01 Jan 2022

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Recommended Citation

J. Liu et al., "Impact of Deicers on Low-Temperature Performance of Missouri Pavements," *International Conference on Transportation and Development 2022: Application of Emerging Technologies - Selected Papers from the Proceedings of the International Conference on Transportation and Development 2022*, vol. 5, pp. 258 - 268, American Society of Civil Engineers, Jan 2022.
The definitive version is available at https://doi.org/10.1061/9780784484357.023

Impact of Deicers on Low-Temperature Performance of Missouri Pavements

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ABSTRACT

The use of deicer chemicals for highway winter maintenance operations is an essential strategy for ensuring a reasonably high level of service. It's critical to quantify their effectiveness and potentially detrimental effects on transportation infrastructure (i.e., asphalt and concrete pavements). In this study, nine deicer chemicals used in the state of Missouri were collected. The ice-melting test was conducted to quantify the performance characteristics of deicer chemicals. Freeze-thaw (F-T) test of concrete in the presence of deicer was conducted to quantify the negative effects of deicers to concrete. Low-temperature behavior of asphalt mixture affected by deicers was quantified by asphalt mixture indirect tensile (IDT) tests. The results showed that the calcium chloride (liquid) treated rock salt had the best ice melting capacity among all the studied products, while the calcium chloride (flake/pellet) treated rock salt showed the lowest ice melting capacity. The IDT creep compliance and strength of asphalt mixture results indicated brine treated rock salt and "Top Film" treated rock salt had insignificant effects on the creep compliance of asphalt mixture, regardless of testing temperatures. The deicer chemicals had different scaling effects on concrete beams after F-T cycles. The calcium chloride (liquid) treated rock salt had little scaling effect on the concrete beams. However, concrete beams with the presence of brine treated rock salt showed the highest mass loss values.

INTRODUCTION

The use of deicer chemicals for highway winter maintenance operations is an essential strategy for ensuring a reasonably high level of service. Chloride-based salts are the most common chemicals used to serve as freezing-point depressants for winter road service applications (Blackburn et al. 2004) such as sodium chloride (NaCl), magnesium chloride ($MgCl_2$), and calcium chloride ($CaCl_2$). They are the most readily available and widely used, in either solid or liquid form (Fay and Shi 2011). They are effective over a wide range of temperatures (Cuelho et al. 2010), and their baseline performance and corrosivity have been reported (Shi et al. 2013). NaCl is the most widely used chemical owing to its abundance and low cost, and in the U.S., approximately 20 million tons of NaCl is used for every typical winter season. However, when air and pavement temperatures are below 10°F, NaCl-based deicers become much less effective and may cause snow to stick to the pavement. At cold temperatures,

$MgCl_2$ brines are often used instead of NaCl because they exhibit better ice melting performance. According to field studies, $CaCl_2$ is more effective than NaCl owing to its ability to attract moisture and stay on the roads. These chloride salts (NaCl, $MgCl_2$, $CaCl_2$) have also been commonly used in the state of Missouri. However, recent studies revealed that the damage by chloride salts deicer may compromise the strengths of concrete without any visible surface distress, thus evading the traditional inspection methods (Xie et al. 2019). Also, the chloride salts are persistent in the environment, posing a significant risk to infrastructure (Shi et al. 2010), motor vehicles (Li et al. 2013; Shi et al. 2013), and the natural environment over time (Corsi et al. 2015). Therefore, it's critical to quantify their effectiveness and potentially detrimental effects on transportation infrastructure (i.e., asphalt and concrete pavements). The objectives of this study are to: (1) quantify the performance characteristics of deicer chemicals in Missouri and (2) evaluate the impact of deicers on low-temperature performance of Missouri pavements.

MATERIALS AND EXPERIMENTAL DETAILS

A total of nine de-icing/anti-icing products were collected from Missouri Department of Transportation (MoDOT), as listed in Table 1. Table 2 presents the pH values of collected deicer solutions (with concentration of 9% by weight). As shown, all the products have pH values around 8. Product #1 which is untreated road salt had the lower pH value of 7.84, while the product #8 (beet juice treated rock salt) had the highest pH value of 8.57. Overall, the deicer products (solution, 9% by weight) evaluated are not too basic or too acidic with pH values ranged from 7.84 to 8.57.

The ice-melting test was conducted to quantify the performance characteristics of deicers as a function of time, by measuring the ice melted by each deicer over time. A modified Strategic Highway Research Program (SHRP) ice-melting test (H-205.1 and H-205.2) was conducted. In this test, 48 mL deionized water was used for making the ice in a 150 × 20 mm petri dish. Then, 1.4 mL liquid deicer (or 1.5 g solid deicer) was applied over the ice at 25°F. After 10, 20, 30, 45, and 60 min, the volume of "icemelt" was measured and it was returned to the ice sample evenly. The tests were triplicated to ensure statistical reliability.

Table 1. List of Evaluated De-Icing/Anti-Icing Products

No. (#)	Products
1	Rock salt – untreated [baseline]
2	Rock salt – brine treated
3	"Snow Slicer" treated rock salt (Magnesium treated #1); from the Marshfield Maintenance Building
4	"Ice Ban" treated rock salt (Magnesium treated #2); from St. Louis
5	"Clear Lane" product (Magnesium treated #3-delivered as a pre-mixed product); from St. Louis
6	Calcium chloride (flake/pellet) treated rock salt
7	Calcium chloride (liquid) treated rock salt
8	Beet juice treated rock salt
9	"Top Film" treated rock salt

Table 2. pH values of deicer solutions (9%wt)

Products	#1	#2	#3	#4	#5	#6	#7	#8	#9
pH value	7.84	7.91	8.03	8.06	7.93	7.84	8.3	8.57	8.19

The freeze-thaw (F-T) test was conducted to quantify the negative effects of deicers to concrete; the more severe freeze-thaw (F-T) damage in the presence of deicer, the less desirable a deicer is. The freeze-thaw (F-T) test of PCC in the presence of deice solutions was conducted following ASTM C666. A mixture recommended by the MoDOT for rigid pavements was used (Sadati and Khayat 2016). This concrete was prepared with 323 kg/m^3 of cementitious materials that included 25% Class C fly ash, by mass, a water cement ratio (w/cm) of 0.40, and virgin aggregate. Crushed limestone with a maximum size of 25 mm was used for the virgin aggregate. Table 3 summarizes the mixture proportions and fresh properties of the concrete. The PCC beam samples were made in 3"x3"x16" (7.62 cm x 7.62 cm x 40.64 cm) molds for both control and samples with the presence of deicer solution. The samples were first cured for 14 days in a water bath and then subjected to F-T cycles either until 300 cycles occurred or until the relative dynamic modulus of elasticity reduced to 60% of the original modulus or lower. Instead of using thawing water as stated in ASTM C666, diluted deicer solution (9%, by weight) was used during the F-T cycles. Measurements before testing begun and then every 36 cycles thereafter were conducted including the mass of the sample and the frequency and velocity of an electrical pulse through the sample. The velocity was measured using a PROCEQ ultrasound with a frequency of 54 Hz. Samples were kept in a temperature-controlled cabinet, which exposed samples to freezing temperatures for four hours, followed by two hours of thawing. To calculate the relative dynamic modulus of elasticity (RDME), Equation 1 was used.

$$\mathrm{RDME}\ (\%) = \frac{\mathrm{v_n}^2}{\mathrm{v_0}^2} \qquad (1)$$

where, v_0 is the initial ultrasonic pulse velocity and v_n is the ultrasonic pulse velocity at n cycles. The durability factor (DF) for each mixture was also determined using Equation 2.

$$\mathrm{DF} = \mathrm{RDME_f} \times \mathrm{n_f}/\mathrm{n_t} \qquad (2)$$

where, n_f is the cycles that the $RDME_f$ represents while n_t is the cycles at which all testing was terminated, which in this case was 300 cycles. The $RDME_f$ represents either the RDME once it reaches 60% or lower, or the RDME after 300 cycles, whichever occurs sooner. The durability factor ranges from 0% to 100%. A higher durability factor suggests the sample has high resistance to F-T cycles. A lower durability factor indicates the sample’s durability is low and degraded quickly after many F-T cycles.

For F-T tests of PCM, the SHRP H205.8 F-T cyclic test method with minor modifications was employed, and the mass loss (difference in mass before and after F-T cycles) was recorded. The PCM cylinder samples was made in 2” (diameter) × 4” (length) molds, using a mix design representative of MoDOT concrete mixes (Table 3). The prepared cylinders were cured for 24 hours in water before being placed in a temperature chamber with 100% relative humidity for 28 days. Then the dry weights of the samples were measured before being placed in plates, equipped with a sponge in their bottom, holding 560 mL of 9% deicer liquid. Plates with PCM cylinders were kept at -20.8 ± 0.2°C for about 2 h then at 23.2 ± 0.2°C for about another 2 h. Thirty F-T cycles were carried out. The scaled-off materials were removed from the samples, and they were air-dried overnight before recording the weight.

Table 3. Mixture proportions and fresh properties of the PCC

Mixture proportions and properties	**Value**
Cementitious materials (kg/m^3)	323
Type I/II cement (kg/m^3)	243
Class C fly ash, by mass (%)	25
Class C fly ash (kg/m^3)	81
Water cementitious materials ratio (w/cm)	0.4
Water (kg/m^3)	129
Sand (kg/m^3)	745
Coarse virgin aggregate (kg/m^3)	1121
Air content (%)	6±1%
Slump (mm)	50

For low-temperature performance of asphalt mixtures in the presence of liquid deicer, indirect tension test (IDT) was conducted according to AASHTO T322-07. Loose mixtures with PG 64-24 used in Missouri was collected and compacted. In this study, tests were conducted at three different temperatures (i.e., -20, -10, and 0°C). During the loading period, vertical and horizontal deformations were measured on the two parallel faces of the specimen using two LVDTs per specimen face. Three replicates were applied. The creep compliance of each mixture was calculated according to the function (Eq. 3) from AASHTO T 322.

$$D_t = \frac{\Delta X \times D_{avg} \times b_{avg}}{P_{avg} \times GL} \times C_{cmpl} \quad (3)$$

where, D_t = creep compliance (1/kPa); ΔX = trimmed mean of the horizontal deformations (m), D_{avg} = average specimen diameters (m); b_{avg} = average specimen thickness (m); P_{avg} = average force during the test (kN); GL = gage length (38mm); and C_{cmpl} = creep compliance parameter at any given time, computed as:

$$C_{cmpl} = 0.6354 \times \left(\frac{X}{Y}\right)^{-1} - 0.332 \quad (4)$$

where, $\frac{X}{Y}$ = the ratio of the horizontal to vertical deformations.

RESULTS AND ANALYSIS

Ice melting test

Ice melting test results for sample measurements during the 60 min test are shown in Figure 1. Ice melted (IMC), (mL/g) at a time point was calculated based on Eq. 5. As shown in Figure 1, the ice melt of all products tended to increase over time, and the increasing rate almost kept constant. The scenarios are consistent with the ice melting results from the other research (Hossain et al. 2015). The products #7, #8, #9 (which are calcium chloride (liquid) treated rock salt, beet juice treated rock salt, and "Top Film" treated rock salt, respectively) showed better ice melting capacities than the other evaluated products. The product #6 which is the calcium chloride (flake/pellet) treated rock salt showed the lowest IMC values at each specific time. A summary of all accumulated volume of the melted ice results at the 20- and 60-min measurements are shown in Figure 2, which present similar scenarios. The product #7 (calcium chloride (liquid) treated rock salt) showed the best ice melting capacity among all the studied products.

$$IMC = \frac{A}{B} \tag{5}$$

where A is the volume of melted ice (mL) at a specific time and B is the initial mass of solid salt (g).

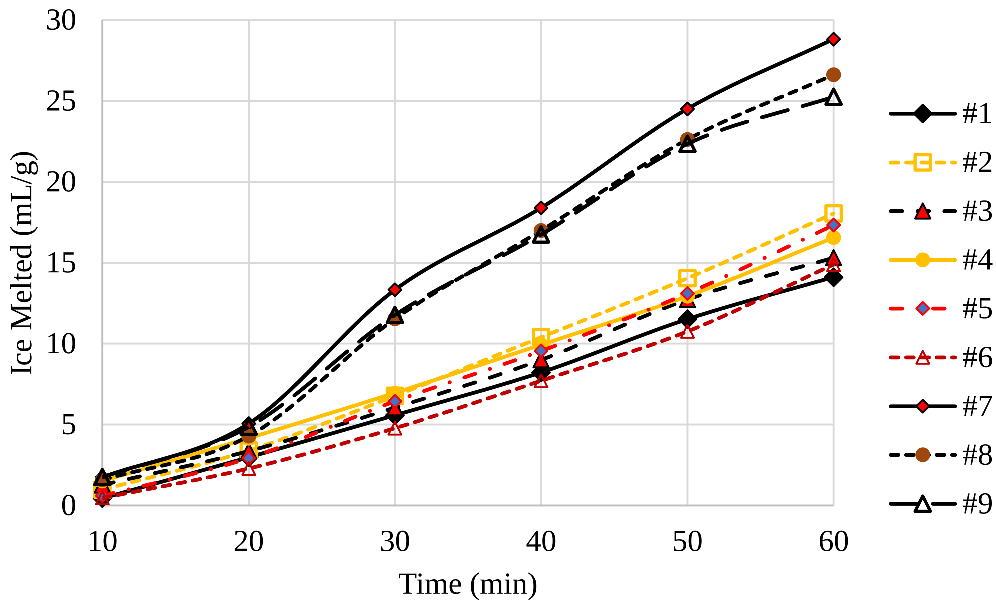


Figure 1. Ice melting test results at −4°C

Concrete freeze-thaw (F-T) test

Table 4 presents the durability factor (DF) results of the PCCs with the presences of different dicer products. As shown in this table, the concrete beams treated with different deicer products showed similar DF values after 300 F-T cycles. All concrete beams had DF values higher than 90%, which indicated that the concrete beams (with the selected typical Missouri mix design) had good durability even with the presence of deicer products. No significant difference (on DF) could be found between the concrete beams with the presence of water and deicer products. The difference among the effects of different deicer products on DF values of concrete beams could not be identified since all concrete beams showed good durability.

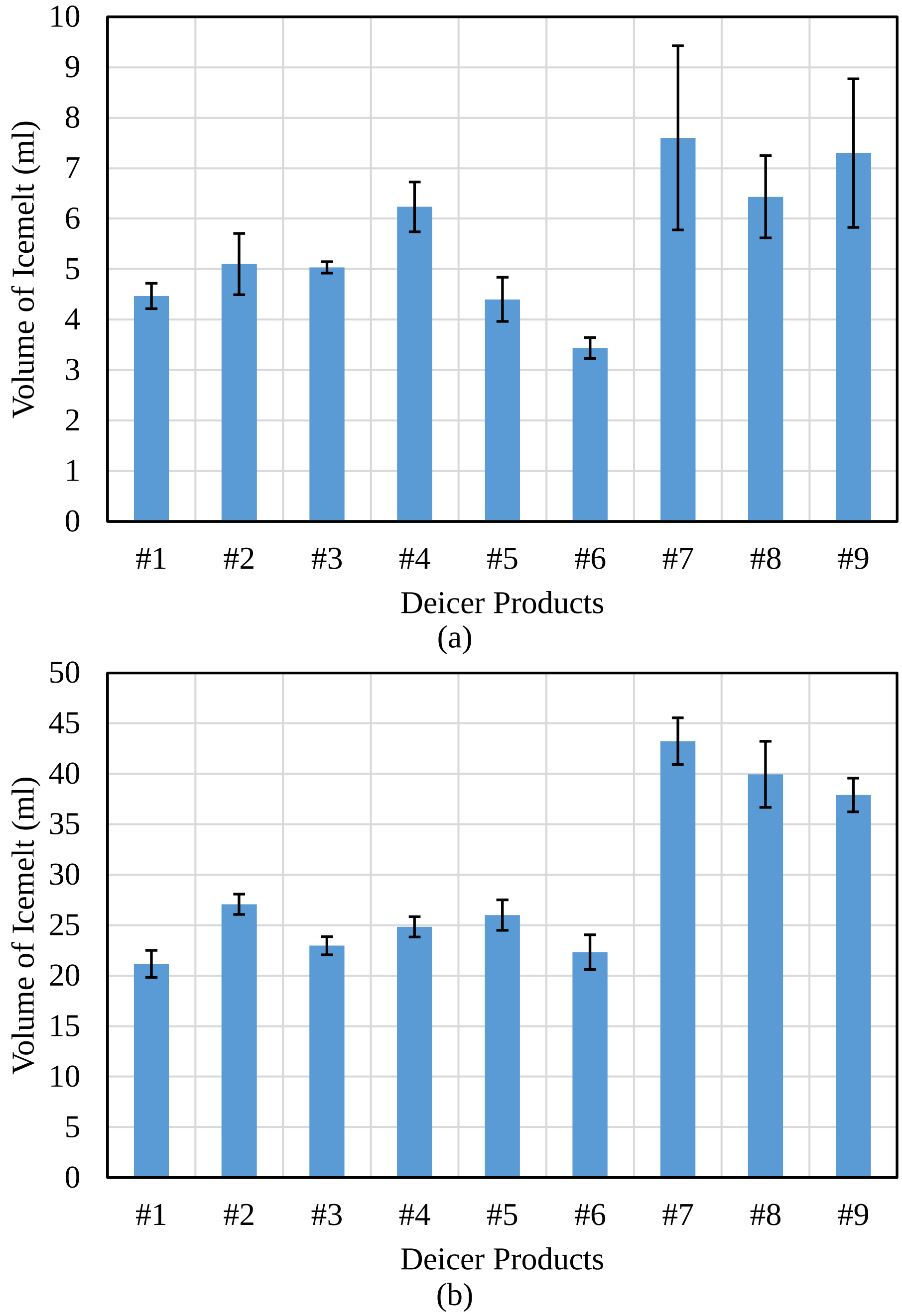


Figure 2. Summary of the accumulated volume of melted ice at different time: (a) 20 min and (b) 60 min

Although the concrete beams showed good DF results, the mass loss values of concrete beams with the presence of different deicer products varied (Figure 3), which indicated that the deicer products had different scaling effects on concrete beams. As shown in Figure 3, the concrete beams with the presence of the product #7 showed the lowest mass loss value than the other beams (even lower than those with the presence of water), indicating that the product #7 had little scaling effect on the concrete beams. The concrete beams with the presence of other deicer products (#2-#9) showed higher mass loss values than that of those with the presence of water. The concrete beams with the presence of product #2 showed the highest mass loss values.

Table 4. Durability Factor Results of the PCCs with the Presences of Different Deicer Products

Products	Durability Factor
Water	96 ± 3
Product #1	99 ± 3
Product #2	98 ± 1
Product #3	96 ± 4
Product #4	98 ± 3
Product #5	95 ± 6
Product #6	97 ± 3
Product #7	96 ± 5
Product #8	97 ± 4
Product #9	96 ± 3

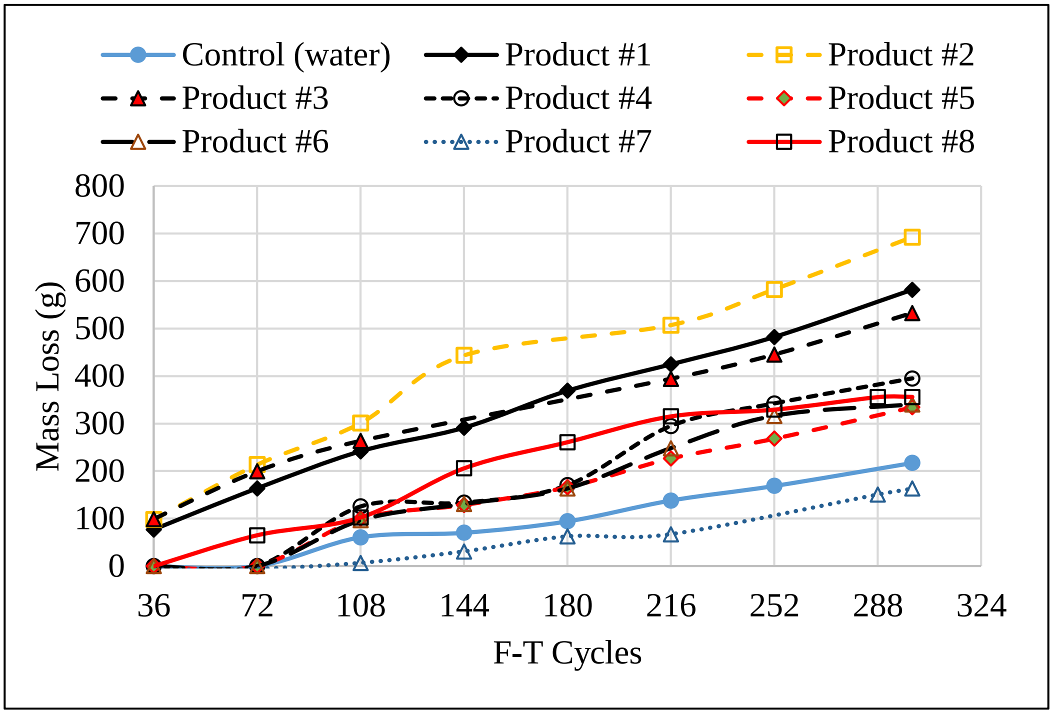


Figure 3. Mass Loss Results of the PCCs with the Presences of Different Deicer Products

Figure 4 presents the mass loss results of the PCM cylinders with the presence of different deicer solutions. The PCM cylinders showed little mass loss after subjecting to F-T cycles (less than 7 gram). These results indicated that the PCM cylinder with the typical Missouri mix design is resistant to F-T damages even with the presence of deicer solutions. Among all the cylinders, the PCM cylinders with the presence of product #9 showed the lowest mass loss value (similar to those with the presence of water), which implied that the product #9 had insignificant effect on the F-T resistance of PCM cylinders.

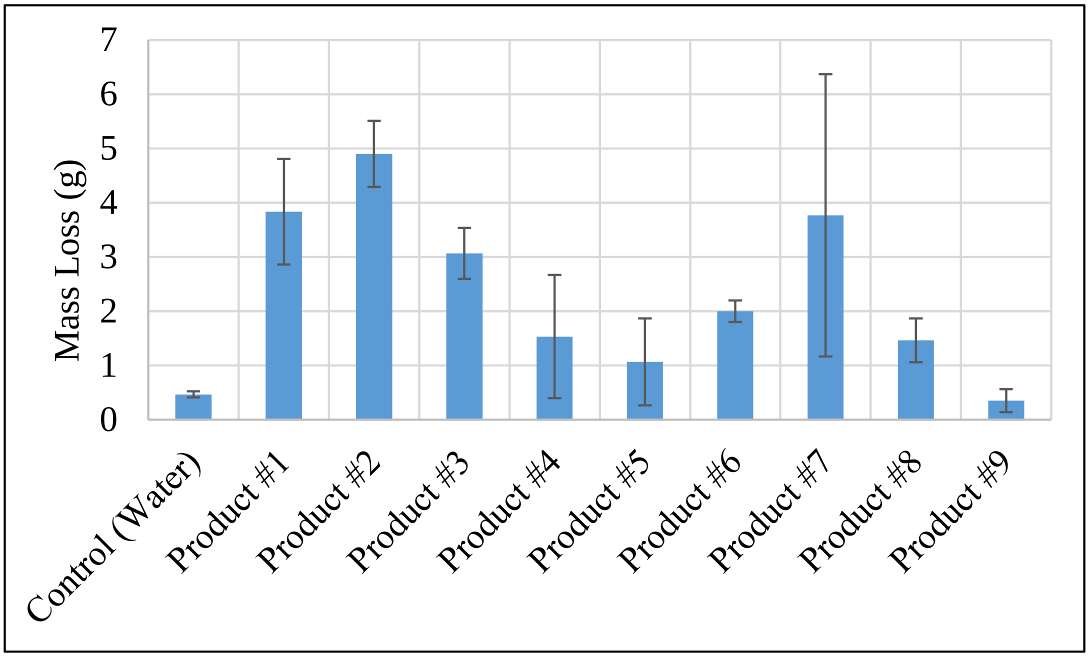
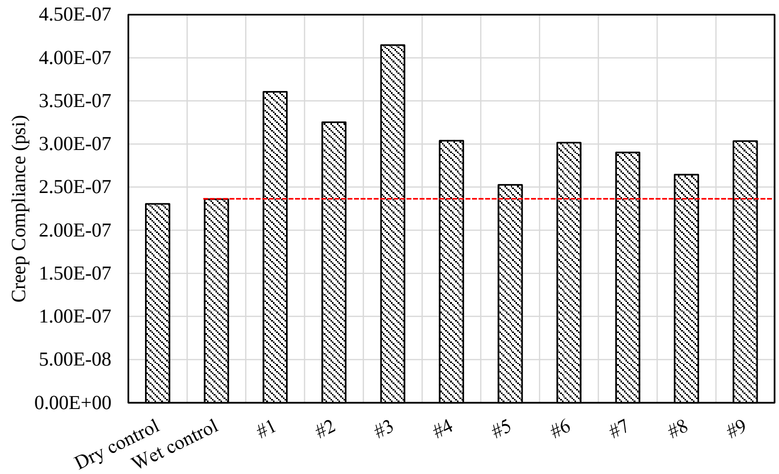


Figure 4. Mass Loss Results of the PCM Cylinders with the Presences of Different Deicer Products

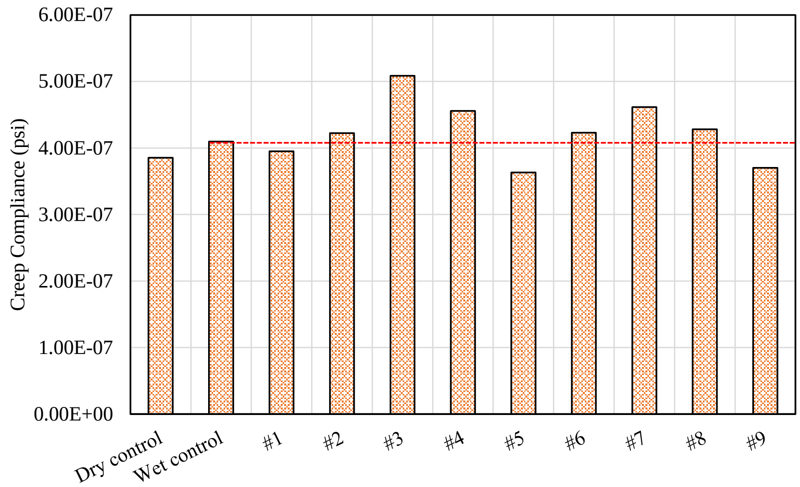
Asphalt mixture IDT test

Figure 5 presents the creep compliance of asphalt mixtures treated by various deicer solutions at a loading time of 50s to further illustrate the results. 50s is selected for the comparison because the tests reach a static status after this amount of loading time. As shown in this figure, at the testing temperature of -20°C, the deicer products seemed increase the creep compliance of asphalt mixture. At the testing temperatures of -10 and 0 °C (which are closer to the air temperature when deicer products applied in the field), products #2 and #9 showed similar creep compliance values to the wet control sample (treated with water only), implied that these two products had insignificant effects on the creep compliance of asphalt mixture. The products #7 (Calcium chloride (liquid) treated rock salt) and #8 (Beet juice treated rock salt) stiffened the asphalt mixture at 0°C. This may relate to good ice melting capacity of these two products at -4°C, which could result in less ice in the asphalt mixture.

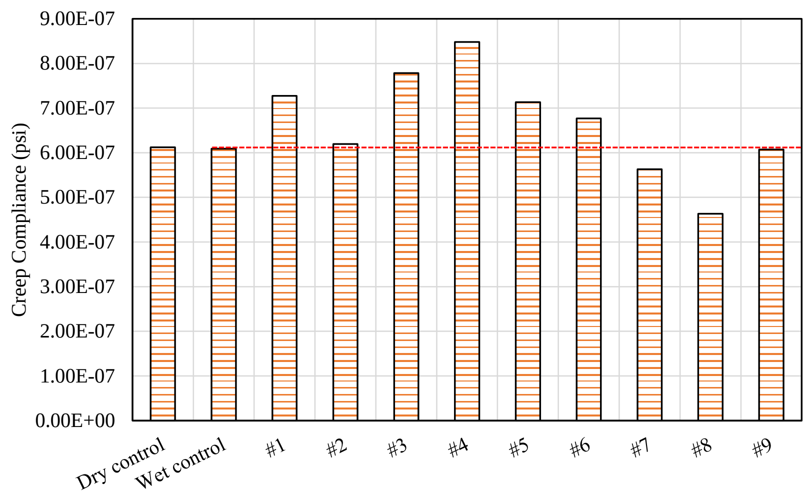
Figure 6 illustrates the effects of deicer solutions on the IDT strength of asphalt mixture at -10°C. Generally, high IDT strength was desirable for asphalt mixture to resist low-temperature cracking. As shown in this figure, the wet control sample showed slightly lower IDT strength value than the dry control sample, indicating that the presence of water could degrade the low-temperature performance of asphalt mixture slightly. The products #1, #2, #4, and #6 degraded the IDT strength of asphalt mixture. The products #5, #7, #8, and #9 showed insignificant effects on the IDT strength of asphalt mixture. The product #3 ("Snow Slicer" treated rock salt) slightly increased the IDT strength as compared to the wet control sample.



(a)



(b)



(c)

Figure 5. IDT creep compliance of asphalt mixtures at time of 50s at various temperatures: (a) -20°C, (b) -10°C, and (c) 0°C

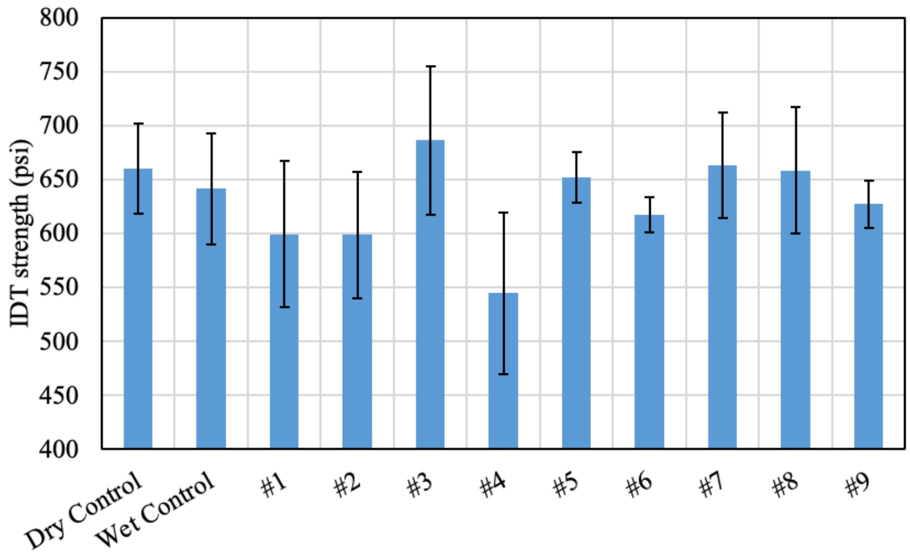


Figure 6. IDT strength of asphalt mixtures treated by deicer solutions at -10°C

CONCLUSIONS

Based on the results and analysis in this study, the following conclusions can be reached:

- The products #7, #8, #9 (which are calcium chloride (liquid) treated rock salt, beet juice treated rock salt, and "Top Film" treated rock salt, respectively) showed better ice melting capacities than the other evaluated products. The product #6 which is the calcium chloride (flake/pellet) treated rock salt showed the lowest ice melting capacity. The product #7 (calcium chloride (liquid) treated rock salt) showed the best ice melting capacity among all the studied products.
- All concrete beams had DF values higher than 90%, which indicated that the concrete beams (with the selected typical Missouri mix design) had excellent durability even with the presence of deicer products. The PCM cylinder with the typical Missouri mix design was resistant to F-T damages, even with the presence of deicer solutions.
- An acceptable deicer product should have little effects on the IDT creep compliance and strength of asphalt mixture. According to the results, products #2 (Rock salt – brine treated) and #9 ("Top Film" treated rock salt) had insignificant effects on the creep compliance of asphalt mixture, regardless of testing temperatures.
- Higher IDT strength of asphalt mixtures indicates higher low-temperature cracking resistance. The products #1, #2, #4, and #6 degraded the IDT strength of asphalt mixture at -10°C. The products #5, #7, #8, and #9 showed insignificant effects on the IDT strength of asphalt mixture. The product #3 ("Snow Slicer" treated rock salt) slightly increased the IDT strength as compared to the wet control sample.
- The research indicated different effects on pavement performance due to different deicer products. Thus, the appropriate use of deicer products has to be balanced with pavement preservation. Other factors including their cost effectiveness, and potentially detrimental effects on the natural environment, and motor vehicles are needed to be considered as well.

ACKNOWLEDGEMENTS

The authors wish to thank the Missouri Department of Transportation (MoDOT) for sponsoring this work. The authors also appreciate Hanli Wu and Anyou Zhu in helping with some laboratory tests.

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