Frost protection in roads using insulation materials

Gustav Grimstad[1*], Seyed Ali Ghoreishian Amiri[1], Inge Hoff[1], Arnstein Watn[1,2]

[1] Department of Civil and Environmental Engineering, Norwegian University of Science and Technology, Trondheim, Norway
[2] WatnConsult AS, Trondheim, Norway
[*] Speaker, e-mail: gustav.grimstad@ntnu.no

Motivation

Between 1968 and 1976 the Norwegian research program “Frost i Jord” (*FiJ* 1976) developed a design basis and practical design principles for design of frost protection of structures founded on frost susceptible materials. The results from the “Frost i Jord” project is still relevant for the design of roads and railways today, but some update due to change in type of material used must be accounted for. Recently, due to some problems on newly constructed highways, the 2014 revision of the Norwegian road construction regulations (N200) introduced a “new” layer in the base of the pavement structure (*NPRA* 2014), namely the “lower frost protection layer” (LFPL). This lower layer is made of granular material located below the insulation layer. Material of class T2 (i.e. with some frost susceptibility due to some fines for keeping relatively high water content) should be used for the LFPL. The layer is meant to provide a "heat storage magazine" and thus give additional resistance to frost penetration into the subgrade in addition to the frost insulation. Alternatively, this layer is meant to replace part of the frost insulation layer of extruded polystyrene (XPS), lightweight expanded clay aggregates, foam glass or the lower part of a thick layer of standard subbase material (although the latter is not part of the regulations). According to the regulation, some fine content is allowed/required in the LFPL. Depending on the grain size distribution, up to 15% of particles can be of size of silt or below, typically 7 to 8 percent will be the actual case. Therefore, a degree of saturation, S_r, at 50% or higher could be accomplished in the LFPL, if a void ratio of 0.5 or less is assumed. However, extra care must be taken during construction to make sure the layer is homogenous both horizontally and vertically. This amount of water gives increased heat capacity and latent heat (i.e. it serves as an energy storage for the system), when compared to coarser and more uniform materials. However, it seems like the effect of this layer is exaggerated. This is also shown by previous and recent results from field trials (Gardermobanen, Røros). Therefore, thermal analyses for some different geometries were carried out in order to quantify the potential effect of the lower frost protection layer. This extended abstract gives an overview of the results from these analyses and discusses the potential role of this layer in terms of consequences on the thermal resistance of the system.

Approach

Different hypothetical cross sections of a highway, similar configuration to the Røros test site, are modelled in a 1D model, where the thickness of the lower frost protection layer (h) and the thickness of the frost insulation layer (z) are varied. The yearly average temperature on the top boundary is assumed to be 4 °C, while the surface *Freezing Index* (*FI*) is varying between 16492 h°C and 39357 h°C. The surface temperature is assumed to vary with a cosine function around the average temperature. The analyses are started in October with initial condition having a uniform temperature distribution equal to the yearly average temperature (considered as a conservative choice, i.e. an unusual cold summer before the winter). The thermal properties of the different layers are given in table 1, where the insulation layer is meant to represent clay aggregates or foam glass. For the water and ice, a heat capacity of C_w = 4200 J/(kg·K) and C_i = 2020 J/(kg·K) are used in the LFPL and subgrade (silt). In these two layers, the thermal properties are calculated from the mixture depending on the temperature dependent composition. The two “extremes”, i.e. with no lower protection layer (h = 0) and with no insulation layer (z = 0), is also included in the calculations. The thermal analyses are carried out using a finite element calculation. At the bottom boundary, a constant temperature equal to the yearly mean temperature is used. In addition analyses not considering heat capacity (C = 0) and with lower degree of saturation (S_r = 30%) in the LFPL are also conducted. Only considering latent heat of fusion exaggerates the effect of the LFPL (when using the geometry described above). However, the results will be extremely sensitive to the distance to the lower boundary of the model, since the only other heat source is through the bottom boundary.

Results and discussion

The results of the analyses produce a diagram of the relationship between *FI* (at the surface) and necessary thicknesses of the different protection layers. Figure 1 gives the resulting contour plot of z vs *FI* with contours of h. The dots are results of the analyses using parameters from table 1. These points fit well to the curves reported in *FiJ* (1976), when scaling the insulation thickness with the heat conductivity used in the 1976 report. The results shows that typically 300 mm of LFPL can replace 150 mm of lightweight expanded clay aggregates/foamglass. The square marks in Figure 1 represents the analyses with $C = 0$. The effect of the LFPL is exaggerated. As an example, as seen both in the curves below and in N200, a *FI* of 20000 h°C, 300 mm of LFPL can replace about 500 mm of insulation layer, which seems unreasonable. Finally, when $z = 0$ ($C \neq 0$) the analyses shows, for *FI* of 25802 h°C, that 1.0 m of LFPL is neeeded and a *FI* of 39367 h°C results in 1.40 m of LFPL.

mm			Density ρ [kg/m^3]	Heat capacity C [J/(kg·K)]	Total conductivity λ [W/(m·K)]	Solid heat capacity C_s [J/(kg·K)]	Frozen conductivity λ_f [W/(m·K)]	Unfrozen conductivity λ_u [W/(m·K)]	Degree of saturation S_r [%]
50		Asphalt	2050	920	1.52				
200		Base	1900	890	1.35				
800		Subbase	1850	890	1.10				
z		Insulation	500	1300	0.14				
h		LFPL	1900			890	1.53	1.42	50
→ tot 7.5 m		Subgrade (silt)	2066		2.17	874			100

Table 1. Layer properties

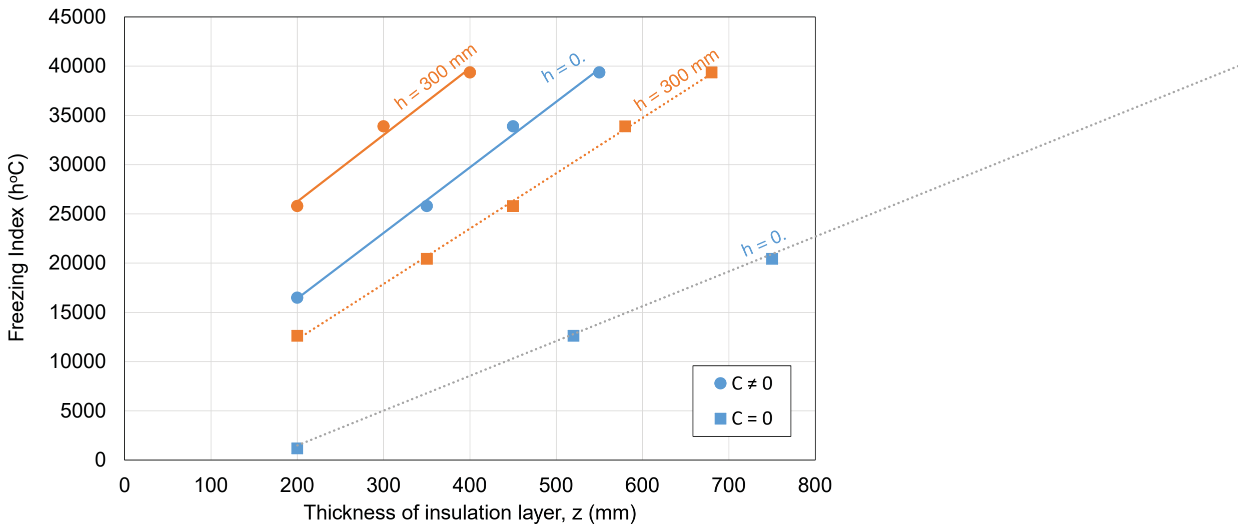

Figure 1. Thickness of insulation layer for different FI and thicknesses of the LFPL (h)

Conclusions and final comments

The presented analyses shows that the LFPL has a minor effect on thermal resistance compared to the gain in resistance by increasing the thickness of the insulation layer. Note that when using a LFPL, the results are highly dependent on the water content in the LFPL and the yearly temperature variation (order of varying winter periods and years). This means that if measures are not taken to acchieve the water content used in the analysis, the structure will be underdesigned. Also if one do not consider the whole lifetime of the structure in the analysis (but only a single extreme winter), one might risk that two cold winters in row with a cold summer in between essentailly keeps the LFPL frozen throughout and as a result the subgrade will freeze. To the authors, some extra thickness of the frost insulation layer seems like a tecnically and economically better solution than relying on a high water content and latent heat of fusion, risking a underdesigned or overprized structure. If the LFPL still is to be used, additional analyses for other yearly middle temperatures and time histories should be run in order to complete a set of curves that might be used for simplified design. This would require a thorough statistical analysis.

References

[1] FiJ, 1976. Publ. 17 “Sikring mot teleskader”. NTNF and NPRA, Oslo.
[2] NPRA, 2014. N200 “Vegbygging”, Norwegian Public Road Administration, Oslo.