EFFECTS OF DEICERS ON CONCRETE DETERIORATION

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2385 Irving Hill Road, Lawrence, Kansas 66045-7563

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ABSTRACT

Concrete specimens were exposed to weekly cycles of wetting and drying in distilled water and in solutions of sodium chloride, calcium chloride, magnesium chloride, and calcium magnesium acetate with either a 6.04 molal ion concentration, equivalent in ion concentration to a 15% solution of NaCl, or a 1.06 molal ion concentration, equivalent in ion concentration to a 3% solution of NaCl, for periods of up to 95 weeks. Specimens were also exposed to air only. The effects of exposure were evaluated based on changes in the dynamic modulus of elasticity and the physical appearance of the specimens at the conclusion of the tests.

Concretes exposed to distilled water and air show, respectively, an increase and a decrease in dynamic modulus of elasticity, due principally to changes in moisture content; overall, no negative impact on the concrete properties of these specimens is observed. At lower concentrations, sodium chloride and calcium chloride have a relatively small negative impact on the properties of concrete. At high concentrations, sodium chloride has a greater but still relatively small negative effect. At low concentrations, magnesium chloride and calcium magnesium acetate can cause measurable damage to concrete. At high concentrations, calcium chloride, magnesium chloride, and calcium magnesium acetate cause significant changes in concrete that result in loss of material and a reduction in stiffness and strength.

Key words: chlorides, concrete, deicing salts, calcium chloride, calcium magnesium acetate, magnesium chloride, sodium chloride

INTRODUCTION

The application of deicing chemicals can result in the deterioration of concrete roads and bridges by causing scaling when the concrete is subjected to cycles of freezing and thawing. Deicing chemicals can also cause concrete to deteriorate as the result of physical and chemical effects that occur whether or not the deicers cause significant scaling damage. Studies (Verbek and Kleiger 1957, Marchand et al. 1999) have demonstrated that sodium chloride and calcium chloride, the two principle deicing chemicals, cause maximum scaling under freeze-thaw conditions at concentrations in water between 2 and 4% by weight, with NaCl having the greater effect. Concentrations outside of this range, both lower and higher, have less effect on scaling. In contrast, studies of concrete deterioration caused by cycles of wetting and drying show that deterioration increases with an increasing concentration of the solution (Cody et al. 1996). The latter observations have important implications because high concentration solutions are often used for deicing and because the concentrated deicers will build up in concrete over time.

One drawback in studies of the effects of wetting and drying with deicers is that comparisons are typically made using solutions that have either an equal weight of deicing chemical or an equal molar concentration (equal number of molecules for a given volume of solution) (Cody et al. 1996, Lee et al. 2000). The problem with this approach is that the ice melting capability of a deicer is more closely related to the number of ions in a given quantity of water than to either the weight or molar concentration. For example, at the same molar concentration, $CaCl_2$ will have 50% more ions in solution than NaCl. The test procedures used in this study account for the number of ions produced when a deicer goes into solution.

A number of different test procedures have been used to evaluate the effects of wetting and drying. These have included cycles at room temperature, cycles at elevated temperatures, as high as 58°C (135°F), and wetting and drying cycles that include changes in temperature during both the wet and dry cycles. Specimens are usually evaluated based on physical changes at the macroscopic and microscopic level, as well as chemical changes that are observed using petrographic analysis, scanning electron microscopy, and x-ray microanalysis.

Previous studies (Cody et al. 1996, Taylor 1997, Lee et al. 2000, Sutter et al. 2006) have indicated that deicers can affect the chemistry of hardened cement paste. Chloride solutions tend to cause the formation of calcium chloride hydrate and calcium oxychloride, while magnesium chloride, in particular, results in the conversion of calcium silicate hydrate to non-cementitious magnesium silicate hydrate. In mixtures of calcium and magnesium acetate (CMA), magnesium acetate has been shown to cause the most severe damage, due to the formation of magnesium silicate hydrate, with little negative effect demonstrated by calcium acetate (Lee et al. 2000).

The effects of CMA on concrete have been observed in on-going corrosion research at the University of Kansas, with molal ion concentrations (based on the number of ions for a given quantity of water) equivalent to a 15% sodium chloride solution causing severe damage, not only to the concrete in corrosion specimens, but also to the adjacent concrete floor. CMA solutions with molal ion concentrations equivalent to a 3% sodium chloride solution have resulted in much less damage.

This report describes the results of a study in which the effects of four deicers, sodium chloride, calcium chloride, magnesium chloride, and calcium magnesium acetate, on concrete are compared using a technique that combines exposure procedures that were originally developed to allow deicing chemicals to rapidly penetrate concrete corrosion specimens with techniques that are used to evaluate the physical effects of cyclic freezing and thawing on concrete.

EXPERIMENTAL STUDY

Materials

In the study, the effects on concrete of cyclic wetting and drying with solutions containing sodium chloride (NaCl), calcium chloride ($CaCl_2$), magnesium chloride ($MgCl_2$), and calcium magnesium acetate (CMA) (4:6 molar ratio of calcium acetate to magnesium acetate) are evaluated. The study also includes control specimens that are exposed to air or to distilled water throughout the test period. Two concentrations are tested for each deicing chemical, a 6.04 molal ion concentration, equivalent in ion concentration to a 15% solution of NaCl, and a 1.06 molal ion concentration, equivalent to a 3% solution of NaCl. The compositions of the solutions are shown in Table 1.

Table 1 Deicer solutions

6.04 molal ion concentration solutions	
NaCl	850g water*, 150g NaCl (100% solids)
$MgCl_2$	612.5g water, 579.2g $MgCl_2$ (33.1% solution)
$CaCl_2$	1000g water, 223.5g $CaCl_2$ (92.36% Solids)
CMA	1000g water, 309.3g CMA (96% solids)
1.06 molal ion concentration solutions	
NaCl	970g water, 30g NaCl (100% solids)
$MgCl_2$	932.1g water, 101.5g $MgCl_2$ (33.1% solution)
$CaCl_2$	1000g water, 42.4g $CaCl_2$ (92.36% solids)
CMA	1000g water, 54g CMA (96% solids)

* distilled water used for all solutions

The concrete mixture used in the study contained Type I/II portland cement and had a water cement ratio of 0.45 and an air content of 6 percent. Mix proportions and aggregate properties are shown in Table 2.

Prismatic test specimens [3 in.^{2} × 12 in. (76 mm^2 ×305 mm)] are used. The concrete is mixed and the specimens fabricated in accordance with ASTM C 192. Specimens are cast horizontally in two layers with each layer consolidated for 30 seconds on a vibrating table with

Table 2 Concrete mixture proportions (SSD basis)

Cement	Water	Fine Aggregate	Coarse Aggregate	Vinsol Resin
lb/yd^3 (kg/m^3)	lb/yd^3 (kg/m^3)	lb/yd^3 (kg/m^3)	lb/yd^3 (kg/m^3)	gal/yd^3 (mL/m^3)
598 (355)	270 (160)	1436 (852)	1473 (874)	0.024 (90)
Concrete Properties: w/c = 0.45, 6 ± 1% entrained air, and 3 ± 0.5 in. (76 ± 13 mm) slump *Cement*: Type I/II portland cement *Fine Aggregate*: Kansas River sand with bulk specific gravity (SSD) = 2.62, absorption = 0.78%, fineness modulus = 2.51 *Coarse Aggregate*: Crushed limestone from Fogle Quarry with ¾ in. (19 mm) nominal maximum size, bulk specific gravity (SSD) = 2.58, absorption = 2.27 %, and unit weight of 95.9 lb/ft^3 (1536 kg/m^3) *Air-entraining Agent*: Daravair 1400, from W. R. Grace, Inc.				

an amplitude of 0.006 in. (0.15 mm) and a frequency of 60 Hz. The upper surface of the specimens is finished using a wooden float.

After casting, the specimens are covered with plastic, cured for 24 hours at room temperature, and then removed from the molds and cured in lime-saturated water at 73 ± 3°F (23 ± 1.7°C) for six days. After six days, the specimens are removed from the curing tank and allowed to dry at a temperature of 73 ± 3°F (23 ± 1.7°C) and a relative humidity of 50% ± 4% for 48 days.

The control specimens were cast separately from those exposed to deicers. For the specimens exposed to air, specimens 1 through 4 were cast in one batch and specimens 5 and 6 in another. For the specimens exposed to distilled water, specimens 1 and 2 were cast in one batch and specimens 3 through 6 in another. To limit variations in performance that might occur due to differences in concrete properties, the specimens exposed to deicers were cast in groups of four, eight, or 16 specimens, with equal numbers of specimens from each batch exposed to one of the four deicers. For the 6.04 molal ion deicer concentrations, specimens 1 and 2 were cast in batches of four, while specimens 3 through 16 were cast in a single batch of 16. For the 1.06 molal ion deicer concentrations, specimens 1 and 2, 3 and 4, and 5 and 6 were cast in batches of eight.

Test Procedure

The test procedure involves wet/dry exposure similar to that used for Southern Exposure corrosion test specimens (McDonald et al., 1998, Darwin et al. 2007a, 2007b), while the effect of the cycles is evaluated by measuring changes in the dynamic modulus of elasticity in accordance to the ASTM C 215, as used for freeze-thaw specimens in ASTM C 666.

Six specimens are used for each of the solutions shown in Table 1, along with six specimens each in air and distilled water. The specimens are submerged in the solutions (or distilled water) for four days at a temperature of 73 ± 4°F (23 ± 2°C). After four days, they are removed from the solution and dried in air at a temperature of 100 ± 3°F (38 ± 1.7°C) for three days under a portable heating tent. The deicer solutions and distilled water are replaced every five weeks. Specimens exposed to air are subjected to the temperature cycles. Cycles are repeated for up to a maximum of 95 weeks. Based on chloride concentrations obtained at a depth of 1 in. (25 mm) in the corrosion specimens (Ji et al. 2005, Darwin et al. 2007b) and on bridge decks (Lindquist et al. 2006), exposure to cyclic wetting and drying using this regimen simulates 10 years of exposure for bridge decks within the first 30 weeks and 30 years within the 95-week maximum duration of the test.

The fundamental transverse resonance frequency of each specimen is measured at the initiation of the tests and every five weeks thereafter (after the three-day drying period) using the procedures described in ASTM C 215. The dynamic modulus of elasticity (Dynamic *E*) can be calculated based on the fundamental transverse frequency, the mass, and dimensions of the test specimens [Equation (1) is taken directly from ASTM C 215]:

$$\text{Dynamic } E = CMn^2 \quad (1)$$

where:

M = mass of specimen, kg

n = fundamental transverse frequency, Hz

C = $0.9464(L^3T/bt^3)$, N•s^2 (kg•m^2)

L = length of specimen, m

t, b = dimensions of cross section of prism, m, t being the direction in which it is driven

T = a correction factor which depends on the ratio of the radius of gyration, K (= t/3.464), to the length of the specimen, L, and on Poisson's ratio. Values of T for Poisson's ratio of 1/6 may be obtained from Table 1 in ASTM C 215.

The masses M of specimens 3 through 6 exposed to the 6.04 molal ion deicer concentrations were not measured. For the calculation in Eq. (1), M for these specimens is replaced by a value calculated using the dimensions of the specimens and the average density of the 24 specimens subjected to the 1.06 molal ion deicer concentrations.

A total of 60 specimens were subjected to cycles of wetting and drying, temperature change, or both. As noted above, these included six specimens subjected to the same temperature history as the others while remaining in air throughout the test period. Changes in concrete properties are evaluated based on the ratio of the dynamic modulus of elasticity at the given number of cycles to the dynamic modulus of elasticity at the initiation of the wet/dry cycles. This ratio is referred to as the *relative dynamic modulus of elasticity (wet-dry)*, or $P_{w/d}$, to distinguish it from the value of P obtained using ASTM C 666 for specimens subjected to cycles of freezing and thawing. Wet/dry cycles continue for a total of 95 weeks or until the $P_{w/d}$ drops below 0.9, at which point the tests are terminated.

TEST RESULTS

The moduli of elasticity of the specimens are tabulated in Appendix A (Tables A.1 through A.10). The tables include the individual values, along with the average, standard deviation, and coefficient of variation for specimens of each type at five week intervals. The average values are used to calculate $P_{w/d}$. The consistency of the procedure is supported by the low coefficients of variation, which are generally at or below 4% except for specimens undergoing significant damage. The latter specimens exhibit coefficients of variation between 7.5 and 10% for values of $P_{w/d}$ below 0.9. The average relative dynamic moduli of elasticity (wet-dry) are presented in Fig. 1 and 2, which show the values of $P_{w/d}$ for specimens exposed to 6.04 and 1.06 molal ion concentration deicer solutions, respectively. The figures also include the results for specimens subjected to wet/dry temperature cycles in distilled water and temperature cycles in air.

Control Specimens

The specimens subjected to wet/dry cycles with distilled water exhibited an increase in the $P_{w/d}$ from 1.0 at the beginning of the test to approximately 1.1 at week 5, increased to 1.2 at week 35, and then remained approximately constant through week 95. The increase in the dynamic modulus of elasticity may be attributed in part to an increase in the degree of hydration but most likely resulted from the absorption of water. The specimens subjected to the temperature variations, but otherwise stored in air, exhibited a small but consistent drop in the dynamic modulus of elasticity throughout the test due to the loss in water (with accompanying microcracking), reaching a $P_{w/d}$ of 0.95 at 95 weeks.

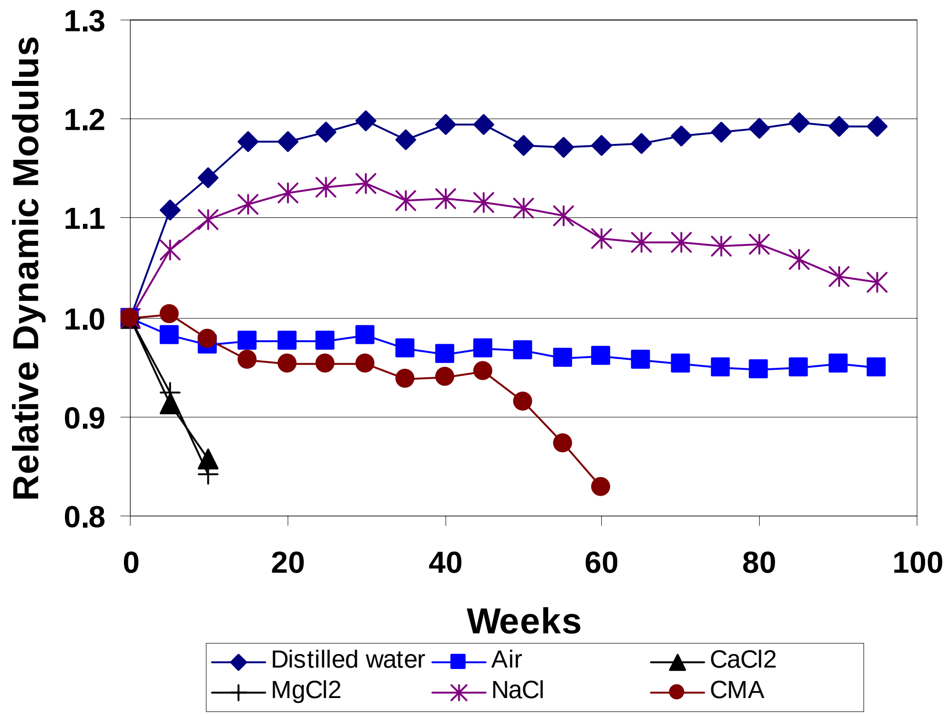

Fig. 1 Relative dynamic modulus of elasticity (wet-dry) $P_{w/d}$ versus number of weekly wet-dry cycles for specimens exposed to 6.04 molal ion concentration deicer solutions

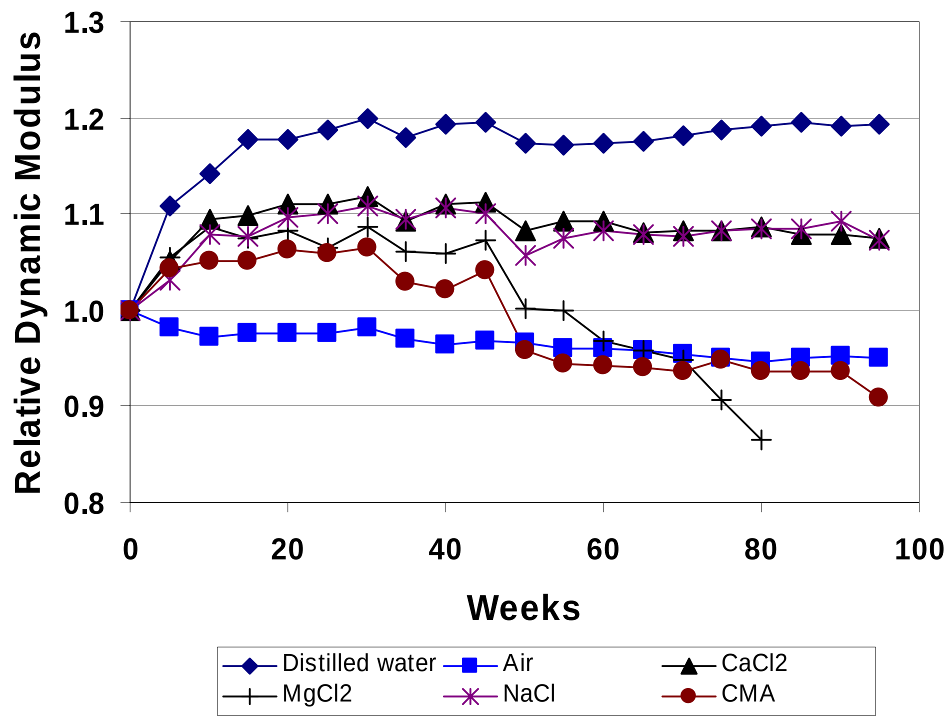

Fig. 2 Relative dynamic modulus of elasticity (wet-dry) $P_{w/d}$ versus number of weekly wet-dry cycles for specimens exposed to 1.06 molal ion concentration deicer solutions

High Concentration of Deicers

As shown in Fig. 1, the specimens exposed to the high concentrations of calcium chloride ($CaCl_2$) and magnesium chloride ($MgCl_2$) deteriorated rapidly, with the $P_{w/d}$ dropping below 0.9 by week 10. The specimens exposed to calcium magnesium acetate (CMA) deteriorated more slowly, with the $P_{w/d}$ dropping below 0.9 by week 55; in this case, the wet/dry cycles were continued for another five weeks. The concrete subjected to the high concentration NaCl solution exhibited a rise in the $P_{w/d}$ through week 30, to 1.14, likely due to the absorption of water and perhaps the formation of salt crystals, which filled some of the pore space within the cement paste, followed by a gradual drop to a value of 1.04 at week 95, indicating damage, also likely due to salt crystal formation (see Visual Evaluation).

Low Concentration of Deicers

As shown in Fig. 2, the use of lower concentrations of deicers reduced the negative effects of all four deicers compared to that obtained at the high concentration, in some cases significantly. During the early weeks of the tests, all specimens submerged in the lower concentration deicer solutions exhibited an increase $P_{w/d}$, as described for the specimens exposed to distilled water. The specimens exposed to $CaCl_2$ and NaCl exhibited the greatest increase, with peak values of $P_{w/d}$ of 1.11. After week 45, $P_{w/d}$ for these specimens began to drop very slowly, indicating some damage, reaching a value of 1.07 at week 95. $P_{w/d}$ of 1.07 is higher than that observed for the higher concentration solutions (0.86 at week 10 for $CaCl_2$ and 1.04 at week 95 for NaCl). The peak value of $P_{w/d}$ for the high concentration NaCl specimens (1.14) was slightly higher than the value observed at the lower concentration (1.11). The difference may be due to the effects of increased crystallization within the pores for the specimens exposed to the higher concentration solution.

$P_{w/d}$ for specimens exposed to CMA and $MgCl_2$ reached values as high as 1.07 and 1.09, respectively, remaining nearly constant through week 45 and then dropping thereafter. $P_{w/d}$ for the CMA specimens dropped below 1.0 at week 50, reaching a value of 0.91 at week 95. The $MgCl_2$ specimens, which initially exhibited a slightly higher value of $P_{w/d}$ than the CMA specimens and maintained $P_{w/d}$ above 1.0 until week 55, exhibited a more rapid drop in dynamic modulus after week 70, reaching a value of $P_{w/d}$ below 0.9 by week 80.

Visual Evaluation

The specimens were evaluated for physical damage and photographs were taken at the conclusion of the tests. The appearance of the specimens is largely in agreement with the performance represented in Fig. 1 and 2.

Specimens subjected to temperature cycles in air (not shown) and wet-dry cycles in distilled water or in 1.06 molal ion concentration NaCl and $CaCl_2$ solutions (Fig. 3, 4 and 5, respectively) show few signs of damage. The only apparent change is a slight discoloration of the $CaCl_2$ specimens (Fig. 5). In contrast to the NaCl and $CaCl_2$ specimens, the specimens subjected to $MgCl_2$ and CMA exhibit signs of damage, as shown in Fig. 6 and 7, respectively. The $MgCl_2$ specimens (Fig. 6) were subjected to wet-dry cycles for 80 weeks, after which the test was terminated because the modulus of elasticity had dropped below 90% of its initial value. The CMA specimen (Fig. 7) completed 95 weeks of wet-dry cycling.

All of the specimens subjected to the 6.04 molal ion concentration solutions exhibited damage at the conclusion of the test. Of these specimens, only the specimens in the NaCl solution lasted for the full 95 weeks. As shown in Fig. 8, the NaCl specimens exhibited some surface scaling, likely the result of crystal growth in the concrete pores. The specimens subjected to 6.04 molal ion concentration $CaCl_2$ and $MgCl_2$ solutions (Fig. 9 and 10) exhibited the greatest

Fig. 3 Specimen subjected to 95 weeks of exposure to distilled water

Fig. 4 Specimen subjected to 95 weeks of exposure to a 1.06 molal ion concentration solution of NaCl

Fig. 5 Specimen subjected to 95 weeks of exposure to a 1.06 molal ion concentration solution of $CaCl_2$

Fig. 6 Specimen subjected to 80 weeks of exposure to a 1.06 molal ion concentration solution of $MgCl_2$

Fig. 7 Specimen subjected to 95 weeks of exposure to a 1.06 molal ion concentration solution of CMA

Fig. 8 Specimen subjected to 95 weeks of exposure to a 6.04 molal ion concentration solution of NaCl

Fig. 9 Specimen subjected to 10 weeks of exposure to a 6.04 molal ion concentration solution of $CaCl_2$

Fig. 10 Specimen subjected to 10 weeks of exposure to a 6.04 molal ion concentration solution of $MgCl_2$

Fig. 11 Specimen subjected to 60 weeks of exposure to a 6.04 molal ion concentration solution of CMA

degree of damage, with a loss of material from the ends and edges of the specimens, as well as some delamination. As suggested in earlier studies (Cody et al. 1996, Taylor 1997, Lee et al. 2000, Sutter et al. 2006), the damage to the $CaCl_2$ and $MgCl_2$ specimens appears to be the result of both physical damage due to crystal formation in the concrete pores and chemical changes in the cement paste. The $CaCl_2$ and $MgCl_2$ specimens also exhibited the greatest reduction in modulus of elasticity, with the tests terminating at 10 weeks, as shown in Fig. 1. The specimens subjected to the 6.04 molal ion concentration CMA solution (Fig. 11) exhibited a nearly uniform loss of material on all exposed surfaces – a change that appears to result primarily from chemical changes in the cement paste (Lee et al. 2000). The relative dynamic modulus of these specimens dropped below 1.0 at week 55 (Fig. 1).

Overall, the results of this study, as represented by the measured changes in modulus of elasticity and observable damage to the test specimens, indicate that calcium chloride, magnesium chloride, and calcium magnesium acetate have a negative impact on the long-term durability of concrete. As shown in Fig. 2, 7, and 8, the effects of magnesium chloride and CMA should become apparent at an earlier age than the effects of calcium chloride (Fig. 6). In the longer-term, all three deicers will significantly weaken concrete (Fig. 1, 9-11). Sodium chloride, the most widely used deicer in U.S. practice, has a more benign impact in both the short and long term.

SUMMARY AND CONCLUSIONS

Concrete specimens were exposed to weekly Southern Exposure-type cycles of wetting and drying in distilled water and in solutions of sodium chloride, calcium chloride, magnesium chloride, and calcium magnesium acetate with either a 6.04 molal ion concentration, equivalent in ion concentration to a 15% solution of NaCl, or a 1.06 molal ion concentration, equivalent in ion concentration to a 3% solution of NaCl, for periods of up to 95 weeks. Specimens were also exposed to air only. The effects of exposure were evaluated based on changes in the dynamic modulus of elasticity and the physical appearance of the specimens at the conclusion of the tests.

The following conclusions are based on the tests and analyses presented in this report.

1. Concretes exposed to distilled water and air show, respectively, an increase and a decrease in dynamic modulus of elasticity, due principally to changes in moisture content. Overall, no negative impact on concrete properties is observed.
2. At lower concentrations, sodium chloride and calcium chloride have a relatively small negative impact on the properties of concrete. At high concentrations, sodium chloride has a greater but still relatively small negative effect. Damage appears to be primarily due to the effects of crystal growth within concrete pores.
3. At low concentrations, magnesium chloride and calcium magnesium acetate can cause measurable damage to concrete.
4. At high concentrations, calcium chloride, magnesium chloride, and calcium magnesium acetate cause significant changes in concrete that result in loss of material and a reduction in stiffness and strength. The damage caused by calcium chloride and magnesium chloride appears to be the result of both physical damage, due to crystal formation in the concrete pores, and chemical changes in the cement paste. The damage caused by calcium magnesium acetate appears to be primarily caused by chemical changes in the cement paste.
5. The application of significant quantities of calcium chloride, magnesium chloride, and calcium magnesium acetate over the life of a structure or pavement will negatively impact the long-term durability of concrete.

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Appendix A

Table A.1 Moduli of elasticity of specimens in air (ksi)

TIME (weeks)	1	2	3	4	5	6	Average	Std Dev	COV
0	4352	4410	4263	4241	4184	4034	4247	132	0.031
5	4264	4325	4213	4089	4164	3985	4173	123	0.029
10	4224	4275	4133	3985	4168	4005	4132	116	0.028
15	4244	4292	4140	4011	4168	4008	4144	117	0.028
20	4247	4332	4153	4027	4076	4024	4143	125	0.030
25	4278	4215	4179	4060	4174	3982	4148	108	0.026
30	4278	4359	4193	4070	4148	3988	4173	135	0.032
35	4247	4312	4163	4011	4083	3879	4116	159	0.039
40	4237	4302	4153	4005	3980	3879	4093	164	0.040
45	4227	4305	4163	3995	4106	3870	4111	159	0.039
50	4261	4302	4163	3988	4089	3828	4105	177	0.043
55	4224	4298	4048	3963	4102	3828	4077	171	0.042
60	4214	4218	4156	3979	4067	3854	4081	144	0.035
65	4224	4191	4068	3988	4089	3841	4067	140	0.034
70	4183	4185	4064	3950	4096	3835	4052	138	0.034
75	4120	4178	4038	3930	4083	3841	4032	125	0.031
80	4110	4151	4015	3898	4106	3844	4021	125	0.031
85	4130	4205	4032	3905	4109	3819	4033	146	0.036
90	4150	4235	4035	3918	4112	3835	4047	150	0.037
95	4150	4086	4084	3921	4132	3825	4033	130	0.032

Table A.2 Moduli of elasticity of specimens in distilled water (ksi)

TIME (weeks)	1	2	3	4	5	6	Average	Std Dev	COV
0	4388	4522	4624	4661	4808	4661	4549	142	0.031
5	5230	4988	4987	4974	5170	5112	5045	109	0.022
10	5332	5088	5174	5184	5378	5341	5194	116	0.022
15	5511	5294	5305	5316	5491	5469	5357	103	0.019
20	5480	5279	5309	5361	5541	5507	5357	111	0.021
25	5620	5389	5272	5313	5507	5454	5398	129	0.024
30	5608	5366	5420	5413	5591	5568	5452	106	0.019
35	5550	5324	5272	5305	5514	5575	5363	137	0.026
40	5596	5362	5379	5387	5575	5641	5431	127	0.023
45	5635	5412	5349	5335	5518	5587	5433	126	0.023
50	5523	5313	5272	5228	5453	5469	5334	121	0.023
55	5461	5267	5272	5309	5484	5394	5327	95	0.018
60	5519	5275	5287	5265	5438	5511	5336	121	0.023
65	5519	5267	5305	5287	5476	5477	5345	113	0.021
70	5542	5309	5346	5316	5545	--	5378	121	0.023
75	5573	5374	5320	5335	5552	--	5400	122	0.023
80	5592	5381	5320	5379	5571	--	5418	124	0.023
85	5631	5431	5364	5335	5571	--	5440	130	0.024
90	5620	5378	5309	5383	5587	--	5422	139	0.026
95	5616	5416	5316	5350	5575	--	5424	134	0.025

Table A.3 Moduli of elasticity of specimens in 6.04 molal ion concentration solution of NaCl (ksi)

TIME (weeks)	1	2	3	4	5	6	Average	Std Dev	COV
0	4500	4785	4834	4956	5018	5107	4867	215	0.044
5	4985	5165	5347	4760	5413	5510	5197	284	0.055
10	4949	5286	5382	5409	5491	5565	5347	217	0.041
15	4996	5297	5428	5594	5561	5668	5424	247	0.046
20	5256	5366	5466	5455	5620	5719	5481	168	0.031
25	5155	5481	5416	5618	5609	5731	5502	203	0.037
30	5298	5532	5458	5629	5561	5679	5526	136	0.025
35	5137	5439	5366	5579	5506	5644	5445	180	0.033
40	5200	5316	5374	5594	5565	5656	5451	180	0.033
45	5207	5420	5393	5375	5546	5675	5436	160	0.029
50	5237	5435	5305	5303	5522	5636	5406	153	0.028
55	5174	5309	5252	5269	5609	5612	5371	191	0.036
60	5185	5082	4998	5130	5514	5628	5256	254	0.048
65	5207	5071	5046	5104	5483	5483	5232	202	0.039
70	5230	5176	4958	5096	5429	5549	5240	217	0.041
75	5207	5172	4991	5074	5371	5510	5221	191	0.037
80	5193	5184	5039	5063	5351	5518	5225	182	0.035
85	5126	5124	5039	4760	5440	5420	5152	254	0.049
90	4862	5150	5057	4760	5405	5190	5071	233	0.046
95	4902	4967	5046	4804	5386	5137	5040	205	0.041

Table A.4 Moduli of elasticity of specimens in 1.06 molal ion concentration solution of NaCl (ksi)

TIME (weeks)	1	2	3	4	5	6	Average	Std Dev	COV
0	4922	5069	4954	5059	5060	4968	5005	65	0.013
5	5036	5242	5183	5288	5176	5034	5160	105	0.020
10	5352	5460	5288	5480	5485	5327	5399	87	0.016
15	5321	5506	5307	5404	5465	5331	5389	83	0.015
20	5452	5608	5363	5461	5582	5449	5486	92	0.017
25	5580	5639	5318	5420	5625	5495	5513	126	0.023
30	5541	5663	5424	5495	5621	5522	5544	86	0.016
35	5421	5479	5447	5537	5601	5411	5483	74	0.013
40	5490	5584	5428	5530	5691	5511	5539	90	0.016
45	5556	5468	5417	5618	5465	5550	5512	75	0.014
50	5133	5322	5183	5307	5446	5323	5286	112	0.021
55	5306	5368	5217	5488	5434	5476	5381	106	0.020
60	5452	5429	5205	5518	5519	5395	5420	116	0.021
65	5291	5487	5217	5473	5543	5411	5403	126	0.023
70	5268	5510	5213	5348	5574	5426	5390	140	0.026
75	5363	5503	5299	5450	5512	5395	5420	83	0.015
80	5386	5518	5288	5469	5547	5380	5431	97	0.018
85	5379	5506	5262	5473	5539	5426	5431	101	0.019
90	5498	5545	5390	5465	5489	5415	5467	57	0.010
95	5463	5549	5394	5281	5206	5323	5369	125	0.023

Table A.5 Moduli of elasticity of specimens in 6.04 molal ion concentration solution of $CaCl_2$ (ksi)

TIME (weeks)	1	2	3	4	5	6	Average	Std Dev	COV
0	4704	4637	5235	4725	5093	5119	4879	258	0.053
5	4181	4361	4677	4387	4663	4488	4454	191	0.043
10	3536	4222	4475	4270	4398	4470	4180	355	0.085

Table A.6 Moduli of elasticity of specimens in 1.06 molal ion concentration solution of $CaCl_2$ (ksi)

TIME (weeks)	1	2	3	4	5	6	Average	Std Dev	COV
0	5069	5075	5175	5221	4956	4939	5072	113	0.022
5	5285	5268	5456	5523	5244	5231	5334	123	0.023
10	5564	5514	5598	5639	5536	5466	5553	62	0.011
15	5598	5465	5661	5702	5548	5435	5568	106	0.019
20	5645	5530	5681	5722	5638	5566	5630	71	0.013
25	5653	5645	5645	5624	5642	5581	5632	27	0.005
30	5641	5634	5729	5777	5646	5577	5667	72	0.013
35	5521	5503	5621	5749	5486	5378	5543	128	0.023
40	5537	5584	5701	5714	5689	5577	5634	76	0.014
45	5676	5649	5729	5726	5618	5462	5643	99	0.018
50	5483	5468	5653	5616	5332	5401	5492	123	0.022
55	5606	5488	5629	5639	5455	5439	5543	92	0.017
60	5802	5434	5598	5608	5439	5355	5539	162	0.029
65	5456	5396	5598	5632	5424	5370	5479	109	0.020
70	5483	5446	5605	5624	5431	5389	5496	97	0.018
75	5460	5449	5590	5608	5466	5386	5493	87	0.016
80	5471	5465	5609	5639	5486	5427	5516	86	0.016
85	5448	5392	5590	5620	5420	5382	5475	103	0.019
90	5448	5453	5574	5604	5416	5355	5475	95	0.017
95	5441	5423	5574	5600	5397	5276	5452	120	0.022

Table A.7 Moduli of elasticity of specimens in 6.04 molal ion concentration solution of $MgCl_2$ (ksi)

TIME (weeks)	1	2	3	4	5	6	Average	Std Dev	COV
0	5080	4606	5177	4932	5098	5086	4978	207	0.042
5	4450	4464	4780	4714	4618	4520	4605	136	0.030
10	4092	4283	4504	4384	3691	3667	4191	356	0.085

Table A.8 Moduli of elasticity of specimens in 1.06 molal ion concentration solution of $MgCl_2$ (ksi)

TIME (weeks)	1	2	3	4	5	6	Average	Std Dev	COV
0	4964	5123	5089	5019	5091	5012	5050	61	0.012
5	5248	5334	5429	5429	5199	5295	5322	94	0.018
10	5497	5568	5448	5352	5568	5485	5486	81	0.015
15	5420	5414	5452	5413	5452	5403	5426	21	0.004
20	5470	5595	5409	5410	5491	5438	5469	70	0.013
25	5316	5448	5248	5220	5533	5477	5374	130	0.024
30	5412	5502	5479	5444	5552	5532	5487	53	0.010
35	5259	5311	5267	5292	5537	5462	5355	116	0.022
40	5290	5368	5375	5254	5319	5485	5348	81	0.015
45	5389	5525	5348	5421	5338	5485	5418	75	0.014
50	4814	4916	5153	5123	5162	5181	5058	154	0.031
55	4890	4960	4988	5205	5069	5155	5045	121	0.024
60	4861	5019	4786	4837	4857	4971	4889	88	0.018
65	4626	4986	4692	4848	4836	5027	4836	157	0.033
70	4450	4909	4570	4891	4803	5087	4785	235	0.049
75	4294	4880	4059	4740	4626	4867	4578	333	0.073
80	4243	4865	3594	4496	4430	4596	4371	432	0.099

Table A.9 Moduli of elasticity of specimens in 6.04 molal ion concentration solution of CMA (ksi)

TIME (weeks)	1	2	3	4	5	6	Average	Std Dev	COV
0	4613	4742	5027	4871	4972	5062	4881	175	0.036
5	4719	4793	4975	4850	4997	5028	4894	125	0.026
10	4592	4807	4780	4618	4943	4932	4779	150	0.031
15	4536	4651	4719	4608	4738	4797	4675	95	0.020
20	4547	4547	4599	4567	4845	4815	4653	138	0.030
25	4557	4713	4582	4574	4716	4764	4651	90	0.019
30	4498	4605	4820	4530	4816	4667	4656	139	0.030
35	4488	4651	4677	4371	4631	4650	4578	122	0.027
40	4463	4385	4716	4421	4713	4822	4587	185	0.040
45	4467	4515	4620	4371	4816	4928	4620	214	0.046
50	4235	4288	4656	4276	4568	4761	4464	225	0.051
55	4119	4188	4443	3986	4238	4575	4258	216	0.051
60	3916	3949	4154	3806	4068	4379	4045	203	0.050

Table A.10 Moduli of elasticity of specimens in 1.06 molal ion concentration solution of CMA (ksi)

TIME (weeks)	1	2	3	4	5	6	Average	Std Dev	COV
0	5201	4868	5128	5010	5485	4816	5085	245	0.048
5	5420	5119	5360	5196	5693	5028	5302	241	0.045
10	5386	5130	5295	5169	5869	5225	5346	272	0.051
15	5469	5107	5333	5181	5805	5154	5342	263	0.049
20	5562	5276	5322	5188	5873	5176	5399	271	0.050
25	5562	5276	5291	5139	5845	5214	5388	266	0.049
30	5562	5227	5368	5294	5805	5225	5413	229	0.042
35	5265	4978	5276	5102	5765	5024	5235	287	0.055
40	5250	4985	5166	5002	5717	5039	5193	276	0.053
45	5462	5126	5283	5143	5781	4976	5295	289	0.055
50	4977	4706	4879	4698	4761	5206	4871	196	0.040
55	4937	4699	4774	4563	4703	5142	4803	206	0.043
60	4882	4688	4748	4542	4664	5251	4796	249	0.052
65	4893	4692	4669	4549	4682	5187	4779	229	0.048
70	4918	4681	4583	4538	4675	5165	4760	238	0.050
75	4980	4603	4698	4598	4768	5308	4826	275	0.057
80	4947	4572	4752	4472	4657	5184	4764	262	0.055
85	5061	4565	4752	4472	4628	5079	4759	257	0.054
90	4882	4649	4694	4531	4592	5199	4758	247	0.052
95	4693	4519	4683	4337	4413	5102	4624	274	0.059