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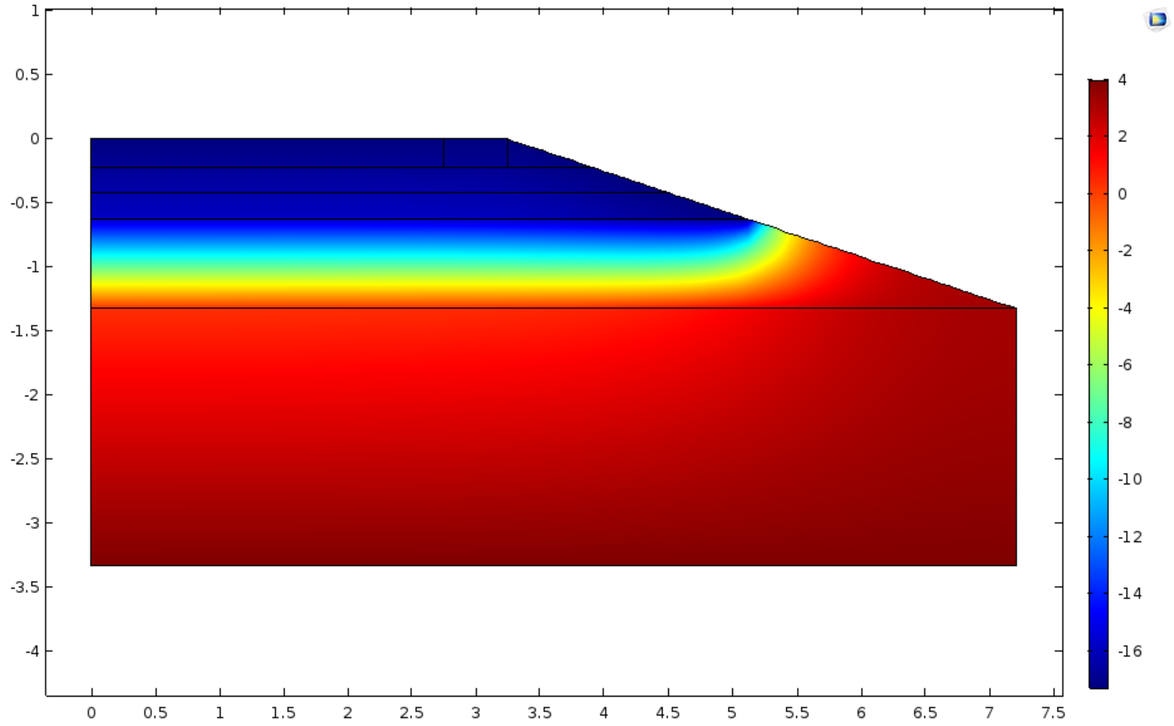

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# Design of roads using frost insulation materials – case study new E6 in Hedmark, Norway

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Abstract

NTNU is currently running a four year project focusing on frost penetration and effect of frost insulation in roads and railways. As a part of the project a set of numerical analyses using COMSOL Multiphysics for the thermal design of a real case, new E6 in Ringsaker, Norway has been conducted.

It is shown that the design given by the pavement design guidelines from the Norwegian Public roads is quite conservative for use of frost insulation materials compared to an alternative design based on numerical analyses. A structure with 1.32 cm total thickness including 60 cm of insulation using light weight aggregates (LWA) or foam glass might be sufficient to protect the road from FROST damages compared to a total thickness of 202 cm using the current design guidelines.

In addition to the specific study it is also demonstrated how the method could be used for general cases.

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# Background

Prediction of frost depth in Norwegian roads have so far been done using simplified calculations based on methods like Stefans (Stefan 1891) or Watzingers (Watzinger, Kindem et al. 1938). Combined with empirical knowledge the design recommendations have been developed based on frost index, mean annual temperature and water content of the crushed rock materials commonly used. This is combined with a schematic frost susceptibility evaluation related to the type and grading of the material in the subsoil. Design guidelines for the use of frost insulating materials like  expanded clay light weight aggregates, foam glass and extruded polystyrene (XPS) is also included in the design guidelines (NPRA 2018).

Modern analytic tools like COMSOL Multiphysics provides possibilities for more advanced modelling and including factors and parameters that was not possible using the traditional methods. It is relatively easy to include 2D or 3D geometry, real daily temperature variations, phase change, difference in conductivity from frozen to unfrozen state and also gives the possibility to investigate the influence of variation of the input parameters. With some more effort you can also include flow of water in frost susceptible materials and flow of air (convection) in coarse granular materials. In this study we have assumed materials $d_{10}$-value low enough to prevent convection and we are not allowing the frost susceptible soil to freeze.

The main challenge is to determine the specific material parameters to be used as input to the analyses. In this study we have used parameters found in the literature and laboratory/field tests performed at NTNU as part of the FROST-project in combination with parameters from the literature. A small parameter study has been made to study the influence of variation of the different parameters.

Design guidelines for the use of frost insulation in Norway has to a large extent been based on the results from the research program "Frost I jord"(Frost action in soils (Frost i Jord,  1976). The requirements for frost protection using traditional materials like crushed rock has however been increased with the latest revision of the design guidelines from NPRA (NPRA 2018). The cost of road construction has accordingly increased. In the case for E6 in Hedmark the extra cost of replacing material to 2.4 m depth is estimated by “Nye veier” to about $1 \times 10^9$ NOK. The extra cost is not mainly due to cost of excavation and mass transport but more related to the logistic and management of the traffic during construction.

Most of the problems and extra cost could been avoided if a thinner structure could be allowed. The road owner has proposed about 1.5 m as a thickness that could be possible to build in an economic beneficial way. The current regulations however do not allow for this. Even with the use of frost insulation materials like Light Weight Clay Aggregates (LWA) or Foam Glass you will end up with a structure of more than 2 m thickness based on the existing guidelines,. Basically the use of frost insulation materials will then give very little benefit compared to conventional materials (crushed rock).

A previous version of the design guidelines (Håndbok 018) based on the results from Frost i jord in comparison would have given a thickness of 1.35 m by the use of frost insulation.

# New E6 in Ringsaker municipality in Norway

The case study for the numerical analyses is located at the new main highway, E6, in Ringsaker Norway. The new road is planned as a four lane motorway with maximum speed limit and traffic group used in Norway. The sub-soil varies, but in many locations it is classified as highly frost susceptible. The average yearly mean temperature is +4 °C, but the frost index $F_{100}$ = 44 000 h°C is relatively high due to the inland location.

The existing E6 is build several years ago and will probably not have full frost protection. However, the existing road is not reported to have severe frost heave problems. The reasons for the good behavior of the existing road has not been thoroughly investigated and the structure and materials used here is not known in detail.

Based on the current design guidelines a design of the road for conventional material and frost insulation material as shown in Figure 1 - left (conventional material) and right (frost insulation with LWA or foamglass)

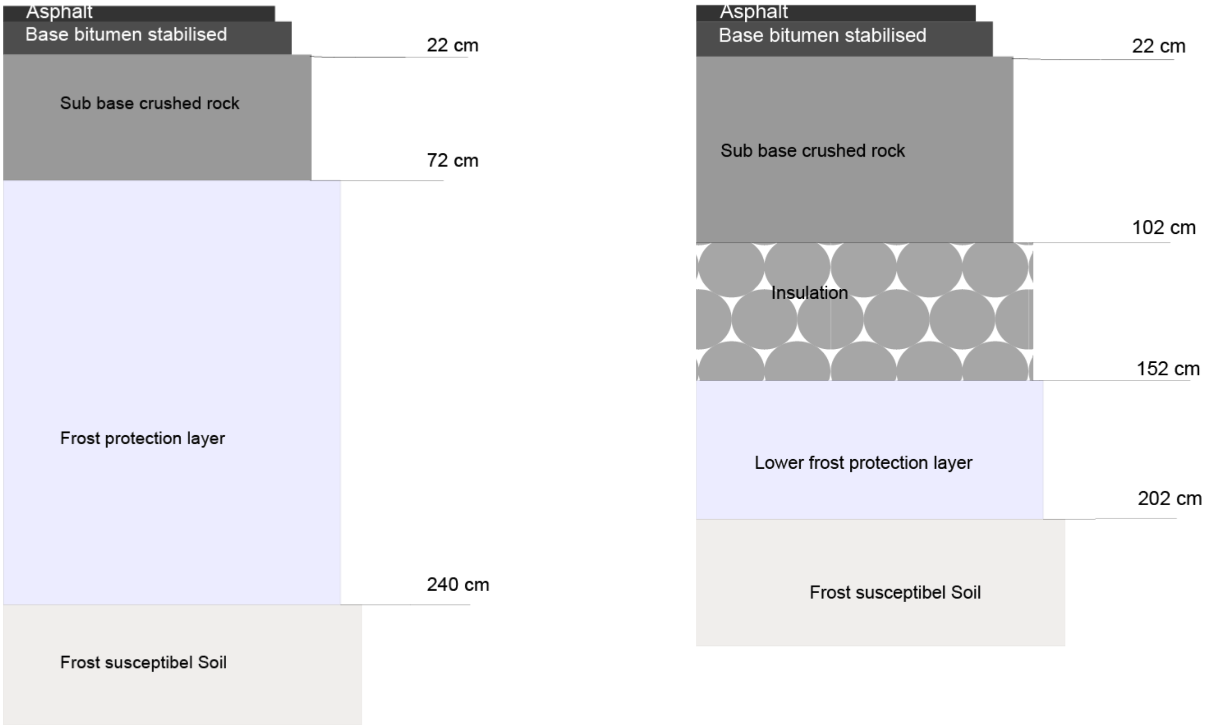


Figure 1 Design with insulation according to N200 with crushed rock (left) and insulated with LWA/foam glass (right)

As can be seen the difference in thickness is relative small. However, for the 2.40 m structure is designed to allow the frost to penetrate into the frost susceptible soil while the insulated structure will prevent frost to reach the susceptible soil. Even if structure with crushed rock can have some frost heave it has been assumed that the frost related unevenness on top of the structure will be limited.

## Winter temperatures

Instead of using a constant temperature a winter with 100 year return period was constructed from real measurements from nearby Kise metrological station from April 2016 to April 2017. Since this winter was not cold enough the temperature for days with colder than +5 °C was modified to reach the $F_{100}$ frost index of 44 000 h°C. The summer was adjusted slightly to get an annual mean of 4 °C as shown in Figure 3. The resulting temperature profile might have unnatural large fluctuations since the mild days are kept as original reading while the cold days are much colder. An alternative would be to search through historic data to find a colder winter. This would probably not influence very much on the overall conclusion. As a comparison to look into the influence of how the frost appears during the winter two constant temperature winters were also analyzed – -20 °C for 92 days and -10 °C for 184 days.

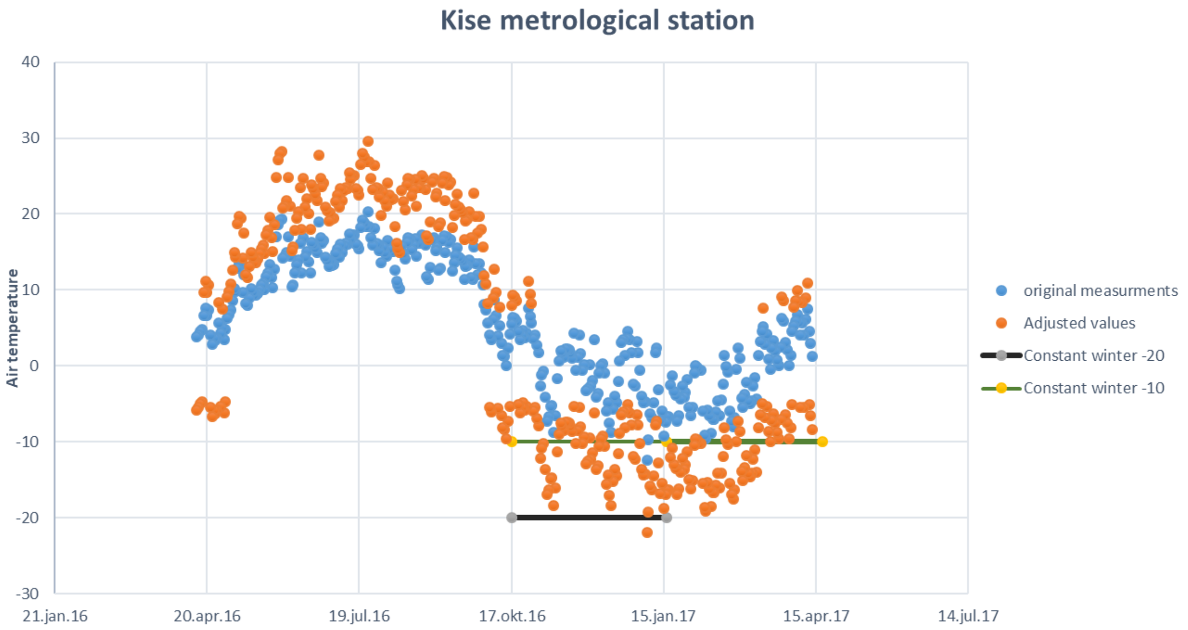


**Figure 2 Real and modified temperature measurements from Kise station April 2016 to April 2017**

## Material parameter used

Table 1 shows the structural layout and the parameters used in this study. The thermal properties of the actual materials that are going to be used in the construction is not yet known. Accordingly we have used typical values found in the literature and also studied how variation will influence on the temperature on top of the silt layer. As shown later the silt layer itself has great influence of the results. The "best estimate" is taken from the European standard (CEN 2007). For the others we have looked at values from FiJ (Frost action in soils (Frost i Jord) 1976) and other publications.

The characteristic parameters used as "best estimate" in the study is shown in Table 1.

Table 1 Parameters used in the study

| Parameters | Best estimate | -20% | +20 % | Comment |
|---|---|---|---|---|
| Asphalt thickness | 22 cm | | | Surface + base |
| Asphalt density | 2300 kg/m$^3$ | | | Average value |
| Asphalt conductivity | 1.5 W/m K | 1.2 | 1.8 | |
| Asphalt heat capacity | 1000 J/kg K | 800 | 1200 | |
| Thickness sub-base | 50 cm | | | Good QA => little variation |
| Sub-base density | 1700 kg/m$^3$ | | | |
| Sub-base conductivity | 1.5 W/m K | 1.2 | 1.8 | |
| Sub-base heat capacity | 850 J/kg K | | | |
| Sub-base water content | 2 % | | | Open graded material |
| Insulation thickness | 50 cm | | | Good QA => little variation |
| Insulation density | 275 kg/m$^3$ | | | |
| Insulation conductivity | 0.13 W/m K | 0.10 | 0.16 | |
| Insulation heat capacity | 840 J/kg K | 672 | 1008 | |
| Insulation water content | 20 % | | | By weight |
| Silt thickness | 2 m | | | Depth to stable temp |
| Silt density | 2000 kg/m$^3$ | | | High water content |
| Silt conductivity | 1.5 W/m K | 1.2 | 1.8 | |
| Silt heat capacity | 1500 J/kg K | 1200 | 1800 | |

# Modeling

The model was adjusted to just avoid freezing temperature in the silt for the best estimates shown in table 1. The sub-base layer was kept at 50 cm (following the older version of the pavement design guide). Figure 3 show the final structure for the analyses with frost insulation.

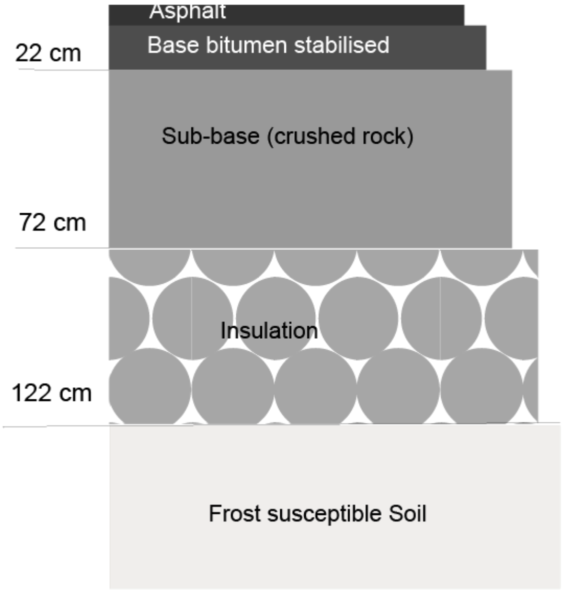


Figure 3 Structure used for finite element analyses

A 2D-model was used to study the thermal behavior as shown in Figure 4

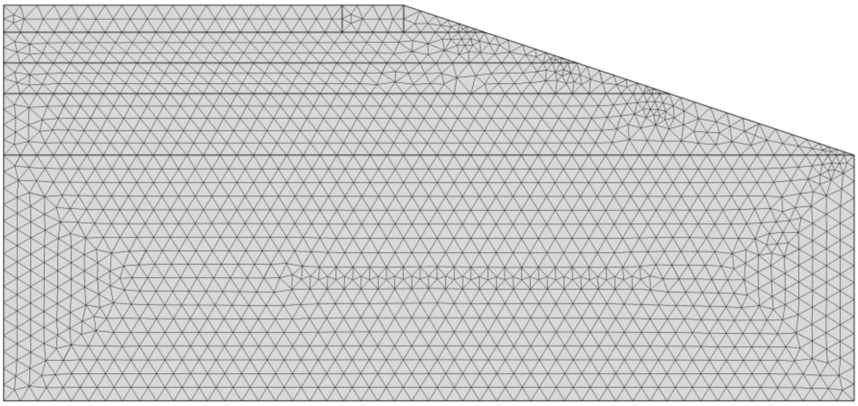


**Figure 4 COMSOL model used for analyzing frost depth.**

The following boundary conditions were applied:

- Top surface, shoulder and the upper half of the slope follows the input air temperature
- The vertical borders to the left and right and the lower part of the slope is assumed to be insulated.
- The bottom border is kept constant at 4$^o$C (yearly average)
- Starting point in april – all layers were set to 4$^o$C

For winter conditions these assumptions will not be far from reality. However, in sunny conditions the temperature of the asphalt could be significantly higher than the air temperature. This means that we may underestimate the heat that could be stored during the summer. The size of this effect has not been investigated but could potentially reduce the need for insulation.

The temperature at 3 m depth is normally assumed to be rather stable at the yearly average independent of the structure above (as long as the heat resistance to heat flow is the same in both directions). In areas with very low average temperature special care should be taken in the analyses to make sure there is no accumulation effect. It is easy to let the analyses run for a longer period than a year, but the computing time obviously increase somewhat. (Approx. 10 min for 5 years on a laptop computer)

The model is not exposed to any other forces from traffic or gravity so it will not change the shape. For this purpose the model does not include deformation due to frost heave since the silt is not allowed to freeze.

## Temperature

The energy from phase change (ice – water) is included by adjusting the heat capacity of the material when the temperature passes through 0 $^o$C. For the base model with relatively dry material the effect of the phase change is limited. Increasing the water content of the material would imply an increased thermal conductivity of the material but also increase the latent heat capacity to freeze out the water. Previous studies (LWAGeolight) have indicated that the effect of water content is relatively small as long as the frost is not penetrating down into the subsoil.

Since ice has higher thermal conductivity than water we have modified the conductivity as a function of water/ice content. Also for this variation the influence on the rather dry materials is limited.

For open graded materials natural air convection will increase the heat flow in the winter (and not in the summer) for high temperature gradients. This could have a negative impact on the temperature in the structure. In these analyses we have assumed that the materials are sufficiently well graded to avoid this effect.

The silt is not allowed to freeze in these analyses. Even for the analyses allowing for frost heave the frost heave is simulated using a thin layer of pure water just above the silt layer where the thickness of the water layer corresponds to the allowed frost heave. This will be a reasonable simulation of the energy involved in building frost lenses inside the silt material.

# Results

## Natural temperature variations vs constant winter

Even if the frost index is the same for all three cases we can see large differences due to how the frost is applied as shown in Table 2 for the structure without insulation.

**Table 2 Differences in frost depth for structure with crushed rock as frost protection (relative low water content)**

| Temperature | Calculated frost depth |
|---|---|
| Variable | 3.0 m |
| Constant -10 ºC 184 days | 2.5 m |
| Constant -20 ºC 92 days | 3.5 m |

As can be seen the variation is quite significant and we should be careful to choose the temperature input to modelling. It seems like very cold temperature over a short time period give deeper penetration than less cold temperature over long time. And that mild periods mixed in especially in the fall would cancel some of the shorter cold periods early in the winter. The approach with a variable temperature input is more realistic and is used for the rest of the study. The main reason for the differences in the analyses related to the cold/short vs the mild/long winter is that more heat is allowed to flow from the bottom boundary. This effect is likely to happen also in reality.

## Temperature profiles for the insulated structure

The temperature at top of the silt layer is shown in Figure 4. The lowest temperature is observed at day 320 from start of simulation (end of February) is 0 ºC. The time for the lowest temperature could vary with a few days depending on the parameters for materials and layer thicknesses.

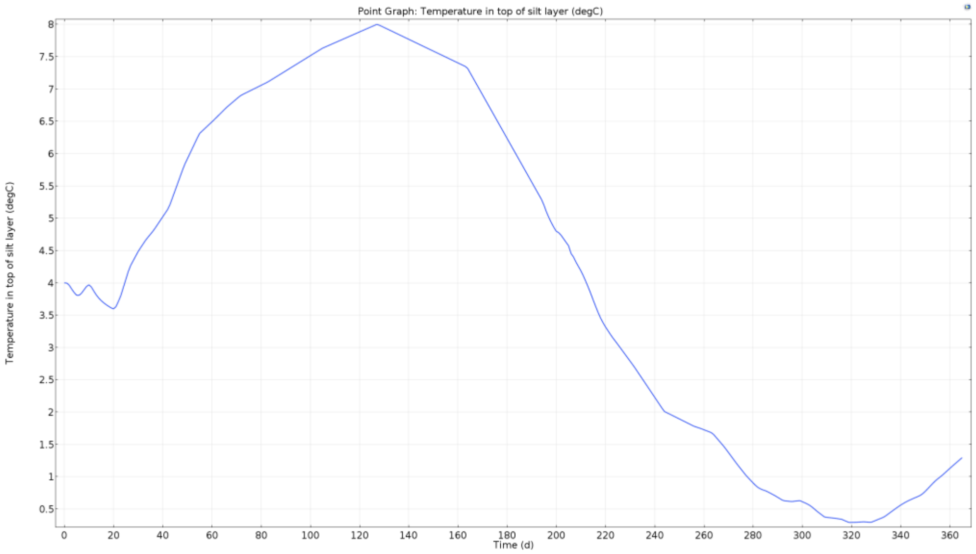


**Figure 5 Temperature in the top part of the silt material**

The temperature difference from start to end is about 2.5 degrees that could indicate a risk for accumulation of frost. However:

- It is highly unlikely to have two 100-year winters in a row.
- Heat from the summer is probably underestimated since the asphalt temperature would be higher than the air temperature on sunny days.

The temperature profile is shown in Figure 5 for the deepest frost penetration where the 0 $^{o}$C contour line is just above the silt layer.

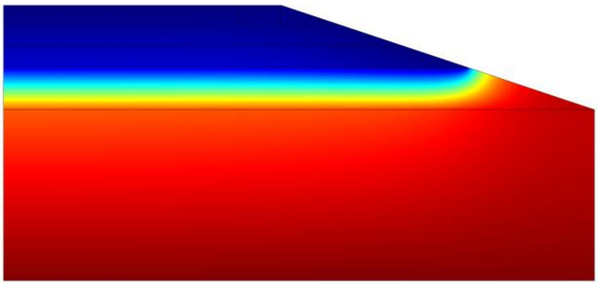


**Figure 6 Temperature profile end of February deepest frost penetration**

This means that the proposed structure with a frost insulation with thicknesss 50cm will survive the 100 year winter without frost heave.

## Allowing some frost heave

An additional analyses were performed to look at the effect of allowing the frost to penetrate slightly into the subsoil. This was done by allowing a given maximum frost heave and adjusting the insulation layer to give about 0$^{o}$C under the “ice lens”. The energy that we free from freezing out the water in the subsoil that would form the ice lenses is enough to allow for reduction of the insulation material to 40 cm compared to 50 without frost heave (see Figure 8)

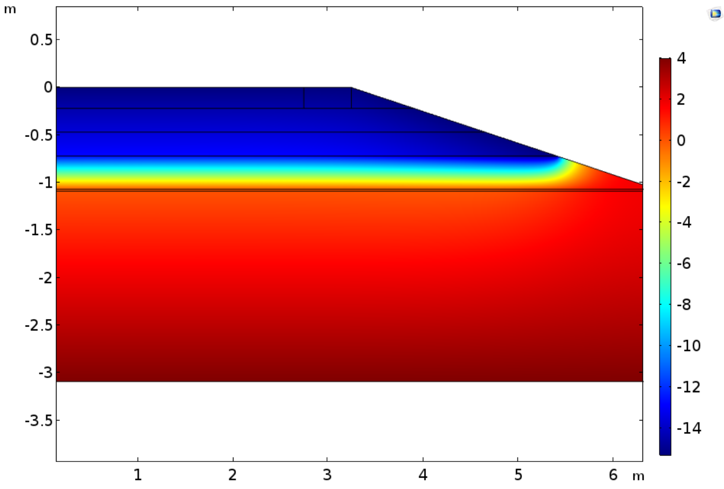


Figure 7 Temperature profile for insulated structure allowing for 22 mm of frost heave.

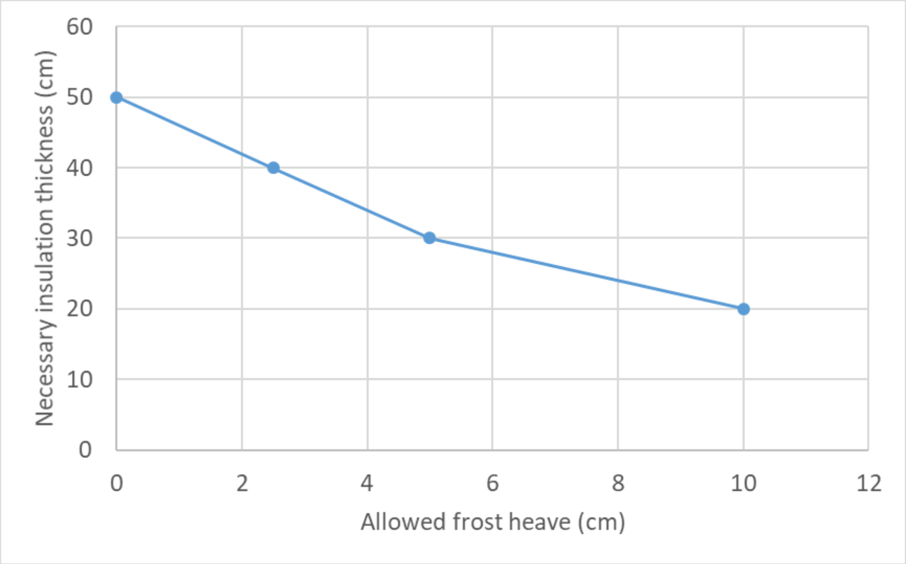


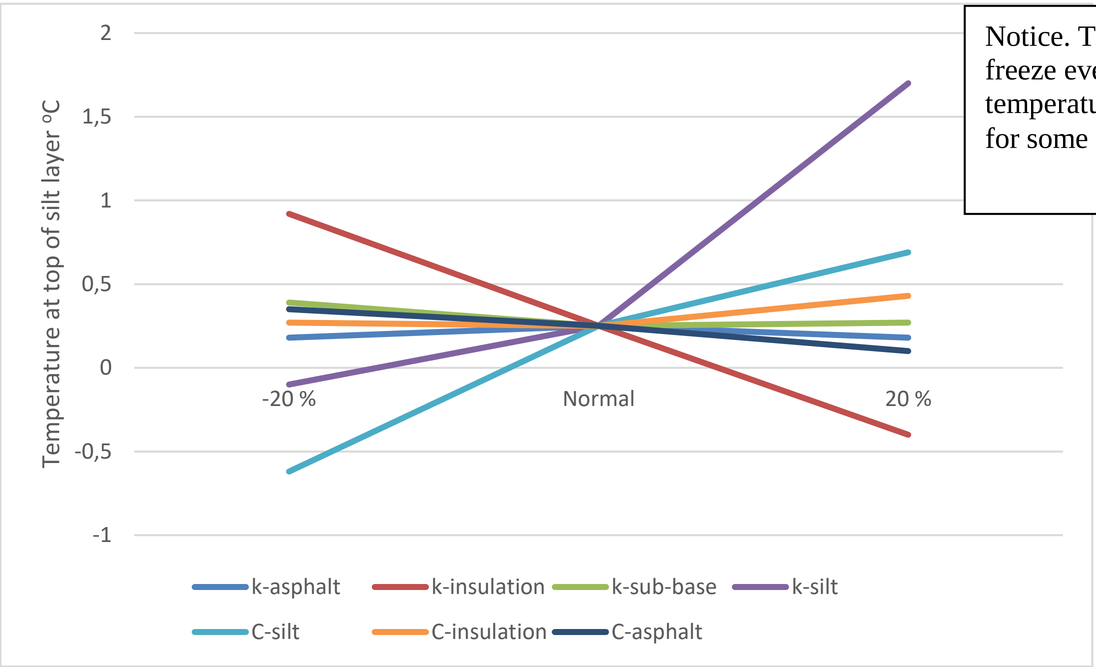
Figure 8 Necessary insulation thickness as function of allowed frost heave

For insulation using only crushed rock and a total thickness of 2.4 m would result in 5-6 cm frost heave (potentially).

## Parameter study

Some of the parameters are rather uncertain and with different types of material and conditions. Some variations are found based on a literature -study. To check which of the parameters are more important a simple parameter study was performed by checking temperature at the top of silt layer. The parameters were varied by 20 % (see table 1). The heat capacity and conductivity of the silt material and the conductivity of the insulation material seems to have most influence. These parameters are very dependent on the water content of the silt that could vary by time and place. However, since high water content will give more frost heave it is possible to argue that the high water content is the most critical and that we should find parameters based on this. Some of the variations in the 0.2 degrees range seems to vary in an odd way. This is probably due to random numerical variations in the analyses tool. The coldest day in the silt layer varies from day 310 to day 330 when the parameters are varied.

In this study we have varied each parameter separately. It is not unlikely that a coupling between two or more parameters (e.g. based on water content) would make it likely that the parameter can change at the same time and amplify the effect.



Notice. The silt does not freeze even if the temperature is below zero for some parameters.

Figure 9 parameter study (thermal conductivity and heat capacity)

The layer thicknesses also influence the total resistance to frost and especially the thickness of the insulation layer. However. We have assumed that this variation could be limited by careful construction and a good QA-system.

## Structure with crushed rock as insulation

A structure without insulation needs to be more than 4 m thick to prevent frost from reaching the silt layer if all materials are dry as shown in Figure 10.

If water and energy from phase change water to ice (latent heat of fusion) is included the necessary thickness is reduced significantly. If we assume water content in base=3%, sub base=5% and frost protection layer=8 % we could reduce the thickness to 3.2 m

This corresponds well with design guidelines in the N200 handbook without the 2.4/1.8 m limit for thickness.

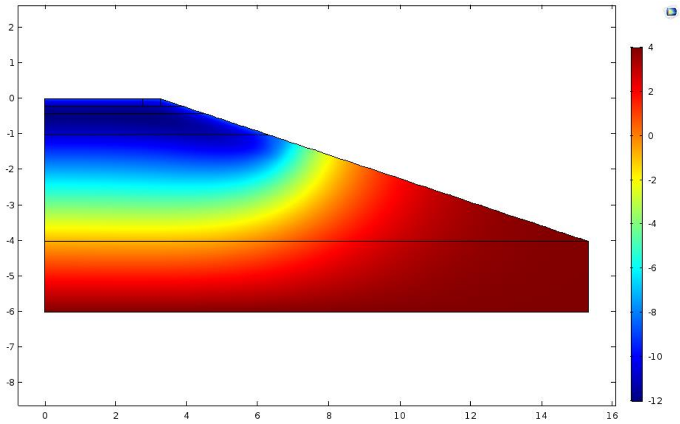


Figure 10 Structure with only dry crushed rock as insulation

# Structural design

Both foam glass and LWA consist of particles that are weaker than crushed rock particles. This means that the stress level needs to be limited to avoid crushing of the grains from traffic loading. Since a crushed particle will reduce in volume there is a danger for a domino effect and severe deformations if the stress levels is too high.

Table 3 Parameters for elastic stress analyses

| Material | Resilient stiffness (MPa) | Resilient stiffness (soft) (MPa) |
|---|---|---|
| Asphalt | 5 000 | 2 000 |
| Base layer | 350 | 250 |
| Insulation | 200 | 200 |
| Silt | 50 | 50 |

Previous testing from laboratory and field (LWAGeolight) show that stress levels below 100 kPa is safe against particle crushing for LWA.

In the last revision of the design guideline (N200) the thickness of the sub-base layer placed on an insulation material was increased from 50 to 80 cm for the high volume roads (Traffic group F). This increase seems to be quite strict and a simplified COMSOL analyses (linear elastic with estimated stiffness) show vertical stress in the insulation layer (Figure 8). The maximal vertical stress based on this analyses is about 43 kPa (45 for the soft structure) and accordingly well beyond the level which should generate crushing and deformations in the frost insulation material. Even if the sub-base thickness is increased to 80 cm the actual reduction in vertical stress is relatively small because the extra weight of the material will also contribute to the vertical stress.

Based on this simplified analyses the stress levels in the insulation materials should be low enough to prevent crushing of particles and permanent deformations.

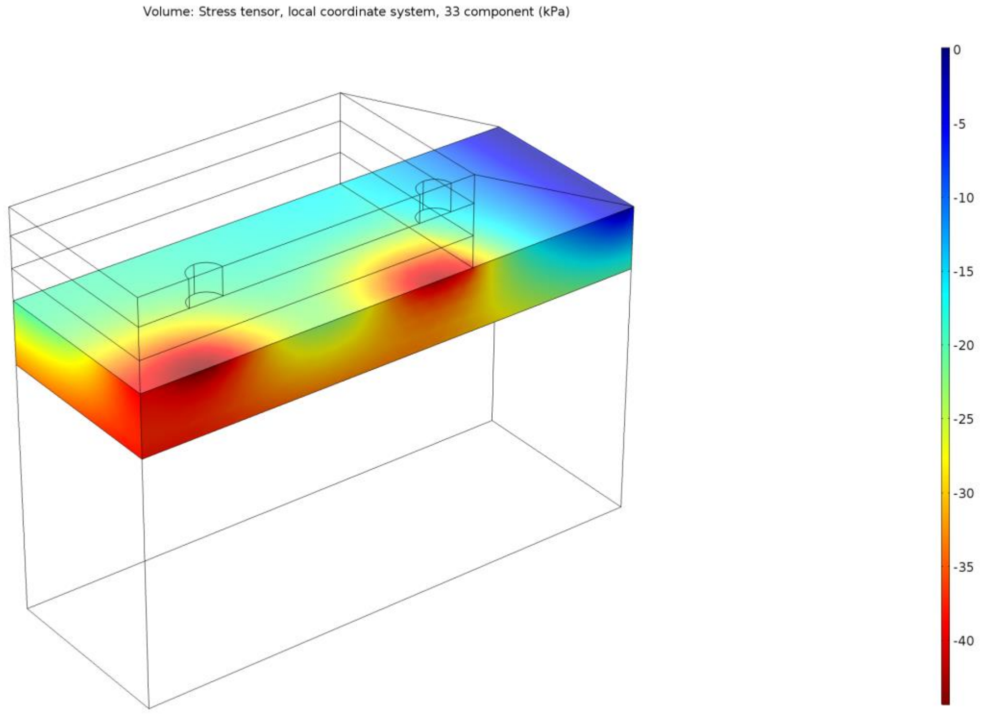


**Figure 11 Vertical stress in insulation material for the proposed structure**

It is important to limit the loading from the construction traffic. If heavy trucks or construction equipment is allowed to use the sub-base without the stabilized materials in place there is a risk for high stress levels in the insulation that could cause crushing and change the material properties.

# Conclusions

COMSOL multiphysics seems to be working very-well for these type of analysis. The program is flexible and relatively user friendly. For the 2D-case presented here the analyses could be done in minutes on a normal lap-top computer using a mesh that is maybe denser than necessary. Even for a full 3D analysis acceptable calculation times could be expected.

How the temperature is given seems to play an important role for the results. Constant or variable temperatures could result in different results even if the frost index is the same.

From these analysis a structure 122 cm thick including 50 cm of insulation should be enough to protect the frost from reaching the frost susceptible materials. This is compared to a required total thickness of 202 cm using the exiting design guidelines. However, no safety factors except on the temperature input has been applied to this design. For a practical design allowing for variation in the construction phase it might be wise to increase e.g. the insulation thickness by some factor to make sure you get a robust design. Still the analyses indicate the potential for significant reduction of thickness by the use of frost insulation material compared to the current design guidelines. If a reasonable safety factor = 1.2 is used to allow for some variation a design thickness of 60 cm could be used.

The stress analyses show that a 50 cm crushed rock sub-base layer is sufficient to reduce the vertical stress to an acceptable level.

Even if the analyses involves simplifications (as all analyses) the design is still conservative and the risk to have frost heave or mechanical crushing of the material is relatively small.

The lower frost protection layer is not necessary in this case as shown by this analyses. Enough energy is released from cooling of the silty material below the insulation. Based on the analyses the lower frost protection layer can be replaced by increasing the thickness of the frost insulation layer and hence reduce the total thickness of the structure significantly.

By allowing some frost penetration into the subsoil with possible limited frost heave the thickness of the insulation layer could be significantly reduced. This is due to the as the energy provided from freezing out the water in the subsoil.

**Table 4 Structure for E6 Ringsaker according to N200 compared to proposed structure**

| | Current design guide N200 | Proposed structure |
|---|---|---|
| Thickness above insulation | 102 cm | 72 |
| Insulation layer | 50 cm | 60 * |
| Lower frost protection layer | 50 cm | 0 |

* including safety factor f=1.2

# References

CEN (2007). Byggematerialer og -produkter. Hygrotermiske egenskaper. Tabulerte dimensjonerende verdier og prosedyrer for bestemmelse av deklarerte og praktiske termiske verdier. **NS-EN ISO 10456:2007+NA:2010**.

Frost action in soils (Frost i Jord) (1976). Sikring mot teleskader [prevention of frost damages] (In Norwegian).

NPRA (2018). Handbook N200 Vegbygging.

Stefan, J. (1891). "Uber die Theorie der Eisbildung im Polarmeere." Ann. Phys und Chem **Bd 2**(Heft 2): 269 - 286.

Watzinger, A., et al. (1938). Undersøkelse av masseutskitningsmaterialer for vei og jernbanebygging [investigations of excavate and fill materials for road and railway construction] (In Norwegian). N. P. R. Administration. Oslo.

SINTEF (2003): LWAGeolight Final Technical Report. http://nordicinnovation.org/Publications/lwageolight/

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