Frost heave in highway tunnels in Nordland County, Norway

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ABSTRACT: Two highway tunnels opened in the years 2005-2006 in Nordland County, Norway has suffered from frost heave and formation of lumps of ice on the road surface up to 3 kilometres into the tunnels. Norwegian Public Roads Administrations (NPRA) started an investigation program to find the reasons for this. This program included sampling of materials in the road structure, measurements of frost indexes and frost penetration into the tunnels, registration of the drainage system and studies of the construction plans and performance of the construction. These investigations showed that errors where made both in planning and construction of the tunnels leading to the problems. The reasons for the frost heaves were mainly that the frost affected areas was larger than estimated partly because of forced ventilation in one direction, inadequate drainage system because it was placed too shallow compared to the formation rock-bed, inadequate cleaning of the frost susceptible fines in the tray after blasting of the mica-rich bedrock and slightly frost susceptible materials in the sub-base where brought in. These tunnels are now being rehabilitated based on these findings by replacing the all the frost susceptible soil and placing of a new drainage system below the level of the formation rock-bed while also ensuring frost protection of the pipes by using XPS-plates. New tunnels in the northern region are now being built more robust with longer frost zones, cleaning of the fines in the tray and deeper drainage systems within the frost zones.

KEY WORDS: Highway tunnels, frost heave, design, construction, rehabilitation

1 INTRODUCTION

Figure 1 shows a map over the location of the tunnels. The 8,6 km long Korgfjellet tunnel situated on the main road Ev6 between the cities of Mosjøen and Mo i Rana was opened in 2005. Since then, the first 3 km of the tunnel from the north has suffered from frost heave and lumps of ice building up on the road surface.

The 3,7 km long Umskardet tunnel is situated on the main road Ev12 east of the city of Mo i Rana near the border to Sweden at about 650 meters above sea level. It was opened in 2006. This tunnel has also suffered from frost heave and lumps of ice. The formation of ice lumps has been even more severe than in Korgfjellet tunnel. Several accidents with personal and material damage have occurred due to this. Figure 2 shows a shallow and frozen drainage well and ice lump formation on the road surface in Umskardet tunnel.

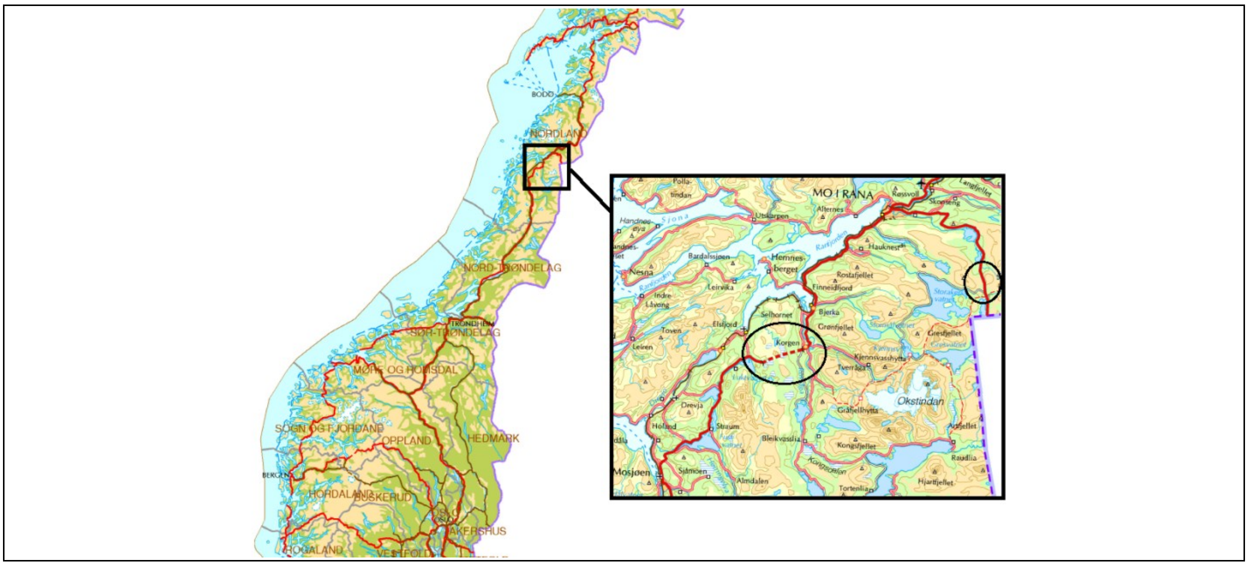

Figure 1: Map of the location of the tunnels.

Figure 2: Shallow and frozen drainage well (left) and ice lump formation (right)

2 INVESTIGATIONS AND FINDINGS

Due to the frost related problems the Norwegian Public Roads Administrations (NPRA) started an investigation programme to find the reasons and propose rehabilitation measures. The investigation program included sampling of materials in the road structure, measurements of frost indexes and frost penetration into the tunnels, registration of the drainage system and studies of the construction plans and performance of the construction.

2.1 Design and construction

The tunnels were designed and build according to NPRA standards with estimated frost zones (frost index >10 000 h^{o}C) of 300-500 meters. The frost heaves has occurred in the part of the tunnel that was assumed to be free of frost. In Korgfjellet tunnel the first 300 meters which was designed to withstand frost has not suffered from frost heave. There has not been reported any frost heave in the south end, and it is assumed this is because of the forced ventilation and tunnel sloping (chimney effect) from north to south, drawing cold air into the tunnel from the north. In Umskardet tunnel there has been frost heave through the whole tunnel except the two frost zones of 500 m meters on each side. Umskardet tunnel has hardly any forced ventilation due to low traffic.

Figure 3 shows the design of the road structures in the two tunnels. A sub-base of coarse grained material (10-64 mm) acting as a drainage layer was supposed to lead any water leakage into the drainage system. Table 1 and 2 shows results from sampling of materials from the sub-base. As it can be seen, the material in the sub-base consists of slightly (T2) to mid (T3) frost susceptible materials according to Nordals classification which is the standard classification method in NPRA. It is clear that there has been done mistakes during the construction and the quality control has not been good enough.

The bedrock of the Korgfjellet and Umskardet tunnel area consists mainly of mica-rich rock. Blasting of mica-rich bedrock will produce crushed rock with high fines content, and the fines will be highly water and frost susceptible. When blasting tunnels the fines content will be even higher than for regular blasting because of the gripping tension. Because of this it is standard method to clean the rock surface for fines in the frost zones, but underestimating the frost zones can therefore be fatal.

Figure 3: Designed road structure in Korgfjellet and Umskardet tunnel.

Table 1: Results from sampling of sub-base material (depth ~0,5m) from Umskardet tunnel

Sample nr.	Meters into tunnel (from north)	% <20µm of material <20mm	Frost susceptibility (Nordals criteria)
1	1230	12,2 %	T3
2	2465	8,8 %	T2
3	3110	6,6 %	T2

Table 2: Results from sampling of sub-base material (depth ~0,5m) from Korgfjellet tunnel

Sample nr.	Meters into tunnel (from north)	% <20µm of material <20mm	Frost susceptibility (Nordals criteria)
1	815	7,8 %	T2
2	1375	13,8 %	T3

2.2 Frost indexes

Korgfjellet tunnel was equipped with temperature sensors as shown in table 3. Figure 4 shows the measured frost index profile for Korgfjellet tunnel. The measured frost indexes correspond to about 115% of F_{10} (Frost index with 10 years return period). F_{10} is also the ruling for frost protection of tunnels in Norway, so the measured winter was well suited for assessing the tunnels performance against design. It can be seen in figure 4 that the frost penetrates at least in to 2500 meters. The frost index outside the tunnel was about 35000 h^{o}C, but at 230 meters into the tunnel the frost index decreased to about 20 000 h^{o}C, so it is clear that the heat from the bedrock lowers the frost index rapidly when moving into the tunnel. From 230 meters to 2270 meters the frost index does not decrease as much as might be assumed from the first 230 meters. At 1740 meters it is still about 13000 h^{o}C. This might has to do with the forced ventilation, and the fact that frost protection of the tunnel arch prevents heat flow from the bedrock. The measurements show that an assumption of frost zones of 300-500 meters was way too low and this design error was an important contributing factor to the problems.

Table 3: Temperature sensors in Korgfjellet tunnel

Meters into tunnel (from north)	Channels
230	1 Base (20 cm depth) 2 Sub-Base (35 cm depth) 3 Sub-base (50 cm depth) 4 Air
1740	1 Air
2270	1 Air

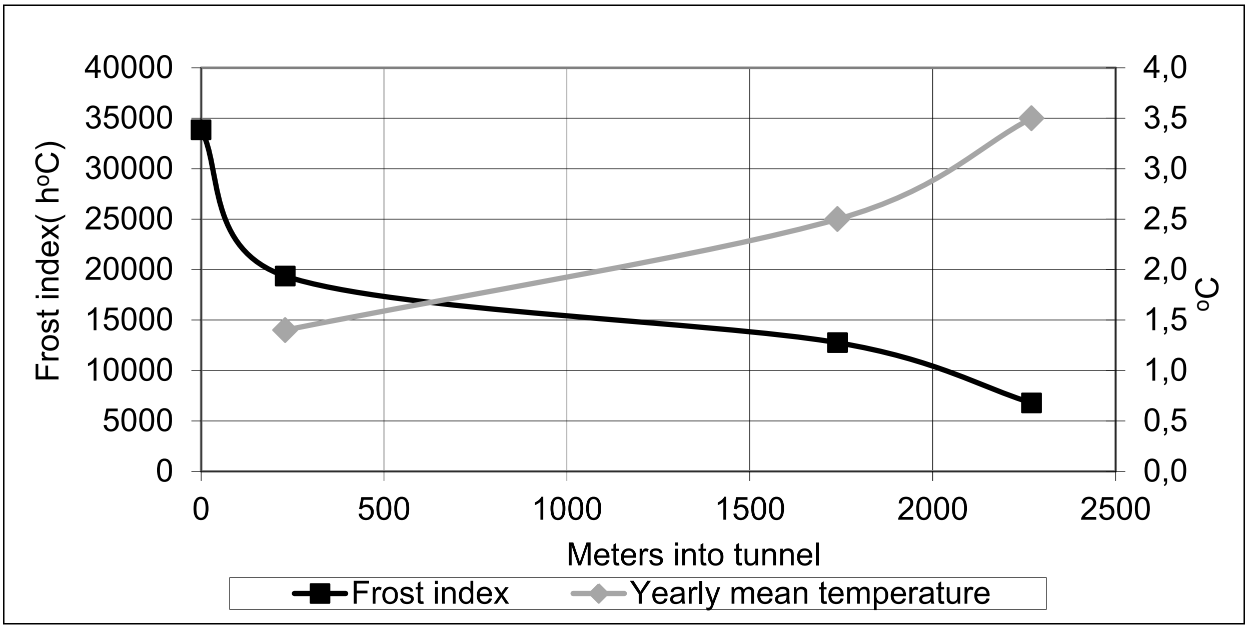

Figure 4: Measured frost index in Korgfjellet tunnel march 2010 – march 2011

Real time measurements from all channels at meter 230 in Korgfjellet tunnel is shown in figure 5. The sub-base started to freeze around mid-November and didn't thaw until the beginning of May. Even though the air temperature in the tunnel drops below -15 ^{o}C, the temperature in the sub base at 50 cm depth hardly drops below -6 ^oC. The temperature in the sub base responds to changes in air temperature, but the fluctuations are smaller and delayed compared to the air temperature. The frost index at 50 cm depth was about 7400 h^{o}C. This shows that the frost susceptible sub-base was subjected to high frost indexes, but the temperature was not very low making it possible for unfrozen water to be present forming ice lenses.

Umskardet is situated high above sea level, and it was not taken into consideration that the frost indexes would be much higher than at the city centre on which the frost index tables in the design manual 018 (NPRA, 2011) are based on. Design manual frost index (F_{10}) for Mo i Rana is 25000 h^{o}C, while an assessment of the theoretical frost index (F_{10}) based on NTNF/NPRA, 1976 for the tunnels location would be about 38500 h^{o}C. Measured frost index in the middle of the tunnel was 13500 h^{o}C.

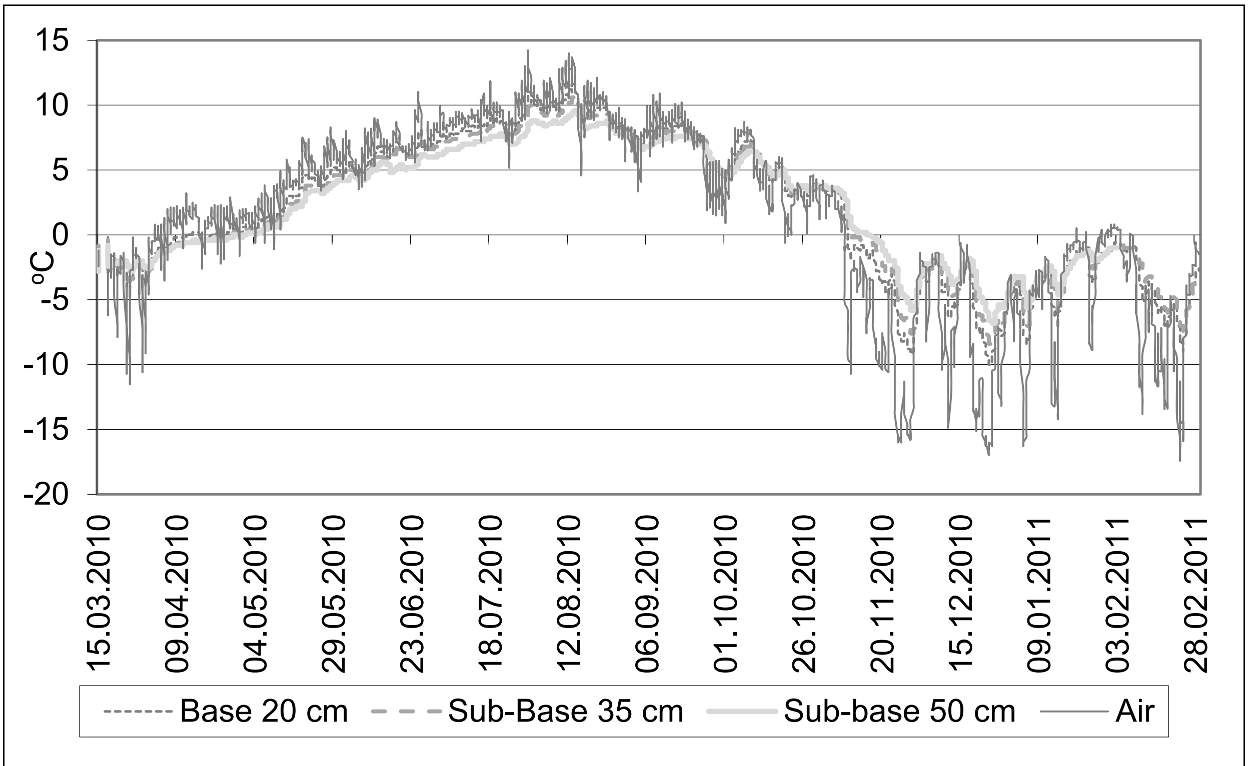

Figure 5: Measured temperatures at meter 230 in Korgfjellet tunnel march 2010 – march 2011.

2.3 Drainage system

Registration of the drainage system was done i both tunnels by marking all wells, and measuring depths to drainage pipes. The investigation showed that the pipes were placed to shallow compared to the real freezing depths in the area and real frost penetration into the tunnels. In Korgfjellet tunnel the depths to drainage pipes was mainly 0,7-0,8 meter while the freezing depth would vary from 0,8-1,5 meter (for F_{10}) depending on the distance from the tunnel entrance. Insulation of the drainage pipes was only placed at the first 300 meters. In Umskardet tunnel which has even larger frost index, the depths to drainage pipes varied from 40-85 cm. Measured frost index in the middle of the tunnel was 13500 h^{o}C.

The pipes where therefore subjected to high frost indexes which lead to clogging and thereby forced unfrozen water upstream to leak into the tunnel space and freeze on the road surface building hazardous lumps of ice. In addition to this, the pipes were not placed on the real formation rock-bed bottom but on the design formation rock-bed. Because of the blasting technique, depressions form every 5 meter in the formation rock-bed. These depressions where not drained because the pipe was placed too shallow, and a water table could form feeding the freezing front with water leading to severe frost heave. Figure 6 shows the depressions and a shallow drainage pipe in Umskardet tunnel.

Figure 6: Undrained depressions in the rock-formation bed and shallow drainage pipe.

3 REHABILITATION MEASURES

After the investigations a study on possible rehabilitation alternatives was preformed (NPRA, 2011). The problem could be solved either by insulation, rehabilitation of the drainage system and/or mass exchange. Two alternatives where assessed: 1) Partially mass exchange and insulation of the whole road width and existing drainage system, or 2) full mass exchange, levelling of the formation rock-bed and a new lowered drainage system. Alternative 2) was finally chosen after a technical and economical evaluation.

Both tunnels will during the years of 2010-2013 be rehabilitated by replacing the all the frost susceptible soil and placing of a new drainage system below the level of the formation rock-bed while also ensuring frost protection of the pipes using XPS-plates. Figure 7 and 8 shows typical profiles of the rehabilitation plans. In Umskardet tunnel the focus was even more against taking care of the excess water, and therefore it was designed with double sided drainage and extra frost protection using foamed glass to ensure that water from the arch could pass through down to the drainage pipes unfrozen.

Figure 7: Principle for rehabilitation of Korgfjellet tunnel. Mass-exchange and new drainage in shaded area.

Figure 8: Principle for rehabilitation of Umskardet tunnel. New double sided drainage with frost protection using XPS-plates and foamed glass.

4 CONCLUSIONS AND RECOMMENDATIONS FOR FURUTRE DESIGN AND CONSTRUCTION OF HIGHWAY TUNNELS IN SEASONAL FROST AREAS

The investigations showed that errors where made both in planning and construction of the tunnels leading to the problems. A summary of the investigations show that all the three factors needed for frost heave to occur was present as follows:

- Frost: Higher frost indexes and longer frost zones than estimated partly because of forced ventilation in one direction.

- Water: The drainage system was inadequate with the pipes placed to shallow leading to freezing of the drainage system.

- Materials: Frost susceptible materials were built into the sub-base and there was no cleaning of frost susceptible fines in the formation rock-bed outside the anticipated frost zones.

Due to the findings the following recommendations are given for future design and construction of highway tunnels in seasonal frost areas:

- Design of road structure: In 2011 the design manual 018 (NPRA, 2011) was revised and a new chapter regarding design of road structures in tunnels was added. In these new guidelines it is stated that for $F_{10tunnel}$ > 10 000 h^{o}C the sub-base should be increased in thickness from 25 cm to 50 cm. This is to ensure better drainage and frost protection. The sub-base should also consist of better draining materials like 20-120 mm.

- Cleaning of fines in the formation rock-bed: If $F_{10tunnel}$ > 10 000 h^{o}C actions should be taken to ensure that no frost heave and formation of lump ice will occur. This is mainly done by cleaning the formation rock-bed for fines. The requirement should be that no more than 5 cm of fines is allowed to be left on the rock surface.

- Adjusting the slope of the formation rock-bed: The slope of the formation rock-bed should always be monitored during construction and if inadequate it should be adjusted by blasting or filling of depressions with concrete to ensure that all water is lead into the drainage system.

- Design of frost zones: It is critical that the frost index at any point in the tunnel can be estimated with a certain degree of safety. Still there are no tools or guidelines for this, but the Internal report nr. 2301 *"Frost index in road tunnels"* (NPRA, 2002) containing a lot of data from real frost measurements in Norwegian road tunnels and the publication *"Protection against frost heave" (*NTNF/NPRA, 1976) can be used.

- Depths and insulation of drainage pipes: Depths to drainage pipes should be designed according to the design frost profile using insulation if necessary to obtain frost free pipes. The design depth of the pipes must be revised during construction to ensure that the pipes is placed as deep as possible and not necessary at the original design depth, but even lower if the blasted formation rock-bed is lower. This is to ensure that no or as little water as possible is left in the formation rock-bed.

- Special consideration should be made to ensure a frost-free passage for water from the arch to the drainage pipes. In many cases there will be a thermal bridge between the lining of the arch and the insulation over the drainage pipes.

- Quality control: The quality control of the formation rock-bed cleaning, depths of drainage pipes and fines in sub-base should be improved to ensure no mistakes are done during construction.

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