CHLORIDE PENETRATION RESISTANCE OF CONCRETE SEALER AND COATING SYSTEMS

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Abstract. This study investigated the chloride penetration resistance of a silane-based sealer (SS1), an acrylic-based coating (AC1), and two cementitious coatings (CC1 and CC2) when applied on concrete surface. Concrete powder samples were collected from 15, 30 and 45 mm depths of sealer and coating treated concrete prism specimens, which were exposed to H_2O and de-icing solutions of NaCl, Geomelt S30, $MgCl_2$ and $CaCl_2$ for 100 freeze-thaw cycles followed by 25 wet-dry cycles. Chloride analysis was carried out to determine the total water-soluble chlorides of concrete. Test results revealed that the chloride penetration for exposure to the de-icing chemicals occurred at a depth of 15 mm from the concrete surface. The highest chloride penetration occurred for the non-treated concrete. The sealer 'SS1' exhibited good performance except with exposure to NaCl solution. Among the three different coating products, the acrylic-based coating 'AC1' was the best-performing coating, whereas the cementitious coating 'CC1' had the worst performance. The amount of penetrated water-soluble chlorides was greater than the maximum recommended value of 0.025% (by concrete weight) at 15 mm depth for the sealer 'SS1' when exposed to NaCl de-icing solution, and for the coating 'CC1' when exposed to NaCl, $CaCl_2$ and $MgCl_2$ solutions.

Keywords: cementitious coating, chloride penetration, concrete, de-icing chemicals, penetrating sealer, water-soluble chlorides.

Introduction

De-icing or anti-icing chemicals are applied on bridge decks during winter for highway maintenance. They were first used on bridge decks in the U.S.A. during the 1940s (TRB 1991). In Canada, the use of de-icing or anti-icing chemicals on bridge decks began during the 1950s (Julio-Betancourt 2009). These chemicals can be classified as chloride-based or non-chloride-based. Chloride-based de-icing or anti-icing chemicals are generally used because of their low cost and relatively high effectiveness (TRB 2007). The most common chloride-based de-icing chemicals are NaCl and $CaCl_2$, and more recently $MgCl_2$ is also used as a de-icer. In addition, a formulated chloride-based de-icing/anti-icing liquid, commercially known as "Geomelt S30" is used in Southern Ontario (Soudki *et al.* 2011). It consists of NaCl brine and an organic salt accelerator derived from desugarized sugar beet juice.

Chloride-based de-icing/anti-icing chemicals are a common source of chloride ions that can penetrate a concrete surface. Many studies reported that the penetration of chlorides causes accelerated corrosion in reinforced concrete structures by destroying the protective passive film of the embedded steel reinforcement (Melchers, Li 2009; Pruckner, Gjørv 2004; Saremi, Mahallati 2002). Several research reports showed that $CaCl_2$ and $MgCl_2$ react with hydration products and form expansive oxy-chlorides (Julio-Betancourt 2009; Sutter *et al.* 2008), which result in cracking, thus causing increased permeability and a substantial loss of compressive strength. Also, Kozikowski *et al.* (2007) reported that $MgCl_2$ forms magnesium silicate hydrate (M-S-H) and brucite [$Mg(OH)_2$] when it reacts with the hydration products of cement used in concrete. M-S-H decreases the strength of concrete at the expense of C-S-H, whereas $Mg(OH)_2$ reduces the pH of the pore solution in the cement paste of concrete and thus accelerates reinforcement corrosion. The effect of chlorides becomes more detrimental in the case of cracked concrete due to increased permeability (Park *et al.* 2012). Moreover, chlorides not only accelerate reinforcement corrosion but also affect the scaling resistance of concrete. Bouteille *et al.*

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(2010) investigated the frost salt scaling resistance of concrete exposed to chloride solution with different concentrations; they found that the chloride concentration directly influences the amount of scaled mass from concrete surface. Though numerous studies were conducted on the chloride penetration into concrete, limited studies have been carried out on the chloride penetration resistance of concrete sealer and coating systems exposed to highly concentrated chloride solutions combined with freezing/thawing or wetting/drying cycles.

Sealers are typically classified as either penetrants or surface sealers that do not change the appearance of concrete to any significant degree. Coatings may be clear liquids, but typically are pigmented to improve the aesthetics of concrete. Safiuddin and Soudki (2011) surveyed the use of sealer and coating systems for the protection of concrete bridge structure; they concluded that sealers or coatings can protect the concrete from damages caused by the aggressive environmental and chemical exposures. The application of a sealer or coating on concrete surface can significantly impede the transport of chloride-laden water into concrete by making the surface layer hydrophobic or forming a physical barrier or combining both effects (Soudki *et al.* 2011).

Sealers and coatings have been applied as surface treatments onto concrete surface to reduce the penetration of chlorides into concrete for the protection of concrete bridge structures against corrosion (Ibrahim *et al.* 1999; Palle, Hopwood II 2006; Wenzlick 2007). The Kentucky Transportation Centre reported that a proper surface coating can protect reinforced concrete from corrosion by impeding the penetration of chloride ions (Palle, Hopwood II 2006). Al-Dulaijan *et al.* (2000), Almusallam *et al.* (2003), Ibrahim *et al.* (1999), Moon *et al.* (2007), and Oshiro and Tanigawa (1988) reported that surface coatings substantially slow down the chloride penetration into concrete and thus reduce the corrosion of steel reinforcement. On the contrary, penetrating sealers are not as efficient as surface coatings in improving the corrosion resistance of reinforced concrete (Ibrahim *et al.* 1999; Wenzlick 2007).

Kamaitis (2007a) analysed the mechanisms of degradation of polymer coatings caused by different aggressive actions and suggested predictive models for the deterioration over time that can be applied in designing the surface polymer coatings to preserve concrete structures. Moreover, Kamaitis (2007b) recommended the use of polymer protective coatings onto concrete surfaces where special protection against aggressive attack is necessary and demonstrated that polymer coatings can protect concrete from a variety of aggressive chemicals; his proposed models can be efficiently applied to assess the service life and performance of polymer protective coatings under different chemical exposure conditions. Kamaitis (2008) also took into account protective surface coating, concrete cover, and steel reinforcement in a whole to study the corrosion protection and service life of reinforced concrete structures. Recently, Yoon (2012) studied the effect of coating on chloride penetration through cracks in high-strength concrete with and without steel fibres; he concluded that coating can substantially reduce the chloride penetration into concrete. Nevertheless, most of the above-mentioned studies mainly focused the performance of polymer-based protective coatings. In addition, none of the aforementioned studies focused the effect of high concentration of different chloride-based de-icing/anti-icing chemicals on the performance of sealers or coatings. The combined effect of highly concentrated chloride solution, freezing/thawing, and wetting/drying was also not investigated in the above studies.

The present research study was undertaken to evaluate the chloride penetration resistance of four commercially available sealer/coating products using H_2O and four de-icing chemicals (NaCl, $CaCl_2$, $MgCl_2$, and Geomelt S30). The chloride penetration resistance of the sealer and coating products was evaluated by quantifying the extent of chloride ingress into concrete. The sealer and coating treated concrete specimens were exposed to different highly concentrated chloride solutions along with freezing/thawing cycles, followed by wetting/drying condition. The chloride penetration at various concrete depths was obtained with respect to water-soluble chlorides, since they are more likely to contribute to corrosion of steel reinforcement (Dhir *et al.* 1990).

1. Materials and methods

The chloride analysis was carried out for control (non-treated) and surface-treated concrete prisms exposed to different de-icing chemicals. The types of surface treatment are shown in Table 1. The silane-based sealer (SS1) was used as a penetrating sealer, whereas the acrylic-based coating (AC1) and the two cementitious coatings (CC1 and CC2) were used as surface coatings. The selected sealer and coating materials were applied on concrete

Table 1. Different surface treatments

Designation	Type of surface treatment
SS1	A silane-based penetrating sealer including corrosion inhibitor
AC1	A pigmented acrylic-based coating
CC1	A highly flexible, fibre-reinforced, two-component cementitious coating
CC2	A flexible, polymer-modified, two-component cementitious coating

prisms (225×225×100 mm) whose surface was prepared by abrasive blasting.

The concrete surface of the prism specimens was blasted using a stream of compressed air and abrasive material at a pressure of 95 psi. After abrasive blasting, the specimens were washed with water to remove the fine dust and loose materials. The profiles achieved after abrasive blasting replicated the degree of roughness for surface profile CSP 3 (Concrete Surface Profile 3), as specified by ICRI (1997). The abrasive blasting provided the required surface roughness for good adhesion of the coatings and opened the surface pores for penetration of the penetrating sealer. The sealer and coating materials were applied on the prepared concrete surface in accordance with the manufacturers' specifications. Before application, depending on the manufacturer's instructions for use, the blasted concrete surfaces were either dried or dampened/wetted.

The control (non-treated) and surface-treated concrete prisms were ponded with normal tap water and four de-icing chemicals with a ponding depth of approximately 6 mm. Dikes were made on the non-treated and treated concrete surface using plexiglass bars to hold the water and solutions of de-icing chemicals during ponding. The de-icing chemical solutions were prepared based on the concentrations and formulations shown in Table 2. To formulate the solutions of different de-icing chemicals, the concentration of Geomelt S30, a commercially available de-icing solution in Southern Ontario, was used as a basis. The molal ion concentration of Geomelt S30, which had 16.3% active NaCl, was 6.67. For comparison purposes, the other three de-icing solutions ($NaCl$, $CaCl_2$, and $MgCl_2$) were prepared to have the same molal ion concentration of Geomelt S30. The molal ion concentration was used, as it is based on the weight of solid salts and independent of temperature.

The ponding on the non-treated and surface-treated concrete prisms was carried out with 100 freeze-thaw cycles (1 cycle: 16 hours freezing to –20 °C and 8 hours thawing to +20 °C) followed by 25 wet-dry cycles (1 cycle: 4 days wetting at 23±2 °C and 3 days drying at 38±5 °C). The equivalent ponding period was significantly greater than the minimum ponding period of 90 days, as specified in AASHTO T 259-02 (2006) and ASTM C 1543-10a (2010).

Concrete powder samples were collected from the prism specimens by drilling at three different depths (15, 30, and 45 mm) following the environmental (freeze-thaw and wet-dry) exposures with de-icing chemicals. Seventy five powder samples were obtained from 25 concrete prisms, including 3 control samples. In addition, 6 powder samples were collected from 2 reference concrete prisms (not subjected to any environmental exposure) to determine the baseline chloride content of original concrete. From each prism, three powder samples were collected from the three selected depths. The weight of each drilled concrete powder sample was 10 to 15 g, as needed for the chloride analysis. The details of the concrete powder samples are given in Table 3. The drilling operation and collection of concrete powder samples are shown in Figure 1. The drilling operation was carried out through the sides of the concrete prism specimens using a rotary-impact-type drill machine and maintaining the drilling direction parallel to the ponded surface. This process helped collecting of a test sample solely from the selected depth without contamination with concrete powder from the surface or other depths. Long small-diameter carbide tipped drill bits (length: 305 mm, diameter: 8 mm) were used in the drilling operation. While collecting the dust sample from each hole, care was taken to avoid contamination due to contact with hands and inclusion of foreign materials. It should be mentioned that the concrete powder from the first 25 mm of drilling depth was discarded, since that concrete segment was outside the ponding area and hence was not directly exposed to water or de-icing chemicals.

The water-soluble chloride content of the collected concrete powder samples was determined according to the RCTW (Rapid Chloride Test, Water-Soluble) method by using a commercially available test kit (RCTW

Table 2. Different chemical solutions

Type of solution	Concentration		
	Molal ion-based	Weight-based	Formulation
H_2O	–	–	100% tap water
NaCl	6.67	16.3%	1000 g tap water, 194.8 g NaCl (100% solids)
Geomelt S30	6.67	16.3% NaCl	70% salt brine (23.3% NaCl plus 76.7% water), 30% Geomelt 55 concentrate (de-sugarized beet juice)
$CaCl_2$	6.67	19.8%	1000 g tap water, 303.8 g $CaCl_2$ (85% solids)
$MgCl_2$	6.67	17.5%	1000 g tap water, 591.6 g $MgCl_2$ (47% solids)

Table 3. Test samples for chloride analysis

| Type of exposure | Number of concrete prism specimens | | Sampling depth (mm) | Number of powdered samples |
	For non-treated (control, no sealer/coating)	For treated (1 sealer and 3 coatings)		
None	2	–	15, 30, 45	6
H_2O	1	4	15, 30, 45	15
NaCl	1	4	15, 30, 45	15
Geomelt S30	1	4	15, 30, 45	15
$CaCl_2$	1	4	15, 30, 45	15
$MgCl_2$	1	4	15, 30, 45	15

Drilling into concrete prism

Extraction of concrete powder

Extracted concrete powder sample

Transfer of concrete powder to plastic bag

Fig. 1. Drilling operation and collection of concrete powder samples

2002). In this test, a 1.5-g concrete powder sample was first mixed with a 9-ml extraction liquid and shaken vigorously for 5 min. Then the mixture of the powder sample and extraction liquid was poured into a filter paper cone for filtering into a vial containing a 1-ml buffer. The filtered solution and buffer was also shaken for 1 min to obtain the final solution for chloride analysis. The calibrated chloride ion sensing electrode was submerged into the vial containing the chloride solution. The potential (mV reading) was recorded from the high impedance electrometer. Later the mV reading was transformed into the water-soluble chloride content of concrete by means of the calibration chart (% Cl^- by concrete weight vs. potential, mV) as shown in Figure 2. The different steps of the RCTW test are shown in Figure 3.

2. Test results and discussion

The baseline chloride content for the test specimens was determined as the average water-soluble chloride content of powder samples obtained from the 15, 30 and 45 mm depths of two concrete prisms that were not ponded with water or any de-icing chemical (Table 4).
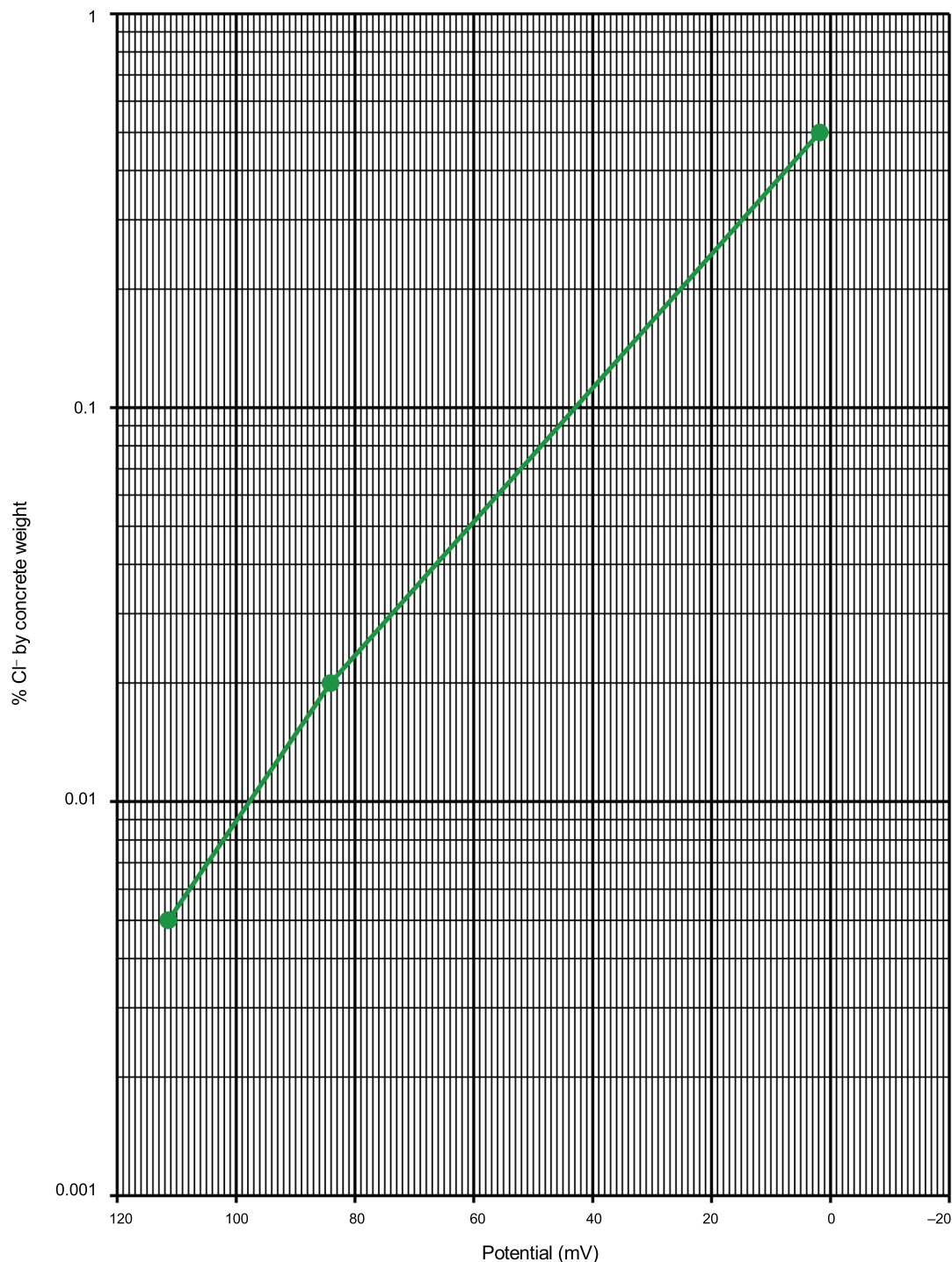
Fig. 2. Calibration chart

The measured total water-soluble chloride contents of non-treated and treated concretes exposed to different chemicals are given in Table 5) The total water-soluble chloride content includes the penetrated chlorides and the baseline chlorides (chloride content of original concrete). The amount of penetrated water-soluble chlorides was calculated by subtracting the baseline chloride content from the total water-soluble chlorides. When the result was negative, it was taken as zero. Table 6 presents the penetrated water-soluble chlorides due to exposure to water and different de-icing chemicals. The chloride results in Table 6 revealed that the penetration of chlorides into concrete prisms occurred at a depth of 15 mm. No penetration of chlorides occurred at the depths of 30 and 45 mm. The detailed discussion of the results is given below.
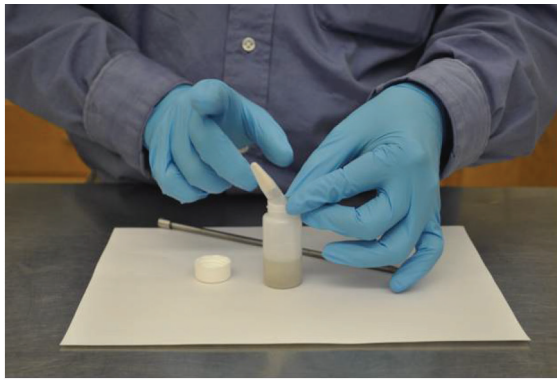
Mixing of concrete powder sample with extraction liquid
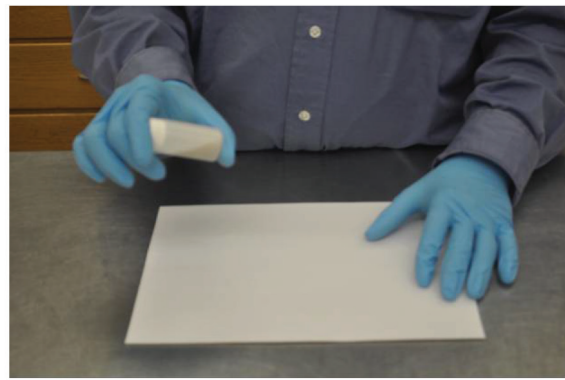
Shaking of concrete powder sample mixed with extraction liquid
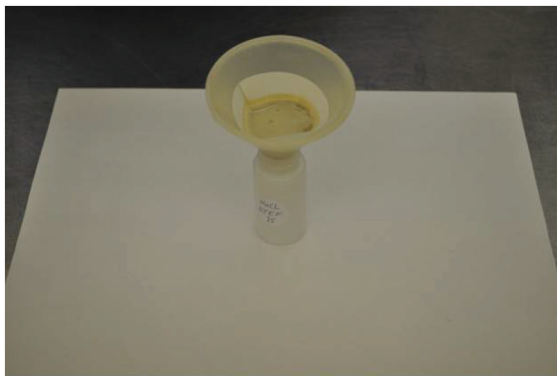
Filtering of mixture of concrete powder sample and extraction liquid

Testing of total water-soluble chloride content of concrete by RCTW method

Fig. 3. Determination of water-soluble chloride content of concrete

Table 4. Water-soluble chloride content of original concrete

Specimen	Depth of sampling					
	15 mm		30 mm		45 mm	
	Potential (mV)	Chloride (% C[1])	Potential (mV)	Chloride (% C)	Potential (mV)	Chloride (% C)
S1	64.9	0.041	67.5	0.038	64.5	0.041
S2	68.4	0.039	62.9	0.044	66.0	0.040
Mean	–	0.040	–	0.041	–	0.041
Average baseline chloride content: 0.041%						

[1]Weight of concrete.

2.1. Non-treated concrete

The maximum levels of chloride penetration occurred in the case of non-treated concrete (NC) exposed to different de-icing chemicals (Table 6). The penetrated water-soluble chloride content at 15 mm depth was 0.164, 0.159, 0.055 and 0.229% due to exposure to NaCl, Geomelt S30, $CaCl_2$, that is, and $MgCl_2$, respectively. The chloride penetration at 15 mm depth was zero due to exposure to H_2O (Table 6).

2.2. Sealer treated concrete

The penetrated water-soluble chloride content of the sealer treated concrete exposed to H_2O was zero at 15, 30 and 45 mm depths (Table 6). In the cases of exposures to NaCl, Geomelt S30, $CaCl_2$ and $MgCl_2$ de-icing chemicals, the penetrated water-soluble chloride content at 15 mm depth was 0.079, 0.019, 0.008 and 0.006%, respectively. At 30 and 45 mm depths, the penetrated water-soluble chloride contents were zero for the aforementioned de-icing chemical exposures (Table 6).

Table 5. Total water-soluble chloride content of concrete exposed to different chemicals

Chemical exposure	Type of surface treatment	Depth of sampling					
		15 mm		30 mm		45 mm	
		Potential (mV)	Chloride (% C[1])	Potential (mV)	Chloride (% C)	Potential (mV)	Chloride (% C)
H$_2$O	NC	65.6	0.040	66.2	0.040	71.1	0.033
	SS1	78.1	0.025	76.3	0.027	64.6	0.041
	AC1	71.7	0.031	76.1	0.027	70.3	0.034
	CC1	64.8	0.041	65.3	0.041	65.5	0.040
	CC2	68.1	0.037	68.8	0.035	65.0	0.041
NaCl	NC	23.8	0.205	74.7	0.028	68.7	0.035
	SS1	37.4	0.120	64.6	0.041	65.1	0.041
	AC1	66.4	0.040	71.5	0.032	71.1	0.033
	CC1	51.9	0.068	69.4	0.035	65.6	0.040
	CC2	61.5	0.047	65.2	0.041	65.3	0.041
Geomelt S30	NC	24.4	0.200	69.9	0.034	73.9	0.029
	SS1	55.7	0.060	64.9	0.041	70.4	0.033
	AC1	66.1	0.040	65.3	0.041	64.5	0.041
	CC1	56.1	0.058	65.4	0.041	70.2	0.034
	CC2	68.1	0.037	64.5	0.041	70.3	0.034
CaCl$_2$	NC	43.5	0.096	72.1	0.031	73.6	0.029
	SS1	60.4	0.049	65.0	0.041	64.8	0.041
	AC1	69.9	0.034	67.2	0.038	67.2	0.038
	CC1	49.9	0.074	64.6	0.041	66.8	0.038
	CC2	55.4	0.060	65.5	0.040	67.0	0.038
MgCl$_2$	NC	16.9	0.270	68.3	0.037	65.5	0.040
	SS1	61.5	0.047	64.9	0.041	71.3	0.032
	AC1	67.1	0.038	64.8	0.041	64.9	0.041
	CC1	50.3	0.074	65.9	0.040	65.7	0.040
	CC2	61.2	0.048	72.5	0.031	71.9	0.031

[1]Weight of concrete

2.3. Acrylic-based coating (AC1) treated concrete

The penetrated water-soluble chloride content of the acrylic-based coating treated concrete was zero at 15, 30 and 45 mm depths when exposed to H$_2$O and NaCl, Geomelt S30, CaCl$_2$, and MgCl$_2$ de-icing chemicals (Table 6).

2.4. First cementitious coating (CC1) treated concrete

The penetrated water-soluble chloride content of the CC1 cementitious coating treated concrete was zero at 15, 30 and 45 mm depths when exposed to H$_2$O (Table 6). When exposed to NaCl, Geomelt S30, CaCl$_2$ and MgCl$_2$ de-icing chemicals, the penetrated water-soluble chloride content at 15 mm depth was 0.027, 0.017, 0.033 and 0.033%, respectively (Table 6). The penetrated chloride content at 30 and 45 mm depths was zero in the case of exposures to all de-icing chemicals (Table 6).

2.5. Second cementitious coating (CC2) treated concrete

The penetrated water-soluble chloride content of the CC2 cementitious coating treated concrete was zero at 15, 30 and 45 mm depths in the case of H$_2$O exposure (Table 6). The penetrated water-soluble chloride content at 15 mm depth was 0.006, 0, 0.019 and 0.007%, when exposed to NaCl, Geomelt S30, CaCl$_2$ and MgCl$_2$ de-icing chemicals, respectively (Table 6). At 30 and 45 mm depths, the penetrated water-soluble chloride content was zero in the cases of exposures to all de-icing chemicals (Table 6).

2.6. Effects of different de-icing chemicals

The penetrated water-soluble chloride content of the non-treated concrete ranged from 0.055 to 0.229% by weight of concrete in the cases of exposures to different de-icing chemicals (Table 6). According to CSA A23.1-09/A23.2-09 (2009), the maximum allowable water-soluble chloride content in new concrete exposed to a moist environment or chlorides or both is 0.15%

Table 6. Penetrated water-soluble chloride content of concrete exposed to different chemicals

Chemical exposure	Avg. baseline chlorides (% C[1])	Type of surface treatment	Total water-soluble chlorides (% C)			Penetrated water-soluble chlorides[2] (% C)		
			Penetration depth (mm)			Penetration depth (mm)		
			15	30	45	15	30	45
NC	0.041	H_2O	0.040	0.040	0.033	0	0	0
		NaCl	0.205	0.028	0.035	0.164	0	0
		Geomelt S30	0.200	0.034	0.029	0.159	0	0
		$CaCl_2$	0.096	0.031	0.029	0.055	0	0
		$MgCl_2$	0.270	0.037	0.040	0.229	0	0
SS1	0.041	H_2O	0.025	0.027	0.041	0	0	0
		NaCl	0.120	0.041	0.041	0.079	0	0
		Geomelt S30	0.060	0.041	0.033	0.019	0	0
		$CaCl_2$	0.049	0.041	0.041	0.008	0	0
		$MgCl_2$	0.047	0.041	0.032	0.006	0	0
AC1	0.041	H_2O	0.031	0.027	0.034	0	0	0
		NaCl	0.040	0.032	0.033	0	0	0
		Geomelt S30	0.040	0.041	0.041	0	0	0
		$CaCl_2$	0.034	0.038	0.038	0	0	0
		$MgCl_2$	0.038	0.041	0.041	0	0	0
CC1	0.041	H_2O	0.041	0.041	0.040	0	0	0
		NaCl	0.068	0.035	0.040	0.027	0	0
		Geomelt S30	0.058	0.041	0.034	0.017	0	0
		$CaCl_2$	0.074	0.041	0.038	0.033	0	0
		$MgCl_2$	0.074	0.040	0.040	0.033	0	0
CC2	0.041	H_2O	0.037	0.035	0.041	0	0	0
		NaCl	0.047	0.041	0.041	0.006	0	0
		Geomelt S30	0.037	0.041	0.034	0	0	0
		$CaCl_2$	0.060	0.040	0.038	0.019	0	0
		$MgCl_2$	0.048	0.031	0.031	0.007	0	0

[1]Weight of concrete;
[2]Penetrated water-soluble chloride = Total chlorides – Baseline chlorides, taken as zero if the number is negative.

by weight of cementing materials. For ordinary concrete produced with a cement content varying in the range of 300–400 kg/m³, this is equivalent to a chloride limit of 0.019–0.025% by weight of concrete (0.45–0.60 kg per 1 m³ of concrete). Hence, the penetrated water-soluble chloride content of the non-treated concrete was significantly more than the maximum allowable chloride limit. This result suggests that the susceptibility of non-treated concrete to reinforcement corrosion is relatively high. Geomelt S30 had a significantly reduced penetration of chlorides as compared to NaCl. This is because Geomelt S30 has a lower amount of NaCl-brine in its solution formulation (Table 2). Exposure to $CaCl_2$ led to the lowest penetrated water-soluble chlorides (0.055%) in the non-treated concrete. Although this chloride content exceeded the maximum allowable limit of 0.019–0.025%, it was significantly lower than the penetrated water-soluble chlorides caused by NaCl and $MgCl_2$ de-icing chemicals. This is because the diffusion of $CaCl_2$

into concrete is slower than that of NaCl (Hooton, Julio-Betancourt 2005; Mussato *et al.* 2004). In addition, calcium oxy-chloride forms in the presence of $CaCl_2$. The formation of such product decreases the amount of water-soluble (free) chlorides in concrete. As a result, the penetrated water-soluble chlorides were lower for the concrete exposed to $CaCl_2$ de-icing chemical. However, the formation of expansive oxy-chloride results in reduced compressive strength and increased permeability due to cracking in concrete (Julio-Betancourt 2009; Sutter *et al.* 2008). These adverse physical effects accelerate concrete deterioration, and thus can supersede the positive effect of reduced water-soluble chloride content in the case $CaCl_2$ exposure.

Exposure to $MgCl_2$ caused the maximum chloride penetration (0.229%) into non-treated concrete (Table 6). It was substantially greater than the penetrated water-soluble chlorides caused by NaCl exposure. This finding suggests that $MgCl_2$ could be more detrimental to cause

corrosion of steel reinforcement in reinforced concrete. $MgCl_2$ diffuses into concrete much slower than NaCl and $CaCl_2$ (Hooton, Julio-Betancourt 2005; Mussato *et al.* 2004). Yet the penetrated water-soluble chloride content was significantly higher in the case of exposure to $MgCl_2$ versus NaCl or $CaCl_2$. Xi and Xie (2002) reported that $MgCl_2$ can be more corrosive than NaCl under humid conditions. When exposed to drying, $MgCl_2$ can adhere and crystallize more easily onto a solid (aggregate, steel reinforcement, etc.) surface because of its higher viscosity; this salt can also easily convert back to a solution during wetting due to its greater hydrophilic nature (Kozikowski *et al.* 2007). Consequently, the penetrated water-soluble chlorides can be higher in the case of exposure to $MgCl_2$ de-icing chemical.

The effect of de-icing chemicals on surface-treated concrete with respect to penetrated water-soluble chlorides significantly varied depending on the type of surface treatment (Table 6). None of the de-icing chemicals caused any chloride penetration into the acrylic-based coating treated concrete. NaCl resulted in the highest penetrated water-soluble chlorides (substantially higher than the maximum allowable limit of 0.019–0.025%) in the case of sealer treated concrete. This suggests that the water repelling performance of the sealer was less effective when exposed to NaCl de-icing solution. This is because NaCl de-icing solution had a relatively low amount of net water in its formulation (Table 2). In the cases of the two cementitious coating treated concretes, $CaCl_2$ and $MgCl_2$ caused more chloride penetration than NaCl and Geomelt S30 (Table 6). However, $CaCl_2$ and $MgCl_2$ produced the maximum chloride penetration (0.033%) for the CC1 coating treated concrete. This is because these two de-icing chemicals formed significant pin holes in the CC1 coating due to dissolution (Soudki *et al.* 2011). Due to the similar reason, exposure to $CaCl_2$ also caused the maximum chloride penetration (0.019%) into the CC2 coating treated concrete. However, all de-icing chemicals produced a higher chloride penetration for CC1 coating than CC2 coating. In the cases of both CC1 and CC2 coatings, Geomelt S30 produced

less chloride penetration than NaCl. This is due to a lower amount of NaCl in its formulation with 70% brine and 30% Geomelt 55 concentrate (Table 2).

2.7. Effects of different sealer and coating products

The sealer and coating products significantly reduced the penetration of chlorides into concrete, as compared with the non-treated concrete (Table 6, Fig. 4). The acrylic-based coating (AC1) had the best performance in resisting the penetration of chloride ions into concrete. The sealer (SS1) had the worst performance in resisting the penetration of chloride ions into concrete when exposed to NaCl (Fig. 4). However, the chloride penetration for the sealer (SS1) was lower than that of the two cementitious coatings (CC1 and CC2) when exposed to $CaCl_2$ and $MgCl_2$ de-icing chemicals (Table 6). Sealer SS1 is a penetrating sealer product that produces hydrophobic reactions by lining capillary pores. As a result, this sealer can repel water or chloride-laden water. The water repelling performance was more effective in the cases of $CaCl_2$ and $MgCl_2$ de-icing solutions, since they have a greater amount of net water in their formulations. It is evident from Table 2 that $CaCl_2$ and $MgCl_2$ contributed 15% and 53% water to their respective solution. Hence, more chloride-laden water was repelled in these two de-icing solutions, resulting in less free chlorides.

The second cementitious coating (CC2) performed better than the first cementitious coating (CC1) in resisting the chloride ion penetration into concrete. Among the three coating products, the highest level of penetrated water-soluble chlorides at 15 mm depth was observed for the coating CC1 (Table 6, Fig. 4). This is due to a greater number of pin holes that occurred in the CC1 coating during exposure to de-icing chemicals. The penetrated water-soluble chloride content of CC1 coating treated concrete was greater than the maximum allowable chloride limit in the cases of exposures to NaCl, $CaCl_2$ and $MgCl_2$ de-icing chemicals.

Conclusions

This study was carried out to determine the chloride ion penetration resistance of four selected sealer/coating products when exposed to five different chemicals (water and de-icing chemicals). Based on the findings of the present study, the following conclusions can be drawn:

1) The maximum levels of chloride ion penetration for all chemical exposures occurred at a 15 mm depth from the concrete surface. No chloride penetration occurred at 30 and 45 mm depths from the concrete surface.

2) The lowest levels of chloride ion penetration for both non-treated and treated concretes occurred when exposed to H_2O. In contrast, the highest degrees of chloride ion penetration were observed when exposed to different de-icing chemicals.

3) The highest chloride ion penetration occurred for the non-treated concrete. $MgCl_2$ exhibited greater chloride ion penetration due to its greater hydrophilic
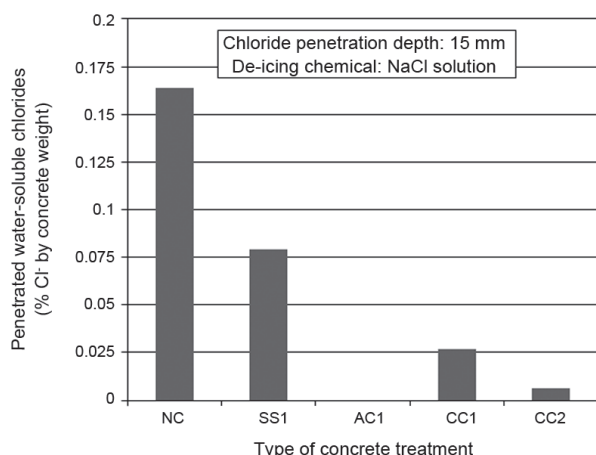

Fig. 4. Chloride ion penetration of non-treated and treated concretes exposed to NaCl solution

nature than other de-icing salts. In contrast, $CaCl_2$ exhibited lower chloride ion penetration due to the involvement of free chlorides in the formation of calcium oxy-chloride.

4) The chloride ion penetration resistance of both treated and non-treated concretes was better when exposed to Geomelt S30 than when exposed to NaCl; this is due to the reduced amount of NaCl in Geomelt S30 including brine and Geomelt 55 concentrate.

5) Sealer SS1 exhibited good performance in the cases of $CaCl_2$ and $MgCl_2$ exposures due to its better water-repellent characteristic in the presence of a higher quantity of water.

6) The performance of the selected sealer and coating products with respect to chloride ion penetration resistance under different environmental exposures with de-icing chemicals can be expressed in the following order from best to worst ranking: AC1 > CC2 > CC1 > SS1.

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