Effect of Freeze-thaw Cycles and Deicing Fluids on Pavements

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ABSTRACT: Winter maintenance has a crucial role in the road management system in Scandinavia. Transportation systems must allow the effective and efficient movement of people and goods under all climatic conditions. Smooth and safe traffic conditions can be achieved with different maintenance strategies. Deicers are widely used to avoid and remove thin ice layers either on the airfields or roads pavements at low temperatures. Although their immediate effect consists of a fast improvement of the pavement conditions, the amount of chemicals, the freeze-thaw cycles and high summer temperatures can affect the performance of the pavement surface.

The purpose of this study is to evaluate the effect of different deicing solutions on asphalt mixtures. Two chemical agents have been selected: sodium chloride used on roads, and potassium formate used on airfields to reduce the freezing point of the water present on the asphalt surface. Solutions with different concentrations of each deicer have been chosen and related with their effect on the asphalt material subjected to a predetermined number of freeze-thaw cycles. Particle loss of the specimen, determined with the Cantabro test, has been selected as an indicator to determine the deterioration of the mixture after several freeze-thaw cycles while immersed in deicing solutions. Alterations of the bitumen have been measured evaluating the performance grade of the retrieved bitumen.

Depending on the amount of chemical agent in the solution, and following results from the Cantabro test and the performance grading of the bituminous binder, the alteration of the asphalt material was determined. Abrasion and bitumen performance, determined as above mentioned, are anticipated to be affected by the chemical action of the deicer.

KEY WORDS: Cantabro, Deicers, Freeze-thaw cycles.

1 INTRODUCTION

Winter maintenance constitutes a great challenge in the Nordic countries. Climatic conditions have a relevant impact on the safety and mobility of highway users. A great effort is therefore applied in order to guarantee a normal traffic flow under all climatic conditions.

Among the possible winter maintenance alternatives, a considerable amount of solid and liquid chemicals (deicers) is applied onto winter roadways as anti-icing or deicing to avoid and remove thin ice layers and/or to provide them with higher values of friction. Both strategies depend on the application of a chemical deicer to break the bond between snow or ice and the pavement (Hassan, Abd El Halim, Razaqpur, Bekheet, & Farha, 2002). Although their immediate effect consists of a fast improvement of the pavement conditions, there are growing concerns over the impact of deicers on the infrastructure, vehicles and environment (Fay & Shi, 2012). Indeed, in the subarctic countries, premature deterioration has been observed on some airfield pavement that had been repeatedly exposed to deicers (Alatyppö & Valtonen, 2007).

Chemicals, freeze-thaw cycles and high summer temperatures can induce a physical and chemical alteration of the mixture and its components. These distresses consist primarily in severe surface damage as degradation and softening of bitumen, and of loss of aggregate material from which the bitumen has been washed away. These alterations can induce a deterioration of the surface layer and lead to a loss of strength (Farha, Hassan et al. 2002; Starck and Löfgren 2007). Farha et al. (2002) indicate that the effect of deicers consists primarily of an increase of ice pressure within the pores and marginally in a chemical reaction with the binder due to the interruption of most of the chemical reactions at sub-zero temperatures.

In general, the deicer choice depends on the pH-value, the hygroscopic capacity and surface tension capacity of the chemical, and on the other hand on the air voids content, type of aggregate and adhesion properties of the mixture and its components (Ekblad & Edwards, 2008). Presently, sodium chloride ($NaCl$) is the most commonly used deicing chemical on roads and highways in Europeans countries and North America due to its abundance and low cost. Potassium formate ($CHKO_2$) is instead widely used on airport runways in order to prevent corrosion of airplanes. In fact, the total amount of salt used in the winter 2010/2011 in Norway is 238 000 tons (StatensVegvesen, 2011) while only in Oslo Gardermoen airport area, the mean consumption of those de-icing chemicals during the winter periods from 1999–2009 were: 24,5 tonnes/km of $NaCl$ and 779 m^3 of $CHKO_2$ (French, Eggestad, Øvstedal, & Jahren, 2010; Hellstén et al., 2005).

In this paper the main focus is to examine how deicing chemicals affect the deterioration of bituminous mixture. In particular, the effects of deicers and indications on the influence of aggregate mineralogy will be evaluated. Since the thermal incompatibility of binder and mineral aggregates is, at low temperatures, a source of thermally induced stresses leading to the deterioration at the asphalt/aggregate interface (El Hussein, Kim, & Ponniah, 1998), and since deicing chemicals increase the sensibility of the material to withstand weathering, the Cantabro test and the PG-grading may prove to be a relevant means of evaluating the performance of the mixture and the binder respectively. Therefore the addressed objectives are: determine whether there is a significant difference in the use of sodium chloride and potassium formate with respect to abrasion rate of asphalt concrete; determine whether the binder performances are affected by the chemicals.

2 EXPERIMENTAL PLAN

The experimental plan consisted in evaluating the particle loss of different asphalt mixtures through the Cantabro test after the samples were subjected to 8 freeze-thaw cycles while immersed in deicing solutions. In order to simulate the cycles, an automated freezer was used. Opening and closing of the freezer were programmed in order to complete a cycle within 24 hours. The temperatures of the fluids were monitored during the process.

2.1 Materials

Two asphalt mix designs were prepared based on the Norwegian specifications for asphalt concrete mixtures. The aggregates, with a maximum size of 11 mm were chosen among those used in the Trøndelag region in Norway: Lauvåsen and Steinkjer.

In Table 1 the content in percentage of the major minerals present are shown. A binder content of 5,90 % and 5,80 % respectively, was determined for a 70/100 penetration binder.

Table 1: Mineralogical composition of the stone material.

		Lauvåsen	Steinkjer
Quartz	(%)	21,25	48,20
Albite	(%)	30,35	18,30
Other	(%)	48,40	33,50

2.2 Deicing fluids

The deicers selected for this investigation are sodium chloride (NaCl) and potassium formate ($KCHO_2$).

Together with the reference samples stored in water, the testing program includes the deicing solutions given in Table 2.

Table 2: Deicing solutions included in the testing program.

Deicer	Concentration (%-by weight)
NaCl	25
NaCl	12,5
$CHKO_2$	50
$CHKO_2$	25
H_2O	100

2.3 Cantabro test

To evaluate the effect of deicers on the asphalt concrete properties, five samples per mixture and per conditioning were prepared using the Marshall hammer and then allowed to cure at room temperature for a minimum of 48 hours. Weight and volumetric characteristics were recorded. The susceptibility of the asphalt mixtures was tested by storing the specimens in NaCl, $CHKO_2$ solutions and water. Samples were conditioned by exposing them to eight freeze-thaw cycles. Afterward, the Cantabro test (CEN, 2007), used as indicator for deicer susceptibility, was performed at room temperature. The surface was then cleaned of loose particles and weighted.

The amount of damage experienced by each sample was quantified in terms of particle loss. The accumulated percentage of particle loss after 300 turns in the Los-Angeles-machine drum was calculated as follows:

$$\mathrm{PL} = 100\frac{W_1 - W_2}{W_1},$$

where W_1 = initial sample weight; and W_2 = final sample weight.

2.4 PG binder grading

After the conditioning in different deicing solutions, the binder present in the samples was characterized using the ASTM performance grading system, PG grading (ASTM, 2007).

In order to perform the PG binder grading, solvent extraction was used to remove the binder from the aggregates from the different sets of samples. First the Dynamic Shear Rheometer test (DSR) was conducted on the extracted bitumen in order to evaluate if there had been relevant changes of the viscoelastic characteristics of the bitumen due to the deicing solutions and/or the aggregates characteristics. The complex shear modulus (G^*) and the phase angle (δ) are calculated from the applied stress and the resulting strain. Higher G^* values imply higher stiffness of the bitumen and therefore an increased resistance to deformation while lower values of δ involve a greater elastic component, thus a greater recover of the deformation. As evaluation criteria, the failing temperature corresponds to the case $G^*/\sin\delta = 1$ kPa. A simulation of short term aging of the material was then obtained with the Rolling Thin-Film Oven (RTFO) procedure. The DSR test was conducted on the aged material. For this material, $G^*/\sin\delta = 2{,}20$ kPa, corresponds to the failure temperature. Long term conditioning was obtained using the pressure ageing vassel (PAV); not enough material was available therefore 30 g of binder were poured in each container in lieu of the amount prescribed by the standard (CEN, 2006). In the final stage, the binder, after the two ageing processes, was tested with the DSR (failure temperature at $G^*\sin\delta = 5000$ kPa) and the Bending Beam Rheometer (BBR) in order to determine the flexural creep stiffness (S) and m-value (failure temperature at $S \leq 300$ MPa, $m \geq 0{,}3$).

The results from the DSR and BBR tests were used to evaluate the PG grade of each binder according to the standard (ASTM, 2007).

3 RESULTS

3.1 Cantabro test

Particle loss is a good indicator of the freeze-thaw resistance of asphalt mixture in presence of deicing solutions. Experimental results show that the bituminous mixtures had higher resistance to freeze-thaw cycles while in water in absence of the chemical agent. As shown in Figure 1, the impact of deicers on the structural integrity of the samples is relevant: the particle loss of the samples reaches in some cases twice the particle loss of those immersed in water. In particular, the mixture with high content of SiO_2 (hereinafter called HQ, Steinkjer aggregates) suffered higher damage than the mixture with low content of SiO_2 (hereinafter called LQ, Lauvåsen aggregates) regardless of the solution and concentration.

However, the damaging effect of road salt at high concentration was significantly higher than the other deicer while at lower concentration it settles on values similar to the potassium formate. In Table 3 the variation in particle loss per each set of conditioning has been calculated compared to the particle loss of the not conditioned samples (dry). Both LQ and HQ have the same percentage increments of damage. This shows that the rate of increment of sensibility of a bituminous mixture to deicers should depend mainly from the type of binder, being it the common element between the two mixtures. This agrees with Farha, Hassan et al. (2002) hypothesis about the chemical interaction of the deicer with the binder and the increment of thermal stresses within the mixture.

From the figure, it can be noticed that, regardless of the concentration of the potassium formate or the aggregate material, the damage to the mixtures was unchanged.

The lower temperature recorded within the solutions compared with the temperature reached by the water, due to the presence of the deicer, might also have affect the binder sensitivity.

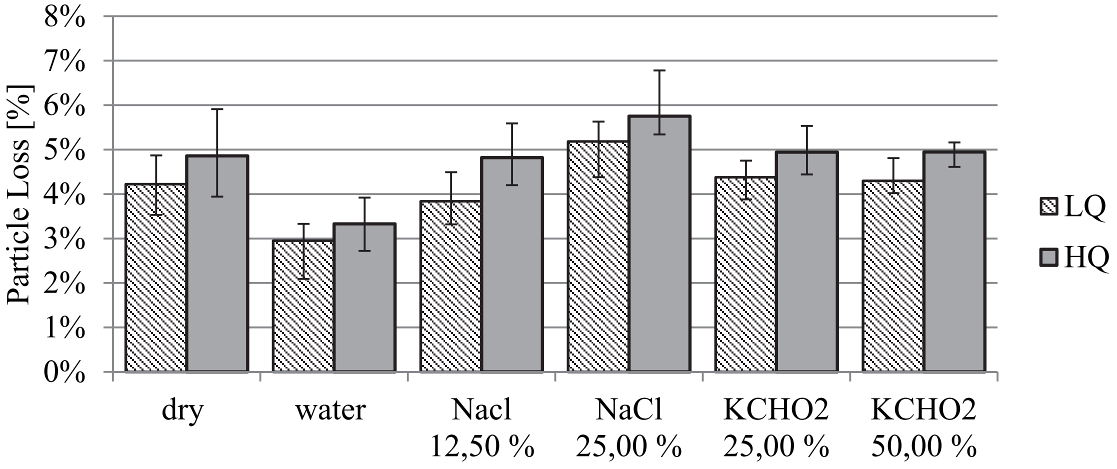

Figure 1: Effect of deicers on particle loss. The error bars represent the minimum and maximum value per each set of samples.

Table 3: Percentage increment of particle loss compared to dry samples.

	dry	water	12,5 % NaCl	25 % NaCl	25 % $KCHO_2$	50 % $KCHO_2$
LQ	100 %	+70 %	+91 %	+123 %	+104 %	+102 %
HQ	100 %	+69 %	+99 %	+118 %	+102 %	+102 %

The rate of particle loss due to freeze-thaw cycles and exposure to deicing materials was calculated as the ratio between the particle loss of the samples subjected to conditioning while immersed in deicing solutions ($PL_{wet,\ ft}$ / PL_{dry}) and the particle loss of dry samples. In Figure 2, the development of the rate of particle loss based on the concentration of the deicing fluids is shown. In both cases, NaCl and $KCHO_2$, the values calculated for the different mixtures are very close. This illustrates that it is the deicer and its concentration that affects the particle loss and not the mineralogy of the aggregates and its effect on the bitumen. In Table 4 are listed the linear models that approximate the variation of particle loss with the increase of concentration of the solution. As foreseeable, the equations defining the model result similar between each other.

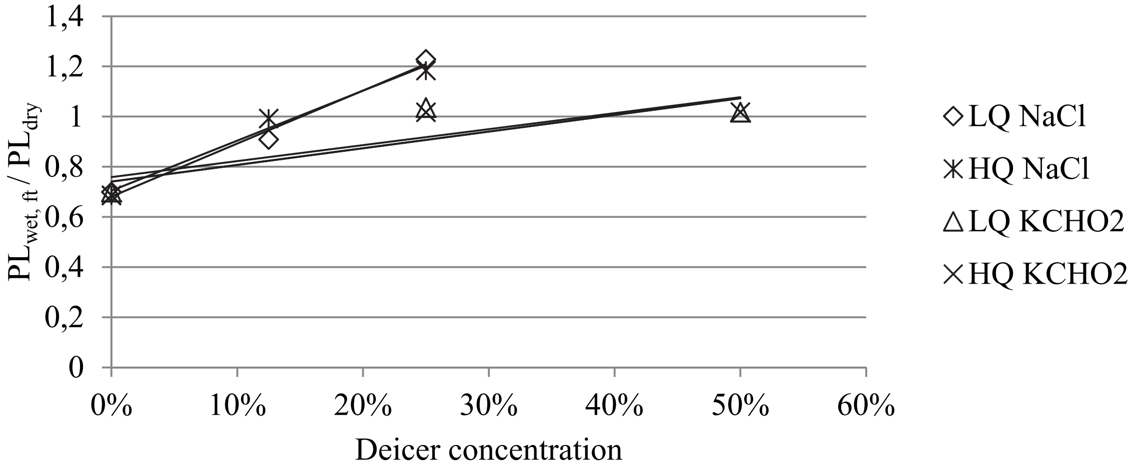

Figure 2: Rate of particle loss of the samples immersed in NaCl and $KCHO_2$ solutions.

Table 4: Linear approximation of the rate of particle loss of the samples immersed in NaCl and $KCHO_2$ solutions.

Samples	Linear model	R^2
LQ NaCl	y = 2,11x + 0,68	0,99
HQ NaCl	y = 1,99x + 0,7	0,98
LQ $KCHO_2$	y = 0,64x + 0,76	0,71
HQ $KCHO_2$	y = 0,66x + 0,74	0,75

3.2 PG binder grading

The rheological characteristics of the binders extracted from the samples have been obtained through the DSR. Figure 3 shows the results from the samples that have been subjected to 8 freeze-thaw cycles in NaCl and $KCHO_2$ respectively. In each figure the values are compared with those obtained from the original, not conditioned, binder (dotted line) and the binder extracted from the samples immersed in water during the conditioning.

After being immersed in NaCl solutions, the samples extracted from the mixture with high content of silicon dioxide show a higher variation in terms of stiffness. In particular the bitumen results softer after being immersed in water and in high concentrated salt solution, conversely much stiffer after conditioning in the 12,5 % NaCl solution. The bitumen extracted from the LQ mixtures shows more compacted results.

Potassium formate instead, has interacted more with the samples: the results from the DSR are more spread over the graph and present a general increment of the stiffness of the material. Only the sample conditioned in a 50 % $KCHO_2$ solution was subjected to a softening process.

The bitumen extracted from LQ samples appears more concentrated and closer to the values measured testing the original binder while the others are more spread. Moreover, for both solutions it is observed that the $G^*/\sin\delta$ does not follow any trend compared to the concentration of the deicers.

In Figure 4, the failure temperature recorded during the DSR test has been used as parameter in order to evaluate if a relation between particle loss and failure temperature of the extracted bitumen subsists. The results do not show any dependence and thus suggest that particle loss is not dependent on binder properties with little to no aging.

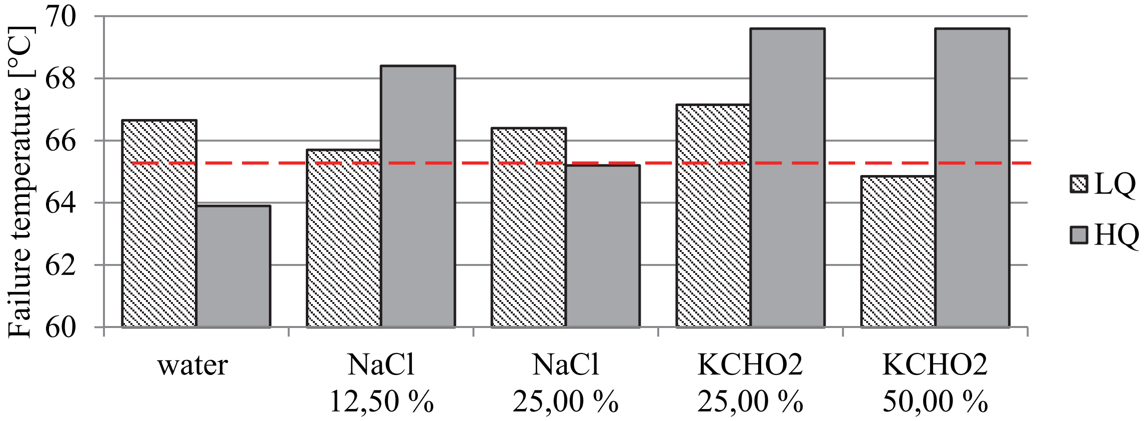

Figure 3: DSR: failure temperature of the extracted binders. The dotted line represents the failure temperature of the original binder.

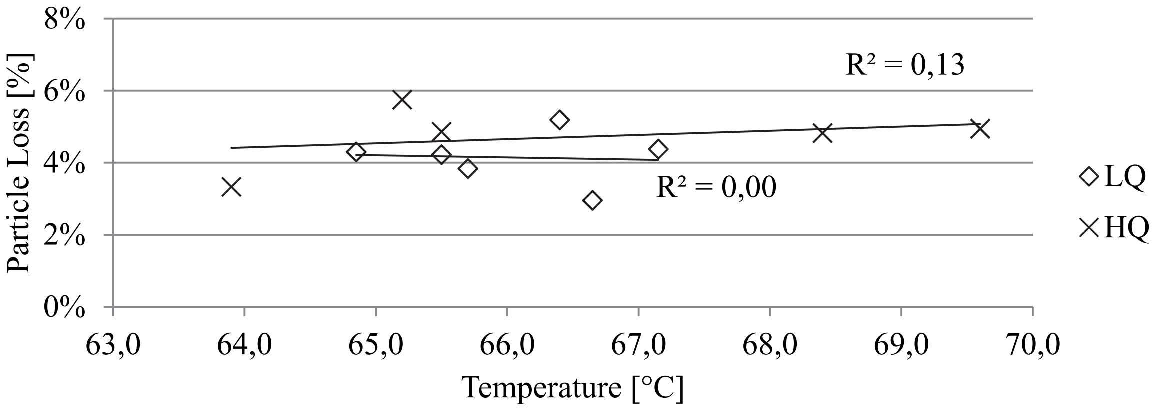

Figure 4: Particle loss of the samples compared with the failure temperature recorded after the DSR test.

The aged material has been tested with the DSR, results are reported in Figure 5. Compared with the original-RTFO binder (dotted line), an increment of the failing temperature is noticeable for all the materials. Particle loss was not compared with failure temperature of the RTFO material because of the similarity of the results.

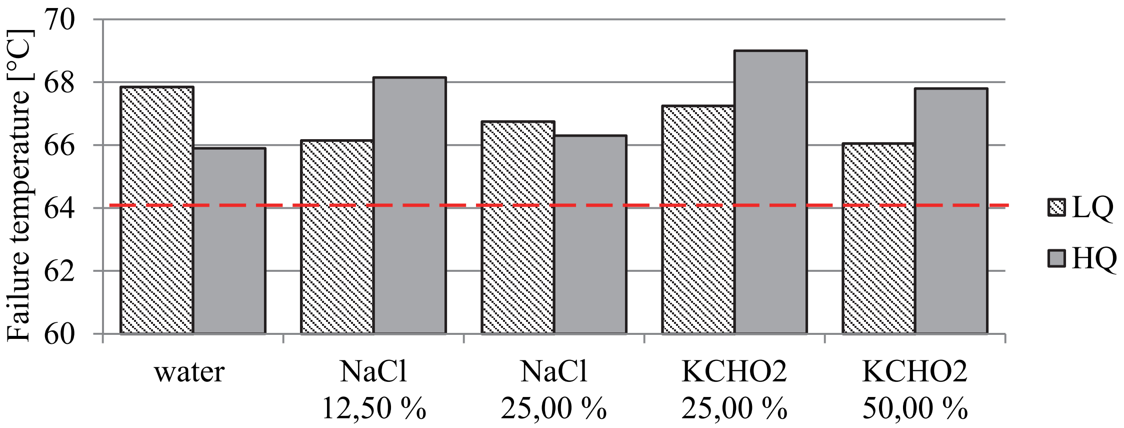

Figure 5 DSR: failure temperature of the binders after the RTFO aging process. The dotted line represents the failure temperature of the original binder after the RTFO aging process.

After the RTFO, the material was subjected to the PAV process and successively to the DSR (Figure 6) and BBR (Figure 8) tests. After conditioning in highly concentrated deicing solutions, LQ-PAV obtains similar results with water-conditioned binder in both tests. HQ material, in particular the samples conditioned in $KCHO_2$ solutions and 25,00 % NaCl solution, shows an increment of the failure temperature during the DSR test.

Similar to the un-aged binder, the failure temperature of the bitumen does not have a high correlation with the particle loss of the mixtures (Figure 7), these findings indicate that particle loss is not driven by intermediate aged binder properties.

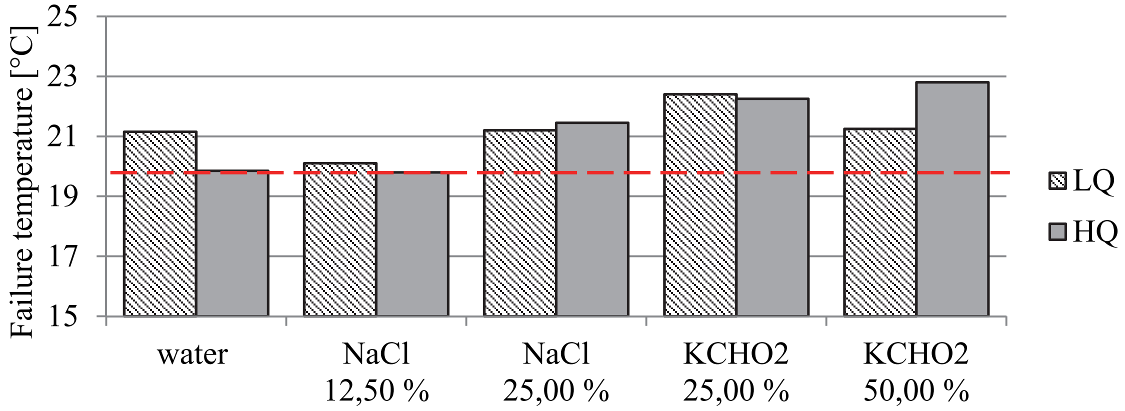

Figure 6: DSR: failure temperature of the binders after the PAV aging process. The dotted line represents the failure temperature of the original binder after the aging process.

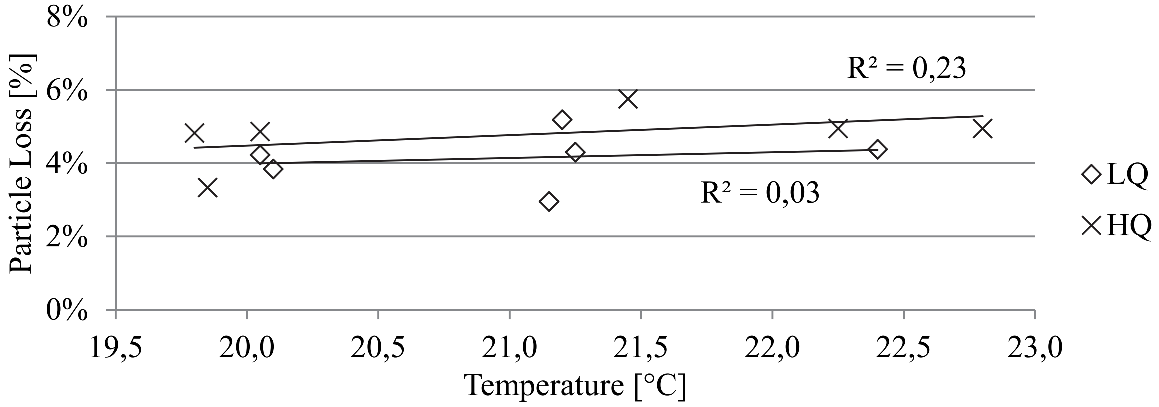

Figure 7: Particle loss of the samples compared with the failure temperature recorded after the DSR test on PAV material.

With regard to the BBR test, potassium formate and sodium chloride strongly affected the low temperature performance of the bitumen (Figure 8). A wide difference in low temperature resistance is observed for the HQ-PAV material: the sample that has been conditioned in water shows a wide reduction of the low temperature performance while the bitumen conditioned in 50,00 % $KCHO_2$ experiences an increase.

Figure 9 shows a slightly significant correlation between the particle loss and the failure temperature of the bitumen during the BBR test.

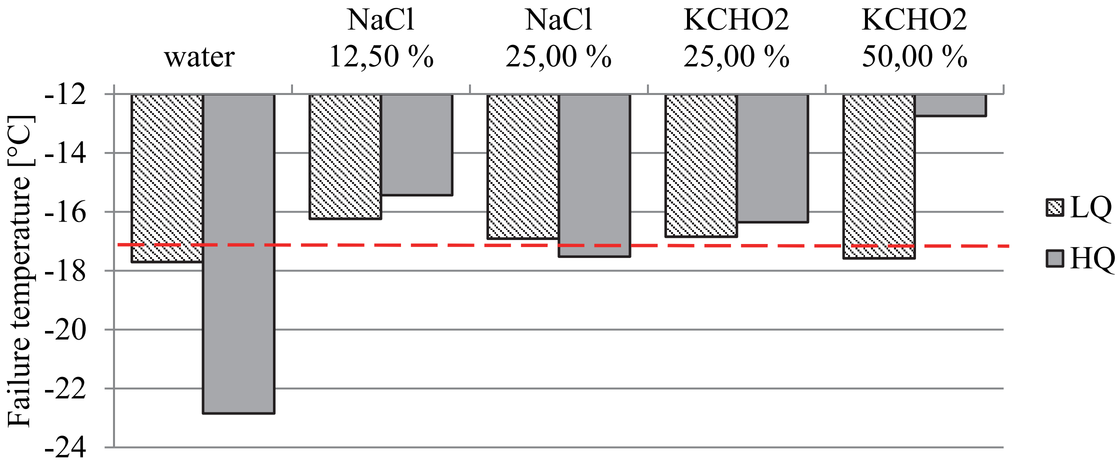

Figure 8: BBR: failure temperature of the binders after the PAV aging process. The dotted line represents the failure temperature of the original binder after the aging process.

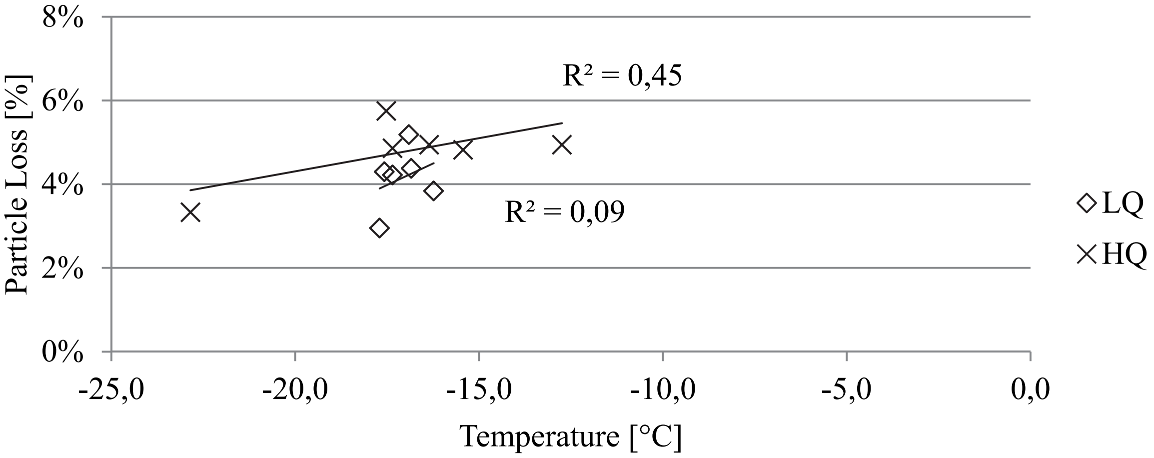

Figure 9: Particle loss of the samples compared with the failure temperature recorded after the BBR test.

The PG-grade, determined according to ASTM (2007) are reported in Table 5. Although there is some variation among the results, all the samples conditioned in deicing solution obtain the same performance grade (64/-22). Only the HQ sample conditioned in water moved to a lower grade both regarding maximum and minimum design temperature (58/-28). The best correlation found between binder properties and particle loss was found for low temperature binder properties and samples with high quartz content.

Table 5: PG grading of the bitumen after conditioning in different deicing solutions.

	water	12,5 % NaCl	25 % NaCl	25 % $KCHO_2$	50 % $KCHO_2$	Original
LQ	64/-22	64/-22	64/-22	64/-22	64/-22	64/-22
HQ	58/-28	64/-22	64/-22	64/-22	64/-22	

4 CONCLUSION

This laboratory investigation was designed to evaluate the damage inflicted on mixtures exposed to freeze-thaw cycles while immersed in deicing fluids as a result of the weakening of the bond between binder and stone aggregate and binder itself.

Sodium chloride and potassium formate, both in higher and lower concentrations, appear to have a significant effect on asphalt durability when using Cantabro particle loss as indicators of durability. Additionally, it appears that the effects of durability differ depending on the type of deicing material used, whereby the rate of particle loss due to exposure to deicing materials and freeze-thaw effects are heavily influenced by the nature of the deicer. These findings indicate that when exposed to freeze thaw cycles, salt can contribute to twice the rate particle loss with half the concentration when compared to $KCHO_2$. Binder testing suggests that the particle loss is not heavily dependent on the binder properties, thus suggesting that variations in the asphalt mixture durability are not due to changes in the binder properties as a result of exposure to deicing materials and freeze-thaw cycles. The binder properties which had the best correlation with durability measured in terms of particle loss was low temperature failure for asphalt samples with high quartz content. This suggests that quartz available in the aggregate has a stiffening effect on the binder in the presence of freeze-thaw cycling and $KCHO_2$, this stiffening does not appear to affect the asphalt durability.

The present research cannot be considered exhaustive since the experimental plan includes only a minimum amount of samples. Therefore further research on the effect of deicing fluids on asphalt durability will be conducted in order to evaluate the component of the mixture that, reacting with deicers, affects the final performance.

REFERENCES

Alatyppö, V., & Valtonen, J. (2007). *Experiences on the effects of de-icing chemicals on bituminous airfield runways in Finland*. Paper presented at the Federal Aviation Administration Worldwide Airport Technology Transfer Conference, Atlantic City, New Jersey, USA.

ASTM. (2007). Designation: D6373 – 07 Standard Specification for Performance Graded Asphalt Binder. West Conshohocken, PA: ASTM International.

CEN. (2006). Bitumen and bituminous binders *Accelerated long-term ageing conditioning by a Pressure Ageing Vessel (PAV)* (Vol. NS-EN 14769).

CEN. (2007). Bituminous mixtures – Test methods for hot mix asphalt *Part 17: Particle loss of porous asphalt specimen* (Vol. NS-EN 12697-17).

Ekblad, J., & Edwards, Y. (2008). Precision of method for determining resistance of bituminous mixtures to de-icing fluids. *Materials and Structures/Materiaux et Constructions, 41*(9), 1551-1562.

El Hussein, H. M., Kim, K. W., & Ponniah, J. (1998). Asphalt concrete damage associated with extreme low temperatures. *Journal of Materials in Civil Engineering, 10*(4), 269-274.

Farha, M. H., Hassan, Y., Halim, A. O. A. E., Razaqpur, A. G., El-Desouky, A., & Mostafa, A. (2002). *Effects of new deicing alternatives on airfield asphalt concrete pavements*. Paper presented at the Federal Aviation Administration Technology Transfer Conference, Atlantic City, New Jersey, USA.

Fay, L., & Shi, X. (2012). Environmental impacts of chemicals for snow and ice control: State of the knowledge. *Water, Air, and Soil Pollution, 223*(5), 2751-2770.

French, H. K., Eggestad, H. O., Øvstedal, J., & Jahren, P. E. (2010). Climate conditions and consequences for de-icing operations as exemplified by the situation on a motorway and airport at Gardermoen, Norway. *Hydrology Research, 41*(3-4), 269-281.

Hassan, Y., Abd El Halim, A., Razaqpur, A., Bekheet, W., & Farha, M. (2002). Effects of Runway Deicers on Pavement Materials and Mixes: Comparison with Road Salt. *Journal of Transportation Engineering, 128*(4), 385-391. doi: doi:10.1061/(ASCE)0733-947X(2002)128:4(385)

Hellstén, P. P., Kivimäki, A. L., Miettinen, I. T., Mäkinen, R. P., Salminen, J. M., & Nystén, T. H. (2005). Degradation of potassium formate in the unsaturated zone of a sandy aquifer. *Journal of Environmental Quality, 34*(5), 1665-1671.

StatensVegvesen. (2011). Mengderapportering vinteren 2010/2011 *VD rapport*: Vegdirektoratet. Trafikksikkerhet, miljø- og teknologiavdelingen. Vegteknologi