Relation of Road Surface Friction and Salt Concentration

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ABSTRACT

We have studied the relation of the apparent salt concentration and coefficient of friction between a paved road surface and a vehicle tire as a function of temperature. The study was conducted by occasional friction measurements and by collecting surface samples under various surface conditions. The main result of the research reveals that astonishingly low concentrations of salt are needed to keep friction at acceptable levels even at the lowest temperatures. With Sodium Chloride (NaCl) the limiting concentration is only about three percent at temperatures down to -20 °C. This result may have dramatic consequences to winter maintenance operations. Instead of controlling salt amount to melt a given amount of ice or snow we should control how much salt is needed to prevent surface to become too slippery and use only a fraction of salt as compared to previous practises. Although our result is obtained in a region where studded tires are used, fundamentally the results should be valid with all types of tires with some adjustment of salt concentration to higher readings.

Keywords: friction, de-icers, soft ice, hard ice, winter maintenance

1 INTRODUCTION

There are a number of research articles evaluating various de-icing chemicals in laboratory environment. One of the most recent can be found in the references [1] and [2] with a good compilation of similar and related research in the list of references. Closest to our work is perhaps the work by Nixon and Wei in the reference [3], but that is also laboratory oriented. The purpose of our research was to study road surface friction as a function of temperature and apparent salt concentration by collecting samples on treated and trafficked roads. Especially we wanted to find out whether there is a limiting concentration of Sodium Chloride to keep surface friction at a tolerable level at a given temperature. The motivation to our research came from an observation that often road surfaces are clearly ice covered, but the measured friction is still fairly high.

Physical reason for icy surfaces staying at fairly high friction readings is caused by the presence of de-icer, which make the ice structure softer than without de-icers. This can be understood by studying phase diagram of salty solutions. In Figure 1 there is a schematic phase diagram of NaCl as a function of temperature and concentration. From the physics of melting compounds we know that when a liquid cooling solution reaches the line connecting the points of 0.0 °C / 0.0 % and -21.1 °C / 23.3 %, the solution starts precipitating clean ice crystals in the solution. As a consequence the concentration of NaCl increases in the solution and the process of freezing can continue only if temperature is reducing further. All the solution will finally solidify at the critical temperature of -21.1 °C.

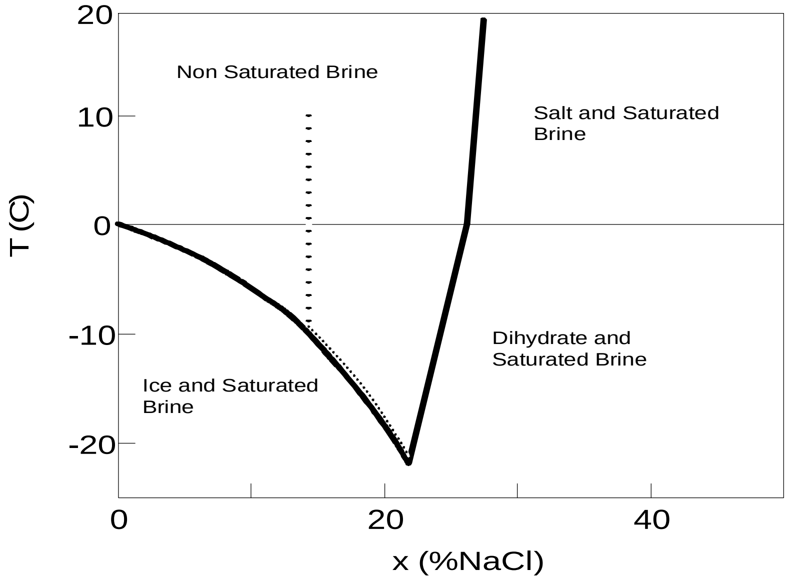

Figure 1. Schematic phase diagram of aqueous Sodium Chloride solutions.

It is obvious that a salty solution starting to freeze at the so called Depression of Freezing Point (DFP) temperature does not become immediately slippery due to a very small amount of ice at DFP. Pure water can become slippery at 0 °C whereas high concentrations need to reach the critical temperature at -21.1 °C before solidifying to a slippery surface. The crucial question is how far down in temperature we have to go to make a surface slippery with given initial concentration of salty solution.

In the following chapters we shall describe data collection procedures, analyse the results with some discussion of consequences and finally there are some concluding remarks.

2 SAMPLE COLLECTION

Samples were collected mainly on roads which were well maintained. There was no special plan of timing the sample taking, but instead the samples were collected more or less in random to obtain a wide spread of friction values. The samples were collected in Southern Finland during the winter season 2010-2011, where Sodium Chloride was used as an anti-icing agent. The friction values were measured with an absolute µTEC friction meter based on deceleration recording during lock braking with an ABS equipped vehicle.

Figure 2. A toolbox (right) and a sample collector (left) with a plastic bag of hot water over it.

Figure 2 shows a toolbox which included a thermos bottle, kitchen towel and a sample collector. A number of dry pieces of kitchen towel cut to about 0.01 m² were weighed as dry with a sealable plastic bag. The surface samples were collected by sucking solution from the road surface to a highly absorbing towel, which was put back in a sealable plastic bag for later weighing to determine increase in mass. If the road surface was partly frozen, the surface contaminant was melted by setting hot water in a plastic bag over the sample. Layer thickness and concentration of an individual sample were determined by weighing and measuring the conductance of a diluted sample, which was compared to a known concentration. There was a small residual amount of the samples left on the road surface, which was estimated to be about 20 µm or less.

The number of samples including determination concentration and layer thickness was 27. In addition we made low temperature outdoor testing with prepared samples so that the total number of samples reached 50. These additional samples included collected slush, which was let to harden and melt with lowering and increasing temperature.

3 ANALYZING THE RESULTS

We have plotted the observed friction readings as a function of measured layer thickness in Figure 3. The solid line is only a guide to the eye to reflect the expected behaviour based on earlier work [4] for frozen clean water, i.e. clean ice. Observe that we should not expect our data to follow that line, since our samples contain often salt. There is only one point at thickness 0.04 mm and friction 0.35, which seems to be clearly under the line. The points with large values of layer thickness and comparably high friction reading are caused by frozen salty solution, which tends to be softer than clean ice and thus the measured friction appears higher. The general trend in Figure 2 is in line with earlier observations that fairly small layer thicknesses, on the order of 30 µm, can reduce friction dramatically.

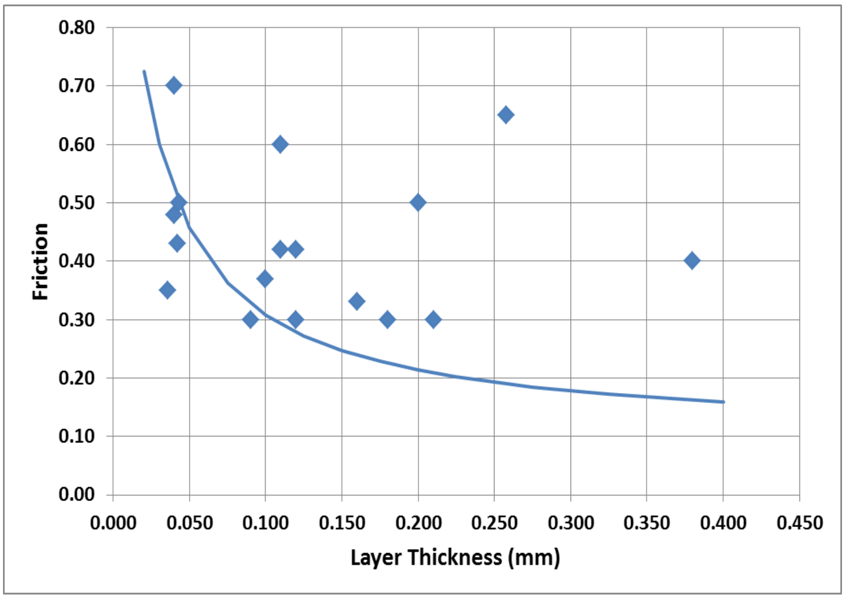

Figure 3. Observed friction as a function of layer thickness.

By plotting the same data as in Figure 3 against concentration and friction is more interesting. This is done in Figure 4 where observed concentration is plotted against friction. Here again the solid line is only a guide to the eye to remind that there seems to be missing points on the left of the line. It is still surprising that the line tends to bend towards higher friction at fairly low concentrations although half of these cases fall in the temperature range -20 … -10 °C. This data suggests that fairly low concentrations of salt in ice can keep friction at acceptable levels.

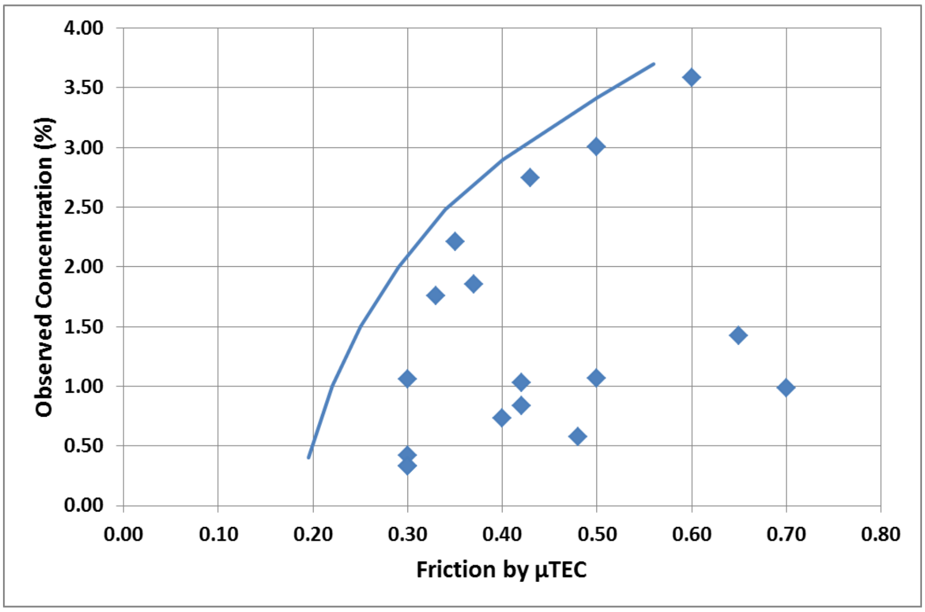

Figure 4. Observed concentration as a function of measured friction.

Apparent amounts of salt and concentration are plotted in Figure 5. This data set contains more points than the previous figures since friction was not measured over all samples. Since units of concentration in percentage are practically equal as 1 % = 10 g/l, the slope of any point in Figure 5 contains information about layer thickness. Surprisingly, the highest slopes correspond to layer thicknesses of about 0.40 mm or less and about half of the points contain less than 0.10 mm. This means that on treated roads the observed layer thicknesses are fairly small. Naturally there will be larger layer thicknesses under heavy precipitation of water or snow, but when the episode is over and the surface is treated properly, the residual amount of ice or slush seems to be only fractions of one millimetre. Combining this result with the increasing friction at fairly low concentrations, very often only a few grams of salt per square meter is enough. The actual amount of salt has been 1 g/m² or less in half of the points in Figure 5 although typical gritted values range from 5 – 20 g/m².

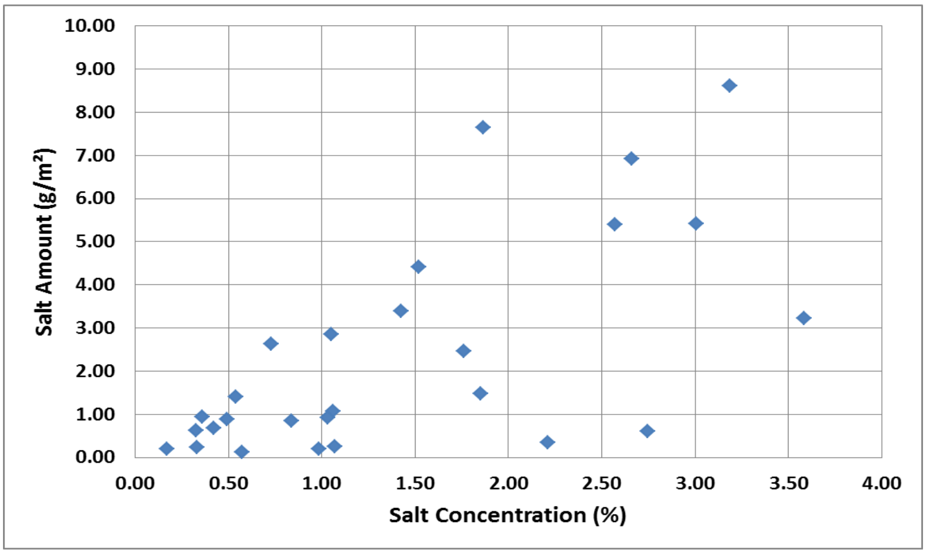

Figure 5. Salt amount (g/m²) and concentration (%) of the collected samples.

Figure 6 shows all the samples on concentration and temperature axes. Total number of points is 50 in Figure 6, since open air tests of freezing and manually collected samples of slush are included here. The data points have been labelled by blue or red colour. The samples which contained brittle ice or just wet slush have a blue label and the samples containing hard ice and appearing dry have a red label. Although this division of the samples to two groups is to some extent subjective, only a few samples were marginal in this respect and most often it was an easy task to label a data point.

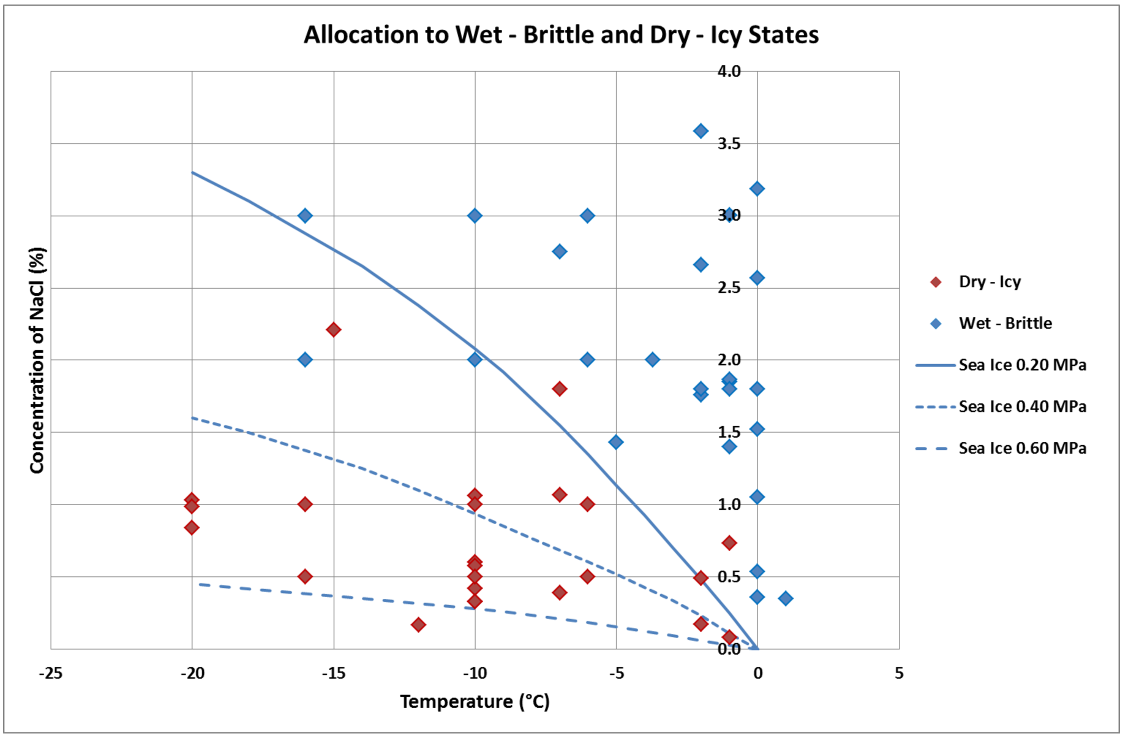

Figure 6. Concentration of all samples as a function of temperature.

As can be seen from Figure 6 the blue samples tend to be at high concentrations and high temperatures whereas the red are at low concentrations and low temperatures as we would expect a salty solution to behave. However, it is surprising that only about 3 % of salt is needed even at the lowest temperatures to make ice soft enough to increase observed friction. It turns out that measured friction seems to increase with increasing salt concentration much faster than expected by studying phase diagram of NaCl solutions at low temperatures. The phase diagram of Figure 1 suggests that 3 % solution starts to freeze at about -2 °C. When temperature drops further down to -20 °C, the concentration of the solution increases by a factor of 7 due to water precipitating to ice from the solution. We end up with a composite structure containing about 15 % of solution and the remainder is porous ice. This amount of solution seems to weaken the strength of ice enough to keep the road surface at a comparably high friction level. However, the brine will finally solidify at -21.1 °C making the composite stronger than at higher temperatures.

For comparison we have plotted equal strength lines of sea ice in this same figure according to Ref. [5]. Surprisingly the 0.20 MPa line falls just about in between the red and blue samples. This pressure 0.20 MPa is the standard tire pressure in passenger vehicles. The result implies that friction reduces only if ice is strong enough to resist the tire pressure in braking condition. Since tire pressure of trucks is higher, up to 0.60 MPa, we expect trucks to experience better friction than passenger vehicles under similar icy and salty conditions. Naturally, the consequences of a truck losing control can be very severe and thus this advantage cannot be exploited fully.

While collecting the samples we noted that soft salty ice tends to break into small icy particles, which do not form packed ice any more, but become collected by the side of the wheel track looking like loose dirty snow. This kind of ice reduces friction marginally, but there is the advantage of road surface remaining drier as compared to a case of applying too much salt and there is no need to wash windscreen at low temperatures. The samples of the loose dirty snow contained some salt, which presumably caused the behaviour of not getting packed under tire pressure.

The observation of a fairly high friction at fairly low concentrations of salt opens up interesting opportunities for winter maintenance. Since the practical amounts of water or ice in slippery conditions on maintained highways are typically about 0.1 mm or even less, the formal required amount of salt is only a few grams per square meter even at lowest temperatures. Thus if we can keep the surface not freezing in the first place, then after winter maintenance operations only very small amounts of salt are enough to keep the road surface at acceptable friction levels. Especially, if we grit initially before freezing, it is possible to follow the level of friction and only add salt when required.

4 CONCLUSIONS

We have studied samples of surface contamination on icy roads and found that surprisingly low concentrations of Sodium Chloride, only about 3 %, is enough to keep friction at acceptable levels of about 0.50 even at temperatures down to -20 °C to be compared to 0.80 on a dry surface and to 0.20 – 0.30 with clean hard ice. This behaviour of salty ice is interpreted to be caused by the composite structure of brine solution pockets in porous ice, which is more brittle under braking action than clean ice. The interpretation is supported by data of practical strength of sea ice at comparable concentrations of salt.

The results suggest some changes in the strategy of winter maintenance. First, we should always avoid letting clean water to freeze, since then the ice will be hard and it is difficult to melt it again. Even a low percentage of salt when applied prior to freezing will clearly increase friction. When there is a risk of refreezing at lower temperatures, adding only small amounts of salt can prevent slippery surfaces and there will be practically no spray of moisture on the wind shield of a following vehicle. Secondly, we should avoid the need to melt ice or snow by salting, since the required amount is nearly an order of magnitude larger than the amount to keep freezing ice soft with salt. The reason is that when ice is melted by salt the composite structure becomes soft only when almost all ice is melted and the required concentration of salt must correspond to the Depression of Freezing Point temperature instead of a much lower percentage needed to keep friction at an acceptable level. Thirdly, by measuring starting conditions and combining weather forecast it is formally possible to calculate required amount of salt in an economic and ecologic manner.

5 REFERENCES

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