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DETERIORATION OF JOINTS IN CONCRETE PAVEMENTS: INVESTIGATION OF FIELD CORES

A.K.M. Rakinul Islam[1], Ahmed A. Ghazy[2] and Mohamed T. Bassuoni[3,4]
[1] M.Sc. Student, Dept. of Civil Eng., University of Manitoba, Winnipeg, MB, Canada.
[2] Ph.D. Candidate, Dept. of Civil Eng., University of Manitoba, Winnipeg, MB, Canada.
[3] Associate Professor, Dept. of Civil Eng., University of Manitoba, Winnipeg, MB, Canada.
[4] Mohamed.Bassuoni@umanitoba.ca

Abstract: Signs of premature deterioration are customarily observed in areas adjacent to longitudinal and transverse joints in concrete pavements. These areas, in many cases, continue to hold water/solution (due to application of de-icing salts) long after wetting events. This solution can contribute to the deterioration process by physical and/or chemical mechanisms. Until now, the root causes of joint deterioration are not fully understood since a multitude of reactions and mechanisms are responsible for this deterioration (de-icing salts, freeze/thaw (F/T) cycles, wetting/drying (W/D) cycles, etc.). The goal of this study is to classify the source of this damage and identify aspects contributing to premature joint deterioration of concrete pavements in Winnipeg, Manitoba. In addition to visual inspection, this study involved analyzing concrete cores collected from both distressed and sound joint locations in concrete pavements. To characterize the quality and pore structure of these cores, absorption and mercury intrusion porosimetry (MIP) tests were performed. The alteration of microstructure in concrete was studied by scanning electron microscopy (SEM) with energy-dispersive X-ray analysis (EDX). It was noted that the microstructure of the cores collected from joints in concrete pavements directly exposed to de-icing salts had high intensity of micro-cracks and most air voids (both small and large) were filled with various levels of secondary depositions compared to the cores collected from concrete pavements not directly exposed to de-icing salts.

Keywords: Concrete pavements; De-icing salts; Absorption; Microstructural analyses; Secondary depositions.

1 INTRODUCTION

Many government agencies in North America and Europe require service life of concrete pavements to be in the range of 30 to 50 years [e.g. Hall et al. 2007, Holt et al. 2011]. Whereas many of these pavements provide excellent long-term performance, a portion of these pavements constructed within the last 10 to 20 years has shown premature deterioration, especially in the areas adjacent to longitudinal and transverse joints. This deterioration is considered problematic because it compromises the performance and potential service life of an otherwise sound pavement, thus impairing the ride quality. Previous field investigations [e.g. Ranjaraju, 2002, Arribas-Colón et al. 2012, Jain et al. 2012] aimed at finding the root causes of this deterioration reported multiple aspects. Structural design (e.g. joint spacing, saw-cutting window and depth, drainage system), construction practices (e.g. addition of excessive amounts of water during placement, vibration rates, improper curing), harsh service conditions (e.g. de-icing salts, freeze/thaw (F/T) cycles, wet/dry (W/D) cycles,) and properties of concrete (e.g. penetrability, air-void quality) have been broadly linked to joint deterioration of concrete pavements.

Previous in-situ evaluations in multiple sites revealed that, in many cases, the joints continued to hold water/solution (due to application of de-icing salts) long after wetting events [Ranjaraju, 2002, Arribas-Colón et al. 2012]. This solution is involved in the deterioration by physical actions (generation of micro- and macro-cracks by increasing the degree of saturation) [Ranjaraju, 2002, Arribas-Colón et al. 2012] or chemical reactions (leaching/decomposition of hydration products and formation of expansive phases) [Jain et al. 2012]. Currently, it has been suspected that the widespread use of specific types of de-icing salts may have played a role in either triggering or accelerating the concrete pavement distress [Ramakrishna et al. 2005, Wang et al. 2006]. Also, changes in de-icing practices such as implementation of anti-icing (to prevent the bonding of ice to the roadway before a storm) and de-icing strategies (to melt and break down the bond between the ice layer and the road surface) may impart deleterious effects on concrete pavements and reduce its integrity and durability. Until now, the root causes behind joint deterioration are not fully understood since a multitude of reactions and mechanisms are responsible for this deterioration (de-icing salts, freeze/thaw [F/T] cycles, wetting/drying [W/D] cycles, degree of saturation, etc.) [Ramakrishna et al. 2005]. Also, they may vary within the same transportation jurisdiction/city, for example, due to implementing varying winter practices (e.g. type and rate of de-icing salts) to different street zones. For a better understanding of the source of this damage and identifying aspects contributing to premature joint deterioration of concrete pavement in Winnipeg, Manitoba, Canada, this study involved analyzing concrete core samples collected from both distressed and sound joint locations in concrete pavements. The pavement sections (regional roads and residential streets) were exposed to different winter treatments (type, rate, and application [direct/indirect] of de-icing salts) and had been in service in wet and long-freezing conditions between 15 and 20 years. This study presents the results of an evaluation for the condition of these concrete pavements through macro- and micro-scale analyses.

2 DESCRIPTION OF FIELD SITES

Representative pavement sections (regional roads and residential streets) were chosen by Public Works Department, City of Winnipeg (COW) at an urban zone in the central area of Winnipeg, Manitoba. The pavement in the test location is subjected to large temperature changes, as the maximum and minimum air temperatures during the last 10 years were +36°C and –36°C, respectively. The investigation started with a detailed inventory of the pavement sections chosen in order to identify and classify the existing types of distresses and select candidate locations for extraction of the cores. The available information of the history of these pavement sections was documented, as listed in Table 1, to informatively provide important preliminary information regarding the potential causes of deterioration. Generally, concrete with target performance of 35 MPa and meeting a class of exposure C-2 (plain concrete subjected to chlorides and freezing-thawing) according to CSA A23.1 was used in all roads under investigation. Typically, the concrete comprised General Use (GU) portland cement and up to 15% fly ash (Class F), as a supplementary cementitious material (SCM), meeting the requirements of CSA A3001, and the water-to-cementitious materials ratio (w/cm) was in the range of 0.36 to 0.38.

According to COW policy for ice control [COW, 2011], the regional roads have been classified as priority I streets where de-icers (mainly chloride-based salts: salt brine with a concentration of 23.3% of sodium chloride by weight) are directly used in winter months to provide an adequate level of service by preventing the formation of ice on the roadway surface due to freezing rain, fog, and traces of snow (anti-icing). Moreover, a liquid salt (proprietary solution comprising 26.6% calcium chloride, 3.1% magnesium chloride, 1.3% sodium chloride and 0.9% potassium chloride) are also added to abrasives (sand) or solid salts to make them easier to manage, distribute and help them stay on roads (pre-wetting). The pre-wetting chemical is applied at 40 l/ton for treated sand and 50 l/ton for road salt. The rates of application for these de-icers are shown in Table 1. In contrast, the existing policy for ice control states that the residential streets (priority II) are maintained to a compacted snow/ice by plowing operations without applying salts, except for specific areas as described in Table 1.

Table 1: Available information on the history of the pavement sections

	Residential street I	**Residential street II**	**Regional road I**	**Regional road II**
Year paved	2001	1999	1996	1996
No. of lanes	2 (traffic lane/ parking lane)	2 (traffic lane/ parking lane)	3 (3 traffic lane/ parking lane)	3 (2 traffic lane/ shoulder)
Average traffic/day (vehicles)	< 2500	< 2500	> 20000	> 20000
Design speed (km/h)	40 - 50	40 - 50	60 - 80	60 - 80
Salt application (kg/lane kilometer) [Avg. frequency/winter]	Not recommended	Not recommended	160 [14]	160 [18]
Treated sand* (kg/lane kilometer)	Specific areas**	Specific areas**	320	320

*Liquid salt is added to the sand (5% by weight).

**Intersections, pedestrian corridors and crosswalks, railway crossings and inclinations.

3 TEST METHODS

A series of macro- and micro-scale tests were conducted to evaluate the nature of the distress, if any, in both regional roads and residential streets. A total of 18 cores were taken at multiple locations to capture the effect of different winter treatments (rate and application [direct/indirect] of de-icing salts) in the pavement sections under investigation. The core diameters ranged from 100 mm to 150 mm. The transport properties of concrete were assessed by capillary absorption and electro-migration of chloride ions. The absorption test was conducted on previously conditioned (dried at a temperature of 50±2 °C and a relative humidity (RH) of 40% for 72 h followed by vacuum pressure [~85 KPa] for 6 h) concrete discs (75 mm diameter and 50 mm thickness) cut from the cores. The initial mass to the nearest 0.01 g was recorded and then the specimens were submerged in 4% calcium chloride solution for up to 360 min, and the amount of absorption after 1, 5, 10, 20, 40, 80, 160 and 360 minutes were determined and normalized by the initial mass (dry mass) of the specimens [Tiznobaik and Bassuoni, 2017].

To complement the results of the absorption, the characteristics of the pore structure of concrete were determined by mercury intrusion porosimetry (MIP) with a maximum pressure of 206 MPa, allowing the detection of pore radii ranging from 3 nm up to 1000 µm. Small pea-sized chunks (around 5-10 mm in size) taken from at least two replicate cores were carefully selected to avoid the inclusion of large aggregates. The chunks were oven-dried at 45±5 °C for 72 h; they were then kept in a desiccator containing calcium sulfate for 24 h before the MIP test. This method of drying at a lower temperature for a longer period was adopted to avoid the formation of micro-cracks, which may occur at higher drying temperatures. The contact angle and the surface tension of mercury were taken as 130º and 485 dynes/cm, respectively.

Finally, to understand the alteration of microstructure and thus gain a fundamental understanding of the principal mechanisms of deterioration, microscopy study had been used. Fracture pieces were extracted from the top and bottom portions in the cores and examined by scanning electron microscopy (SEM) assisted with energy-dispersive X-ray analysis (EDX). The SEM samples were coated with a fine layer of carbon before performing the analysis to make the surface conductive and to improve the sample imaging.

4 RESULTS AND DISCUSSION

4.1 Visual observations

A condition assessment survey was filled out for each site visited, incorporating information about the general description of the surrounding environment, drainage system, maintenance, sealant condition, visual damage. The extent of damage on the surface and along joints was observed and described as minimum, medium (considerable), or high (extensive) for each site. The visual inspection provided reasonable information about possible factors affecting the damage.

For regional roads, most of the sites showed distinctive signs of damage (Figure 1). The visual evaluation of the condition of these sites revealed that the drainage of the joints contributed significantly to their performance. In many cases, the joints continued to entrap water (solution) long after wetting events (Figure 1a). Also, accumulation of dirt and other road debris in these joints was visible (Figure 1b). Joint sealants were mostly de-bonded from both sides of the saw-cut joints (Figure 1c). The most intensive damage occurred at the intersection of the transverse and longitudinal joints, where these areas exhibited significant loss of material. Therefore, based on the visual evaluation of the condition of these sites, the extent of damage was considered as 'medium or high' deterioration in both longitudinal and transverse joints. Due to the differences in the pavement conditions for the streets selected, the cores had been extracted from different sections at and adjacent to the joints. In many cases, the damage to the joints was extensive and the concrete crumbled during the coring process (Figure 2a); therefore, it was not possible to obtain full cores in these locations, where they ended up into several pieces, as for example shown in Figure 2b.

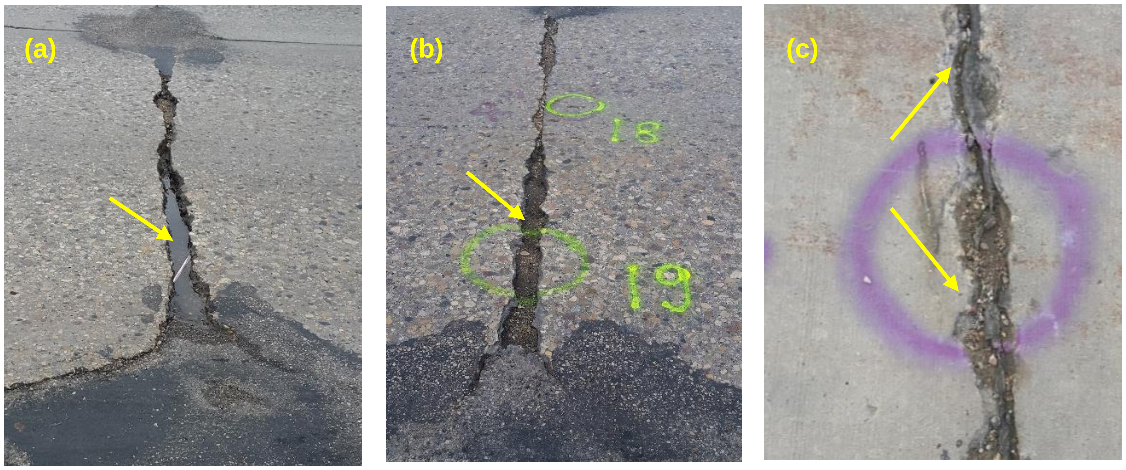

Figure 1: Evidence of joint deterioration in regional roads: (a) widening of joints and entrapment of water/solution, (b) accumulation of dirt and other road debris, and (c) de-bonded sealants.

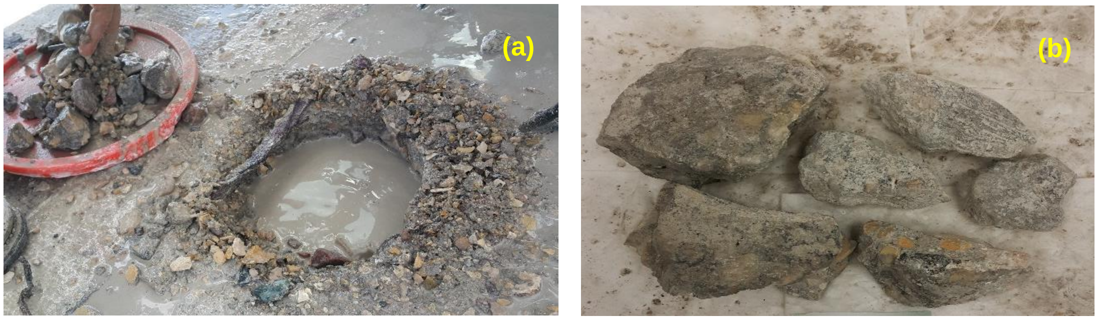

Figure 2: An example from regional roads showing: (a) damage of concrete during the coring process, and (b) fractured core.

In comparison to the regional roads, the residential streets were in excellent conditions. Most of the joints were clean and sound, and there was no evidence of faulting or spalling (e.g. Figure 3a). The pavement cross slope and drainage system appeared to be effective as water continued draining after wet events as adequately as designed. During coring, it was observed that core holes drained well compared that of regional roads. Also, the cores extracted at and near joints appeared sound and intact; they were cleanly and fully drilled with excellent conditions (e.g. Figure 3b).

Figure 3: An example from a residential street showing: (a) sound joint without evidence of faulting or spalling, and (b) whole/intact core.

4.2 Transport properties

Most durability issues of concrete pavements, particularly under aggressive environments such as F/T and W/D cycles, are controlled by the pore structure characteristics and transport properties of concrete. The porosity of concrete and interconnectivity of the pore structure are key parameters for understanding the transport of fluids and ionic species into concrete, which indicates the ease of saturation of concrete and in turn its vulnerability to damage. Therefore, absorption and MIP tests were carried out to identify the pore structure characteristics for the cores extracted from different locations in both regional and residential streets. All the results were statistically evaluated by the Analysis of Variance (ANOVA) method at a significance level (α) of 0.05. According to ANOVA, exceeding the critical value (F_{cr}) of an F-distribution density function reflects that the tested variable significantly affects the mean of the results [Montgomery, 2014].

Water absorption test indicates mass transport of fluids into concrete by capillary suction [Hall, 1989]. The rate and total absorption were determined for at least six samples from each location in both regional and residential streets, as shown in Figure 4. It can be noted that the general trend of the absorption curves indicates a significant difference between the cores extracted from the regional and residential streets. For example, the initial absorption, at 1 min, for the cores extracted from the residential and regional streets gained about 25% and 55%, respectively of their total absorption after 360 min. Also, the rate and total absorption values for the cores extracted from the regional streets are significantly higher (two to three times) than that of the cores extracted from the residential streets. This was statistically supported by ANVOA for the total absorption results, as the samples extracted from the regional roads yielded F values of 90.4 which was larger than the F_{cr} value of 4.2.

The MIP results (cumulative intrusions, porosity, threshold pore diameters and proportion of micro-pores [less than 0.1 μm]) for all the field cores are listed in Table 2. The MIP tests were done on at least four small chunks extracted from two replicate cores for each street, which were put in the same test compartment (porosimeter). Thus, the results shown in Table 2 can be reasonably considered the averages of representative populations to the physical features of microstructure for the concrete cores tested in this study. The trends of MIP conformed to the transport properties (absorption) determined for these cores in the sense that there was a significant increase in the proportion of macro-pores, threshold pore diameter, and total porosity of the cores extracted from regional roads relative to the cores extracted from residential streets (Table 2). For example, the total porosity for the concrete extracted from regional roads was significant 58% higher than that of corresponding cores extracted from the residential streets. Again, this significant difference among these samples was statistically supported by ANVOA for the total porosity results, as the total porosity for the samples extracted from the regional roads yielded *F* values of 29.7 which was larger than the F_{cr} value of 18.5. Also, the threshold pore diameter for these cores was, approximately, 3 µm, which was one order of magnitude higher than the lowest threshold of macro-pores (0.1 µm). Correspondingly, the proportion of micro-pores in these cores was less than 35% of the total pore volume (Table 2). Thus, the ease of percolation in a larger proportion of macro-pores facilitated the absorption and penetrability processes in cores extracted from the regional roads.

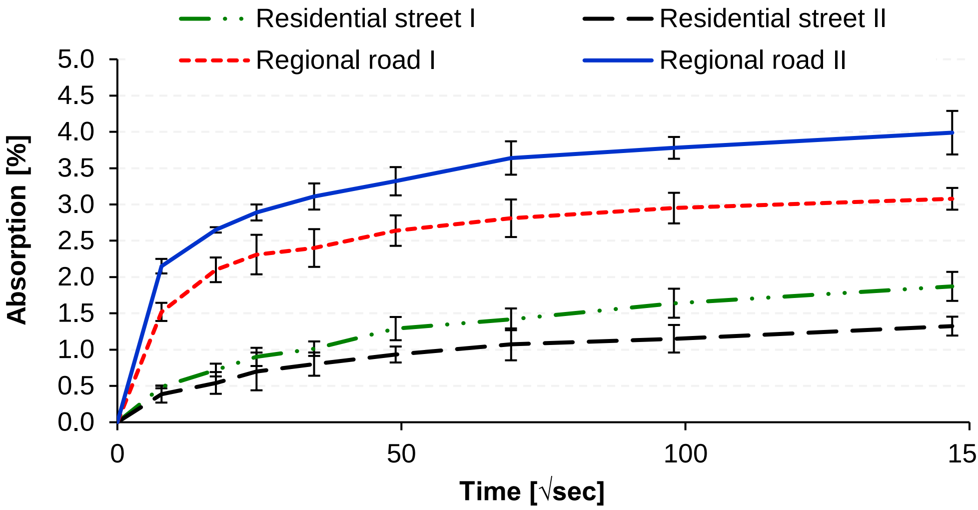

Figure 4: Rate of water absorption of cores extracted from different pavement sections.

Table 2: Mercury intrusion porosimetry (MIP) test results for field cores

	Apparent Total Porosity (%)	**Threshold Pore Diameter (µm)**	**Proportion of Micro-Pores (<0.1 µm) (%)**
Residential street I	13.2	0.21	47.1
Residential street II	12.4	0.14	53.2
Regional road I	18.7	2.12	35.4
Regional road II	21.2	3.89	32.4

4.3 Microstructural Analyses

SEM analysis complied with the absorption and MIP findings. Homogenous and dense matrix was observed in various specimens extracted from the residential streets (e.g. Fig. 5a), except that Friedel's salt and ettringite crystals (e.g. Fig. 5b) infilling some voids near (within 10 mm) the exposed surface. The presence of Friedel's salt is likely a result of the substitution of sulfate ions by chloride ions (i.e. binding chloride as salts are borne by vehicles tires) in aluminate phases such as monosulfate, and unreacted tri-calcium aluminate, if any; however, this phase may not be detrimental to the integrity of concrete as no marked symptoms of cracking and softening were observed.

Comparatively, SEM micrographs for samples extracted from the regional roads showed that this concrete had high intensity of micro-cracks (Fig. 6a) and most air voids (both small and large) were filled with various levels of secondary depositions (mostly ettringite) (e.g. Fig. 6b). This observation complies with previous research on field performance of concrete pavements which reported presence of secondary depositions in the cementitious matrix [Ranjaraju, 2002, Arribas-Colón et al. 2012]. The more formation of Friedel's salt can be attributed to the higher availability of chloride ions at these locations due to chloride binding, as discussed earlier, while ettringite formation might be attributed to two possible sources. First, if external sources of sulfate ions are present (i.e., as impurities in de-icing salts, or dissolved in ground water), the penetrating sulfates react with monosulfate to form ettringite with consequent deposition in open spaces, such as air voids. However, if no external sources of sulfate are available, ettringite may form due to repetitive saturation in the system (W/D and F/T cycles), which include expansion due to its formation [Detwiler et al. 1999]. However, it is not certain if the growth of secondary ettringite in air voids is expansive and can cause deterioration, as expansive damage of paste is attributed to micro-crystalline ettringite intermixed in the paste. Detwiler et al. (1999) reported that expansion and distress of pavements in Wisconsin occurred before much ettringite deposited in air voids. Also, Ouyang et al. (1999) and Famy et al. (2001) stated that ettringite found in this benign state as large needle-like crystals (Fig. 11b), should not necessarily be interpreted as the cause of damage of concrete since this may be just a consequence of re-crystallization of micro-crystalline ettringite due to 'Ostwald ripening'. Whether ettringite crystals formed in air voids are expansive or not, infilling of the air voids (especially smaller air voids) with secondary products (ettringite and/or Friedel's salt) reduced its effectiveness with respect to providing an adequate level of F/T protection. In-filling of the air voids with ettringite or any precipitates eases reaching critical saturation levels due to formation of inadequate air-void system, in turn, susceptible to F/T cracking and shortening the life of the concrete. Likewise, holding solution (due to application of de-icing salts) in these joints further increased the degree of saturation as salt solutions have a lower vapor pressure than that of pure water [Mindess et al. 2002]. These observations imply that concrete in regional roads might have suffered from F/T damage as the primary mechanism of deterioration.

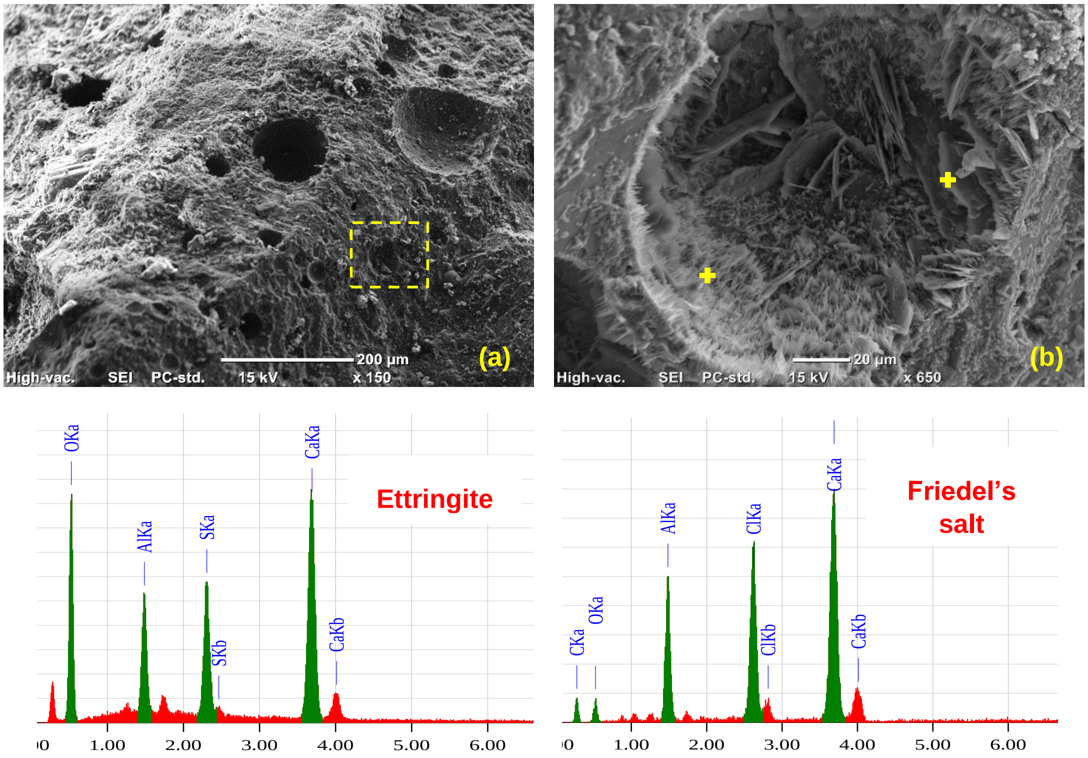

Figure 5: Samples collected from residential street showing: (a) homogenous and dense matrix; and (b) traces of Friedel's salt and ettringite crystals precipitating in air voids with associated EDX spectra.

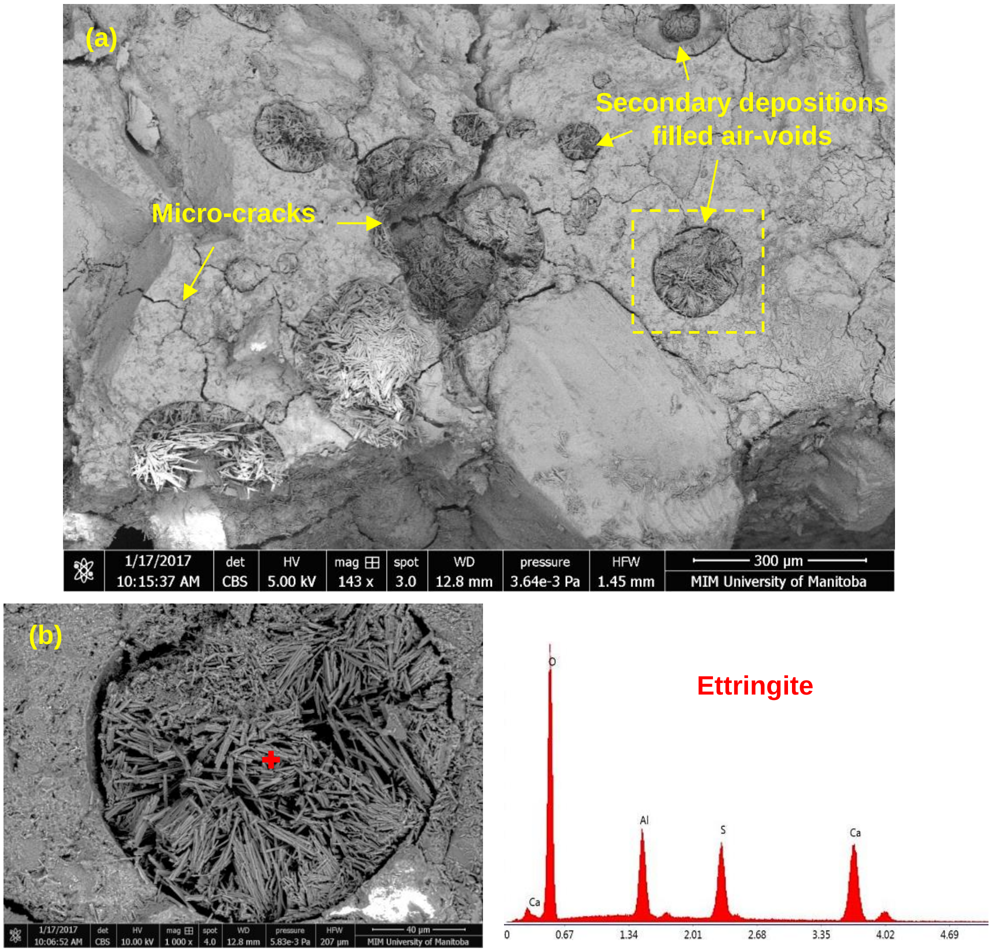

Figure 6: Samples collected from regional roads showing: (a) high intensity of micro-cracks; and (b) ettringite crystals filling an air void with associated EDX spectrum.

5 CONCLUSIONS

This study involved the evaluation of pavement sections (regional roads and residential streets) exposed to different winter treatments (direct/indirect de-icing salts). The following conclusions can be drawn from the results of this investigation:

- The pavement cross slope and drainage system played a significant role in the performance of the joints in the residential streets by preventing them from critical saturation compared to that in regional roads which continued to entrap brine solution long after wetting events.

- The direct application of de-icing salts in the regional roads further increased the degree of saturation as salt solutions have a lower vapor pressure than that of pure water.

- Cores extracted from the regional roads mostly exhibited higher rates of absorption, poor air void system, high intensity of micro-cracking, and the majority of air voids were filled with secondary depositions. Hence, the principal reason for the deterioration of concrete in regional roads appears to be related to F/T damage due to the gradual infilling of air voids with secondary products.

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