Light-weight fill aggregates as frost protection in roads – The design chart developed for the Norwegian guidelines, Handbook 018 Road Construction

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ABSTRACT: Large deformations and reduced bearing capacity caused by frost heave and thawing every year cause significant problems and result in major maintenance costs of the roads in the Nordic countries. Extruded polystyrene has been the most preferred material for frost protection for some years. However, light weight clay aggregate (LWA) has now become a regular material used for frost insulation in roads in Norway based on a research project by SINTEF. To optimize the design, SINTEF has performed a number of numerical analyses and developed a design chart that gives the required layer thickness of frost insulation. The design chart in the latest Norwegian guidelines for road construction, Handbook 018 Road Construction, is based on this design chart. The calculations showed that the frost protection layer using LWA should be 3-5 times thicker than a frost protection of extruded polystyrene (XPS).

KEY WORDS: LWA, Leca, frost protection, thermal insulation, pavement design.

1 INTRODUCTION

The Nordic countries have difficult geotechnical conditions with soft and frost susceptible soil combined with severe climatic conditions with frost and rapid temperature variations. Every year frost heave and spring thawing leads to unevenness and reduced bearing capacity of road pavements with considerable damages and costs.

Traditional materials used in pavements have low insulation values, which leads to frost penetration through the entire structure and into the subground. Frost depths of two meters or more are not uncommon in Norway. It is expensive and not always practical to use non-frost heave susceptible materials in the zone exposed to freezing. Different types of insulation materials in the road pavement have been tried occasionally to reduce the frost penetration. However both material properties and economical considerations have so far limited the possibilities for a more extensive use.

Light Expanded Clay Aggregate (Leca) has been used for several other applications as light- weight fill and frost insulation materials. The Leca material is a granular material and thus easy to install with common construction equipment. The Norwegian producer, A.S Norsk Leca, started in 1997 a research and development project called “MiljøIso” aiming at developing environmentally friendly solutions for using the material as light weight fill and frost insulation in roads and other traffic areas. The project verified that the material sustained both the traffic loads during the design life time and the construction loads without been crushed or develop deformation that would result in damage of the pavement.

The new research gave a possibility to optimize the design using LWA compared to the recommendations in the old guidelines. Supplied with a number of numerical analyses the thermal characteristics for LWA are verified and a new design chart is developed.

2 MATERIAL PROPERTIES FOR LIGHT EXPANDED CLAY AGGRAGATE (LECA)

In an earlier SINTEF project (Furuberg T. et. al., 2000) the physical, thermal and mechanical properties of the Leca material where investigated, which included laboratory testing, large-scale laboratory tests, full-scale field tests and theoretical analyses. The project showed that the elastic stiffness and resistance against permanent deformations of the Leca material are in the same range as conventional materials for road construction. However, the stiffness and resistance against permanent deformations of the Leca material decrease at high stress levels due to crushing of the particles. The results from a large-scale model test and an instrumented field test verified the results from laboratory tests and theoretical analyses. The performed project showed that the stiffness and strength properties of the Leca material are sufficient to be used as a part of the sub-base of a pavement structure.

2.1 Physical properties

The Leca material is produced by burning of clay at high temperatures in an oven while adding air during the process. The resulting product is a granular material with a particle size varying from 0-32 mm. The most common gradings are 0-32, 4-20 and 10-20.

The densities of the materials as found from laboratory testing and field investigations are presented in Table 1.

Table 1: Density of Leca-material

Grading	Loose density (*kg/m*^{3})	Density after compaction (*kg/m*^{3})	
		Dry	25 % water content
Leca 0-32	335	370	460
Leca 4-20	295	330	410
Leca 10-20	280	310	390

As can be seen the densities in the field for the Leca materials are about 20-25 % of conventional granular materials for this application.

2.2 Thermal properties

The Leca material has very good insulation properties. Based on laboratory investigations and field measurements the thermal conductivity related to the water content is presented in Figure 1.

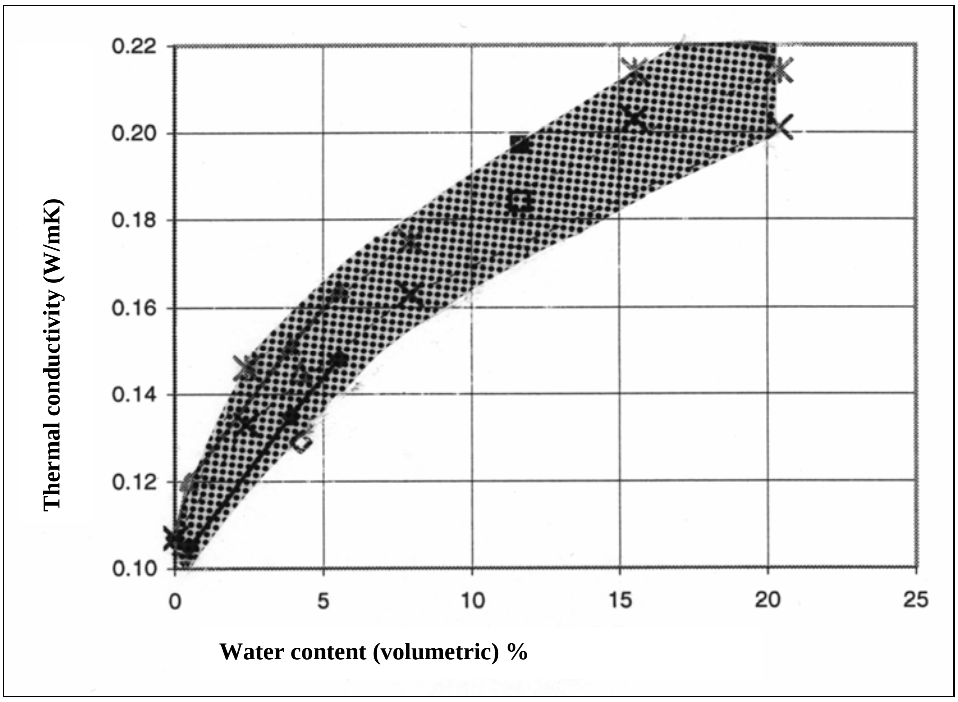

Figure 1: Thermal conductivity of Leca-material

The mechanical properties for Leca is presented by Watn A. et.al. (Watn A. et. al. 2000).

3 NUMERICAL MODEL

There are several models being developed to estimate frost penetration. Some models are discussed and compared in another paper at this conference (Horvli I. et. al., 2005). The conclusion was that the compared models gives results that corresponds well with the measured frost penetration, and that uncertainties in the characteristic parameters used for the soil may be more important than the calculation model itself. However, some differences are registered for special conditions, and it is important to be aware the limitations for the model used. The calculations in this paper are run with the finite element program TEMP/W. The actual problem is modeled with a one-dimensional model, i.e. only vertical heat transfer is modeled. This is believed to be a good approximation for the condition in the middle of the road.

The governing differential equation used in the formulation of TEMP/W is the general heat flow equilibrium equation (TEMP/W Users manual, 2004):

$$\frac{\partial}{\partial x}\left(kx\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(ky\frac{\partial T}{\partial y}\right)+Q=\lambda\frac{\partial T}{\partial t} \qquad (1)$$

where:

T = temperature
kx = thermal conductivity in the x-direction
ky = thermal conductivity in the y-direction
Q = applied boundary flux
λ = capacity for heat storage
t = time

This equation states that the difference between the heat flux entering and leaving an elemental volume of soil at a point in time is equal to the change in the stored heat energy.

The capacity to store heat is composed of two parts. The first part is the volumetric heat capacity of the material (either frozen or unfrozen) and the second part is the latent heat associated with the phase change. In equation form:

$$\lambda = c + L\frac{\partial w_u}{\partial T} \qquad (2)$$

where:

c = volumetric heat capacity (material property)
L = latent heat of water
w_u = total unfrozen volumetric water content
T = temperature
λ = capacity for heat storage

TEMP/W uses the unfrozen water content function of a soil to estimate the latent heat absorbed or released by the soil medium due to the phase changes of the soil water. When the unfrozen water content function of a soil is defined, the total unfrozen volumetric water content can be expressed as:

$$w_u = W_u w \qquad (3)$$

where:

W_u = unfrozen water content ($0 < W_u < 1$)
w = volumetric water content of the soil

Substituting for w_u in Equation (2) and then substituting for λ in Equation (1) leads to the complete differential equation:

$$\frac{\partial}{\partial x}\left(kx\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(ky\frac{\partial T}{\partial y}\right) + Q = \left(c + Lw\frac{\partial W_u}{\partial T}\right)\frac{\partial T}{\partial t} \qquad (4)$$

4 CLIMATIC DATA

Frost penetration is influenced by a number of factors such as solar radiation, wind, air temperature, surface color in addition to the material parameters and the water content in the pavement and subgrade, ground water level, etc. The only climatic data that needed as input to the calculation model is the surface temperature, and all results refer to the frost index for air temperature. The variation in the air temperature and the surface temperature for different part of Norway are modeled as described in the book Sikring mot teleskader (Frost action in soils) (Public Roads Administration, 1976). The winter amplitude is varied to give different frost index values (FI). Se Figure 2 for example Drammen. The frost indexes are named by the return period, e.g. how often the frost index for a winter at this place is equal or higher than the given value. Compared to the air temperature, the surface temperature is colder during the winter and warmer during the summer. This is valid for a pavement surface without snow or hoar frost and may therefore be a conservative assumption, especially for small roads.

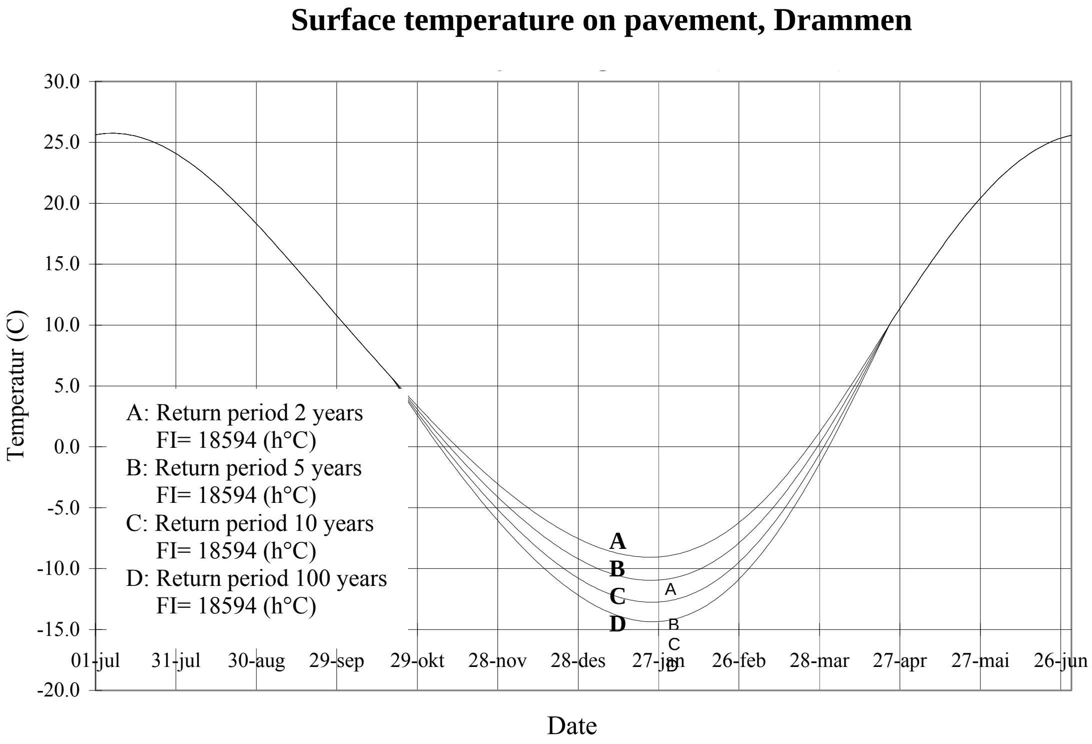

Figure 2: Ideal variation in surface temperature during a year, Drammen

Since the climate in Norway varies very much in different parts of Norway, the performed calculations also have to include different types of climates. The places are selected to have different annual mean temperatures. The frost indexes and the annual mean temperature (vm) for the places selected are shown in Figure 3.

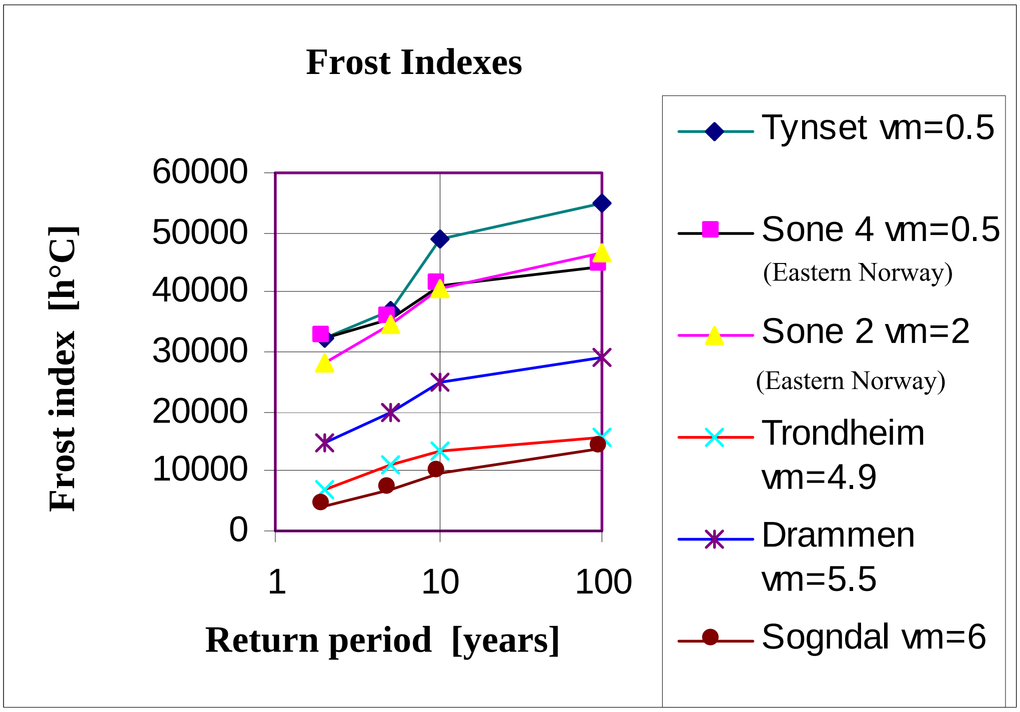

Figure 3: Frost indexes

5 MATERIAL PARAMETERS AND A STANDARD PAVEMENT STRUCTURE

All calculated pavements has a total thickness above the frost insulating material of 50 cm. This part is modelled as 5 cm asphalt, 15 cm crushed gravel and 30 cm crushed rock, see Figure 4. The subsoil is silty clay. Leca ISO 10-20 is chosen as frost protection, and the layer thickness is varied between 15 cm and 70 cm. Some calculations are also run with XPS as frost protection.

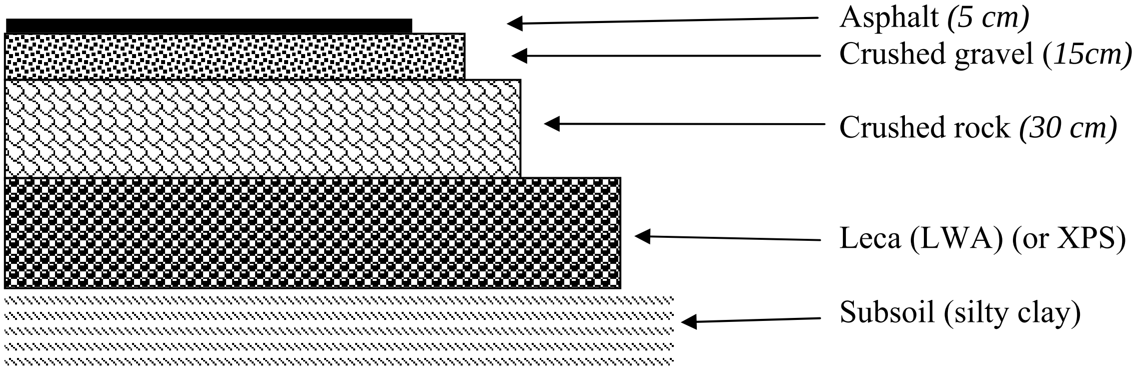

Figure 4: Pavement structure

Only one set of material parameters are used for the materials above the frost insulation in my calculations, but the influence of variations in the water content is to some extend evaluated for the LWA. The applied material parameters are shown in Table 2. The parameters for the XPS are the best material quality available, and it might be correct to use some higher conductivity in case of a lower material quality or water absorption. The selected water content for the LWA is a mean value for several field samples collected from many different projects. SINTEF has also performed some calculations for evaluating the influence of variations in the water content of the LWA, and the result are given in the next chapter. The thermal conductivity for LWA varies for different temperatures. The values given in Table 2 is for -20, -0, +0 and +20 °C.

Table 2: Material properties

Material	Layer thickness	Dry density	Water content		Thermal conductivity		Heat capacity	
			W	w_{vol}	λ_f	λ_u	C_f	C_u
	Mm	*kN/m³*	*%*	*%*	*W/mK*	*W/mK*	*kJ/m³K*	*kJ/m³K*
Asphalt	50	2100	0	0.0	1.50	1.50	2520	2520
Cr. gravel	150	1950	6	11.7	1.90	2.00	1600	1800
Cr. rock	300	1800	3	5.4	0.75	0.95	1240	1360
LWCA (Leca)	Varies	300	25	7.7	0.162-0.175	0.153-0.208	354	512
Extruded polystyrene	Varies	Ca 30	0	0.0	0.033	0.033	43.5	43.5
Subsoil			25	36.2	2.00	1.10	1900	2700

λ_f – *Thermal conductivity – frozen material*

λ_u – *Thermal conductivity – unfrozen material*

6 RESULTS

To be able to develop a design chart it was necessary to evaluate how much the different factors influence on the results, and which factors those have to be input values to the design chart.

The frost index is an obvious parameters to be input to the design chart, but the climatic data varies much all over Norway and the calculations showed that different climatic zones gave some variation in the results even when the frost index and the mean temperature was equal. However, the main difference came from variations in the mean temperature. The results for a pavement with 50 cm Leca in Figure 5 shows the variation in frost penetration for different frost indexes. The frost penetration is deeper for a winter with the same frost index for a place with low mean temperature as in Tynset, than for a place with higher mean temperature as in Drammen. (The most extreme frost indexes calculated for Drammen will most probably never take place and is only calculated to find the required frost index for frost penetration into the subsoil)

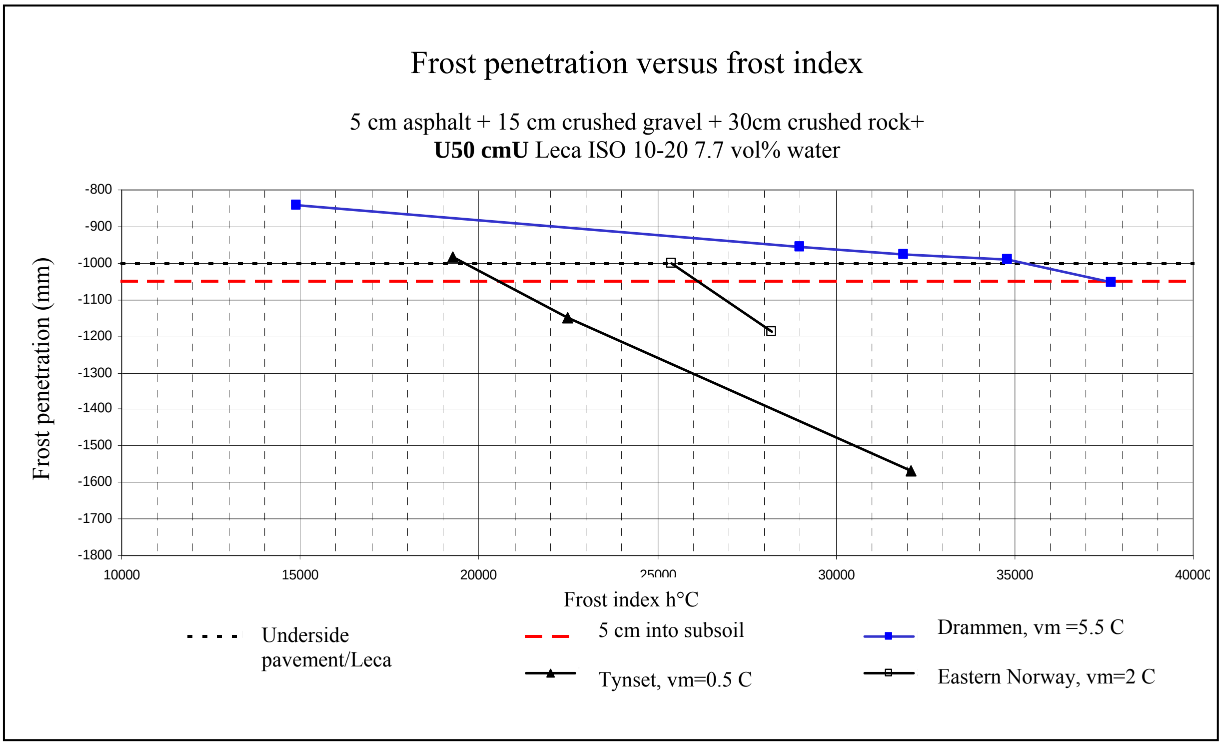

Figure 5: Variation in frost penetration for different annual mean temperatures

The pavement design and material parameters above the frost insulation material are of course important for the results, but these parameters are often unknown when the design is chosen. These parameters therefore need to be selected as probable parameters and not to optimistic. A variation in these parameters is not practical.

The selected water content for the LWA is a mean value for several field samples collected from many different projects. When the design is performed, the water content is of course not known. SINTEF has performed some calculations for evaluating the influence of variations in the water content and material quality for the LWA. The results showed that the influence in the expected range is within the uncertainties for other parameters in the calculation model and can therefore be neglected in the design charts, see Figure 6. The calculation model for these calculations differs some from the model used for the design chart, but the influence of variation in water content is still shown. When both a material quality with higher conductivity was chosen and the water content was doubled, the frost penetration increased only approximately 10 cm.

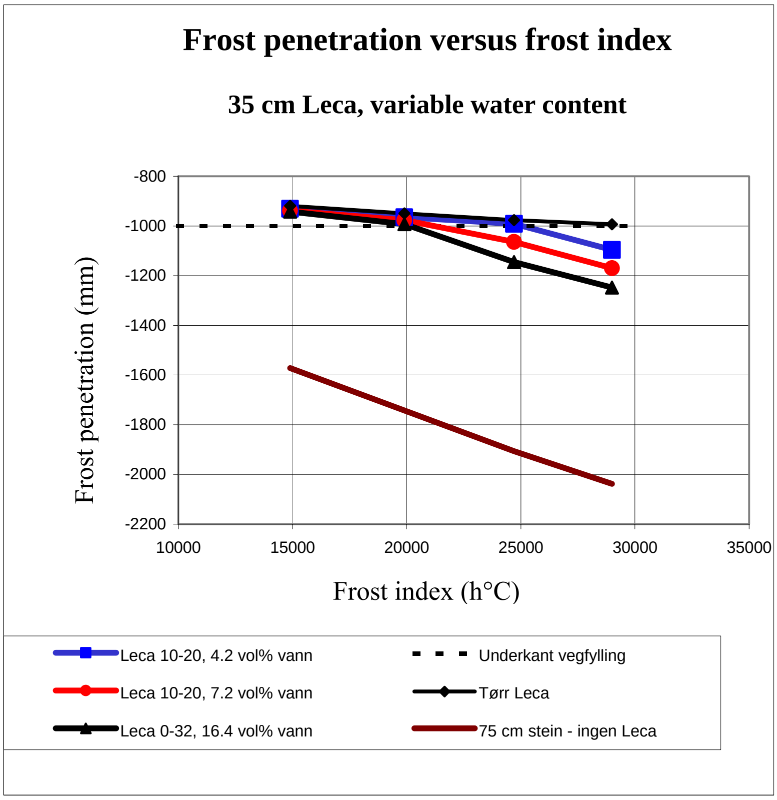

Figure 6: Variation in frost penetration for variable water content

The calculated results are shown in the proposed design chart in Figure 7. The required layer thickness of LWA, based on the maximum frost penetration during the winter, is given as a function of the annual mean temperature and the frost index.

The national road department decided to allow the frost front to penetrate 5 cm into the subsoil. The proposed design chart may give less frost penetration into the subsoil for many structures due to that the subsoil was modeled to have some unfrozen water content below 0 °C. This may be valid for marine clays with high salt content in the pore water, but on the other hand the unfrozen water does not result in frost heave. Later calculations performed at SINTEF shows that unfrozen water may give calculation results with substantial larger frost penetration when the frost front penetrates into the actual layer.

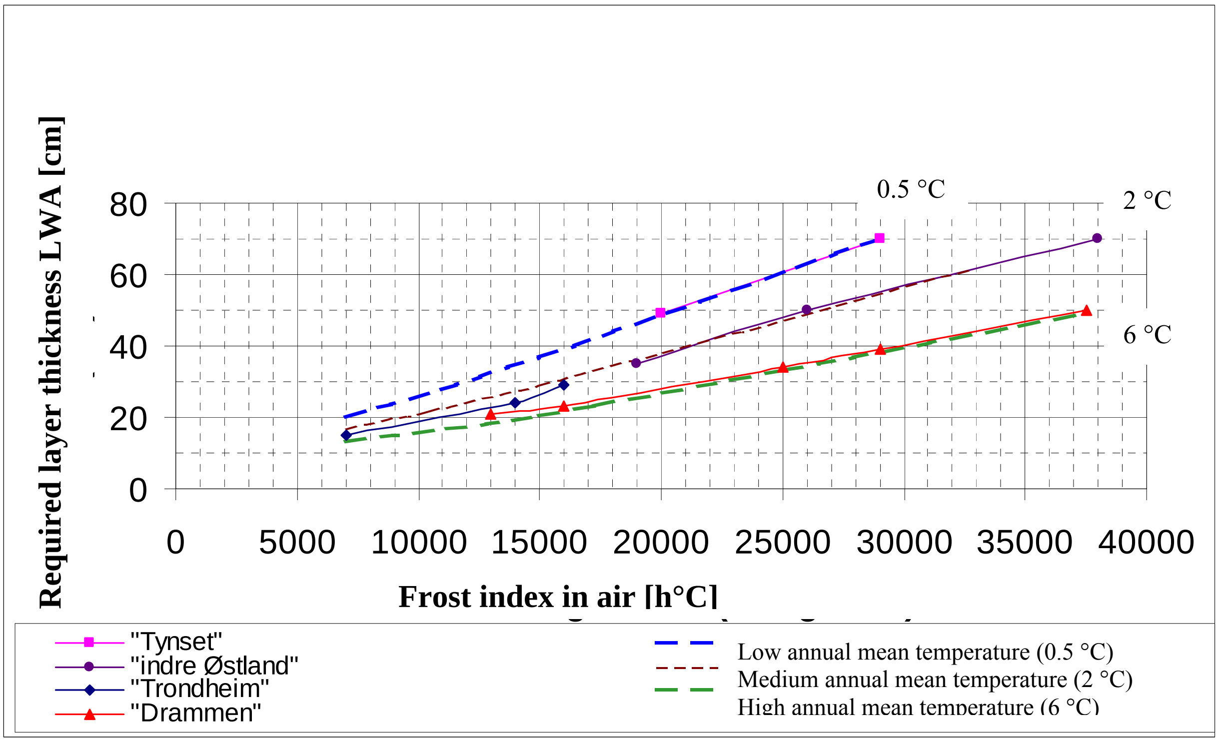

Figure 7: Design chart – LWA as frost protecting layer in pavement structures

This design chart is the basis for the chart included in the latest Norwegian guidelines, Handbook 018 Road construction. A similar design chart is also developed for extruded polystyrene (XPS), requiring some thicker insulation layer than in the old design table.

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