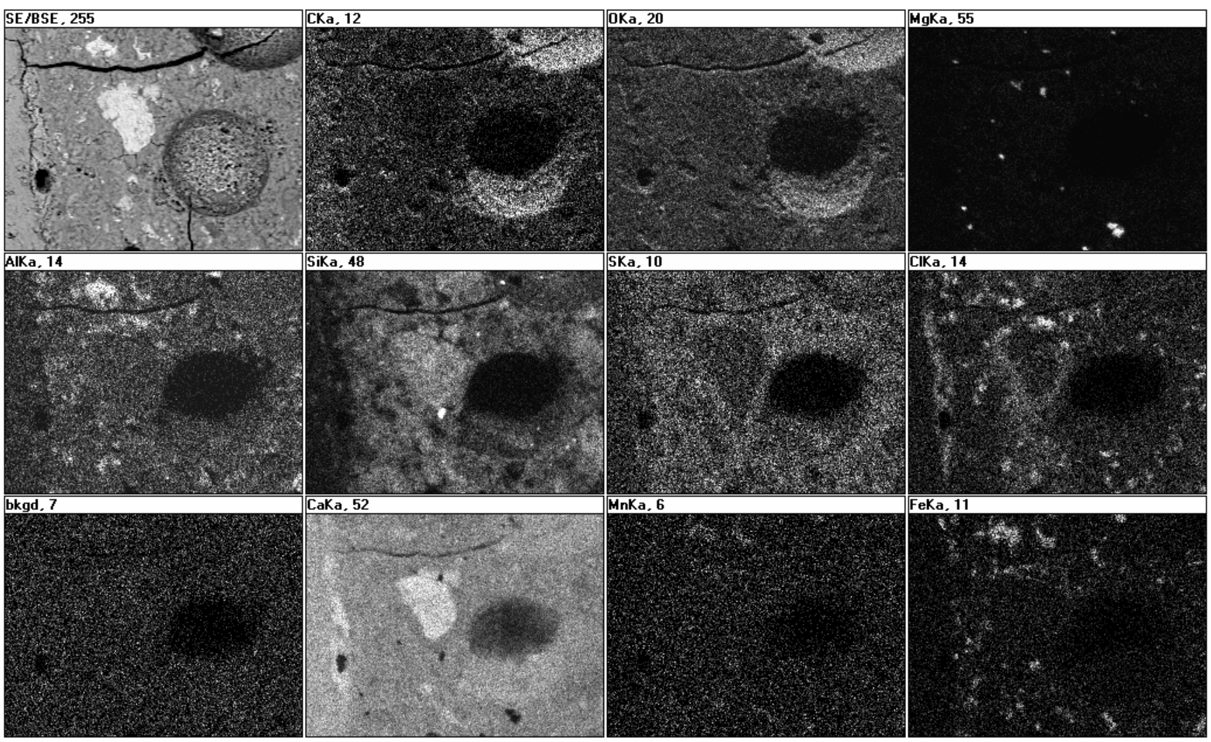

Figure 8. SEM analysis on distressed samples under cyclic freeze thaw

Conclusion and Recommendation

Factors affecting the concrete interfacial transition zone (ITZ) were evaluated in this study. These, include w/cm, aggregate type, and addition of silica fume. Concrete samples were evaluated using an absorption test, air permeability test, cyclic freezing-thawing test and visual observation of surfaces sprayed with silver nitrate.

The tests results show that concrete mix with the higher w/cm ratio (0.5) exhibited higher absorption, high air permeability. High w/cm samples also exhibited more salt accumulation around aggregate particles.

The collected evidence from the permeability tests and the microcopy all indicated that the ITZ can indeed be contributing to the accelerated deterioration of joints in concrete pavements.

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