Frost design/use of frost protection layer

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Background

Frost heave problems on new constructed motorways during the winters 2009/2010 and 2010/2011.

NPRA established an expert group to review the frost protection design.

Requirements for the frost protection design
Directive NA 12/09 from the Directorate of Public Roads

- 4 lane motorways with the road foundation shall be frost free when the frost susceptibility for the subgrade is high to very high (category T3 and T4) and the design frost index shall be equal to the frost we statistically have once every 100 year. (F_{100}). No maximum frost depth.
- For road whit AADT 1500-8000 the design frost index shall be equal F_{10}. The maximum frost depth is set to 1,8 m.
- For road where the AADT<1500 there are no changes in the requirements.

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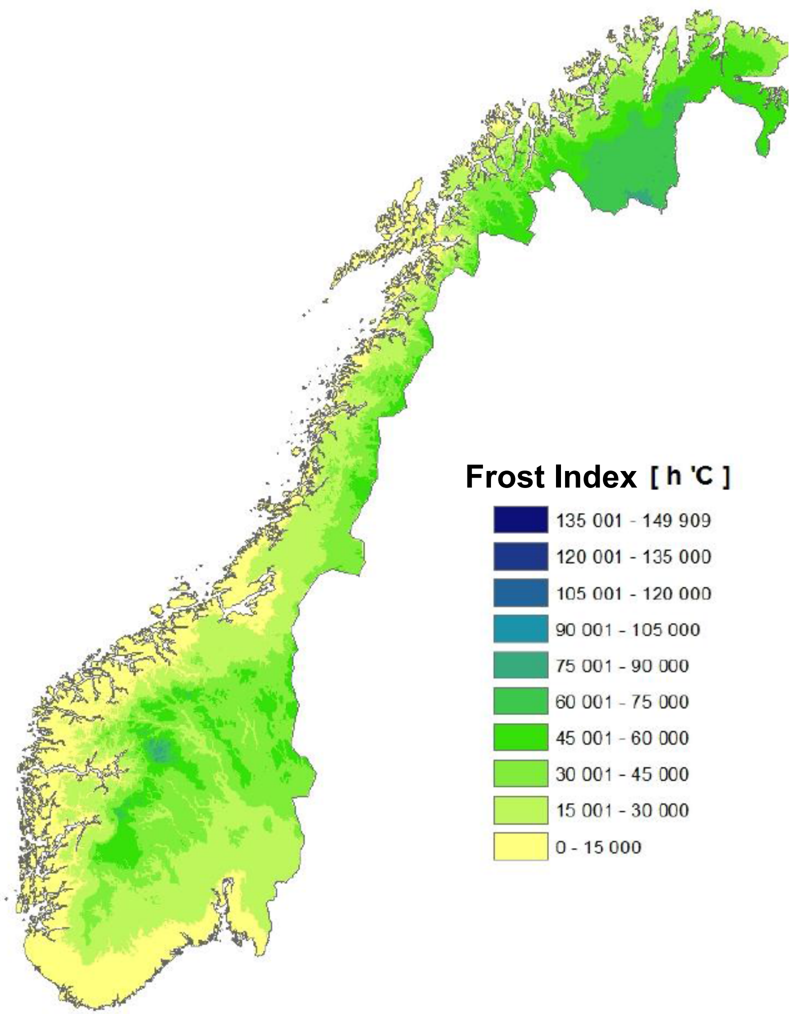
Presentation

- Updated climate data
- Recalculating frost penetration for the pavement structure
- Recalculating required thickness of insulation layer

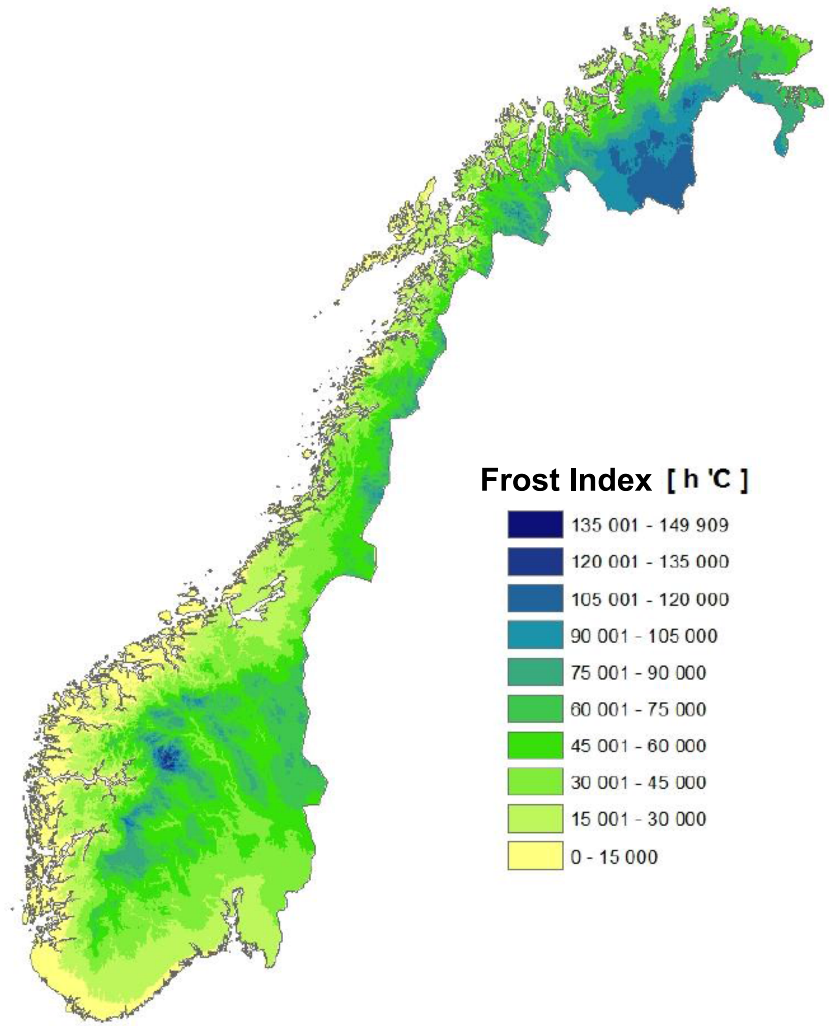
  - input parameters
  - design of the pavement structure
  - requirements for aggregates used as frost protection layer

Map – Frost Index

F10



F100



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Frost index – 1981-2010

Municipality	Municipal administration center	County	Annual avg. temperature [°C]	Frost Index F2 [h°C]	F5	F10	F100	Correction factor for min. and max. frost Kmin	Kmax
101	Halden	Østfold	6,3	4000	9000	11000	20000	0,86	1,22
104	Moss	Østfold	6,4	4000	8000	11000	19000	0,93	1,15
105	Sarpsborg	Østfold	6,3	4000	9000	12000	21000	0,83	1,24
106	Fredrikstad	Østfold	6,7	3000	7000	10000	18000	0,84	1,21
111	Hvaler	Østfold	7,2	2000	6000	8000	14000	0,94	1,07
118	Aremark	Østfold	5,4	6000	12000	15000	26000	0,90	1,09
119	Marker	Østfold	5,0	8000	14000	18000	30000	0,89	1,14
121	Rømskog	Østfold	4,4	9000	16000	20000	34000	0,97	1,04
122	Trøgstad	Østfold	4,9	7000	13000	17000	29000	0,94	1,11
123	Spydeberg	Østfold	5,3	6000	12000	15000	27000	0,95	1,07
124	Askim	Østfold	5,2	6000	12000	16000	27000	0,97	1,04

Correction factor (for frost index) within the municipality that is covered by roads

Why do we have to recalculate the frost depths?

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- Dense graded sand/gravel was previously used as base and subbase materials. Typical water content 5-10 %.
- Today the fine particles are removed from the aggregate and the water content is very low. Typical fraction used as subbase is 20/120, and fractions like 8/22 and 8/32 are commonly used as levelling layer and unbound basecourse.
- The frost resistance depends mainly on the water content.

- The design frost index has been increased for the main roads. (F_{100} exceed the existing design charts and tables.)

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Stefan's equation – homogeneous subgrade

- The equation calculates only the heat released when water is freezing – **L** (Wh/kg)
- Frost depth: $Z = \sqrt{\frac{2 \cdot l_f \cdot F}{L}}$

1 Joule = 1 Ws => 1 Wh = 3600 Joule

- When L is given in J/kg => Frost depth: $Z = \sqrt{\frac{3600 \cdot 2 \cdot l_f \cdot F}{L}}$ =>

$$Z = \sqrt{\frac{7600 \cdot l_f \cdot F}{L}}$$

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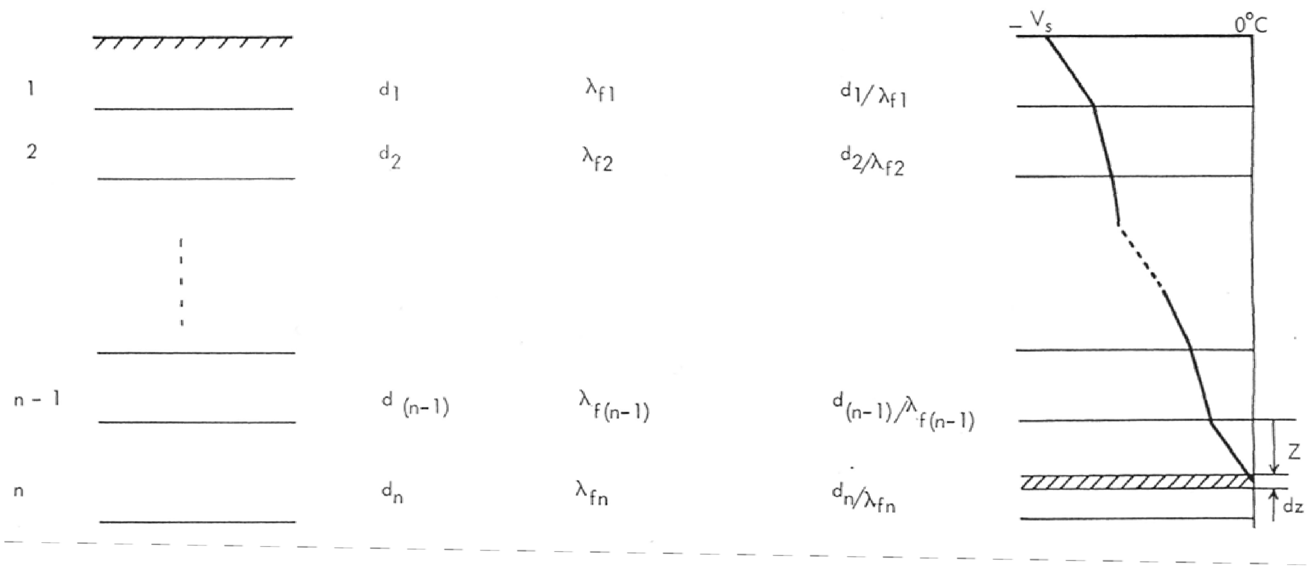
Frost depth – layered structure



$$dQ = \frac{v_s}{R_{(nz)}} \cdot dt = L_n \cdot dz \;\rightarrow\; v_s \cdot dt = L_n \cdot R_{(nz)} \cdot dt$$

t_n – time to freeze layer n

$$\int_0^{t_n} v_n \cdot dt = \int_0^{d_n} L_n \cdot \left(\frac{d_1}{\mathrm{l}_{f1}} + \frac{d_2}{\mathrm{l}_{f2}} + \cdots + \frac{d_{n-1}}{\mathrm{l}_{f(n-1)}} + \frac{z}{\mathrm{l}_{fn}} \right)$$

Frost depth – layered structure (2)

By integration and setting $v_s \cdot t_n = F_n$ we get the frost index necessary to freeze layer n:

$$F_n = d_n \cdot L_n \cdot \left(\frac{d_1}{\lambda_{f1}} + \frac{d_2}{\lambda_{f2}} + \cdots + \frac{d_{n-1}}{\lambda_{f(n-1)}} + \frac{z}{2 \cdot \lambda_{fn}}\right) = d_n \cdot L_n \cdot \left(\frac{z}{2 \cdot \lambda_{fn}} + \sum_{i=1}^{n-1} \frac{d_i}{\lambda_{fi}}\right)$$

Equation – frost depth – homogeneous subgrade

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$$H_0 = \sqrt{\frac{7200 \cdot F_d \cdot \lambda_f}{L + C \cdot \theta_m}}$$

addition to Stefan's equation

where:

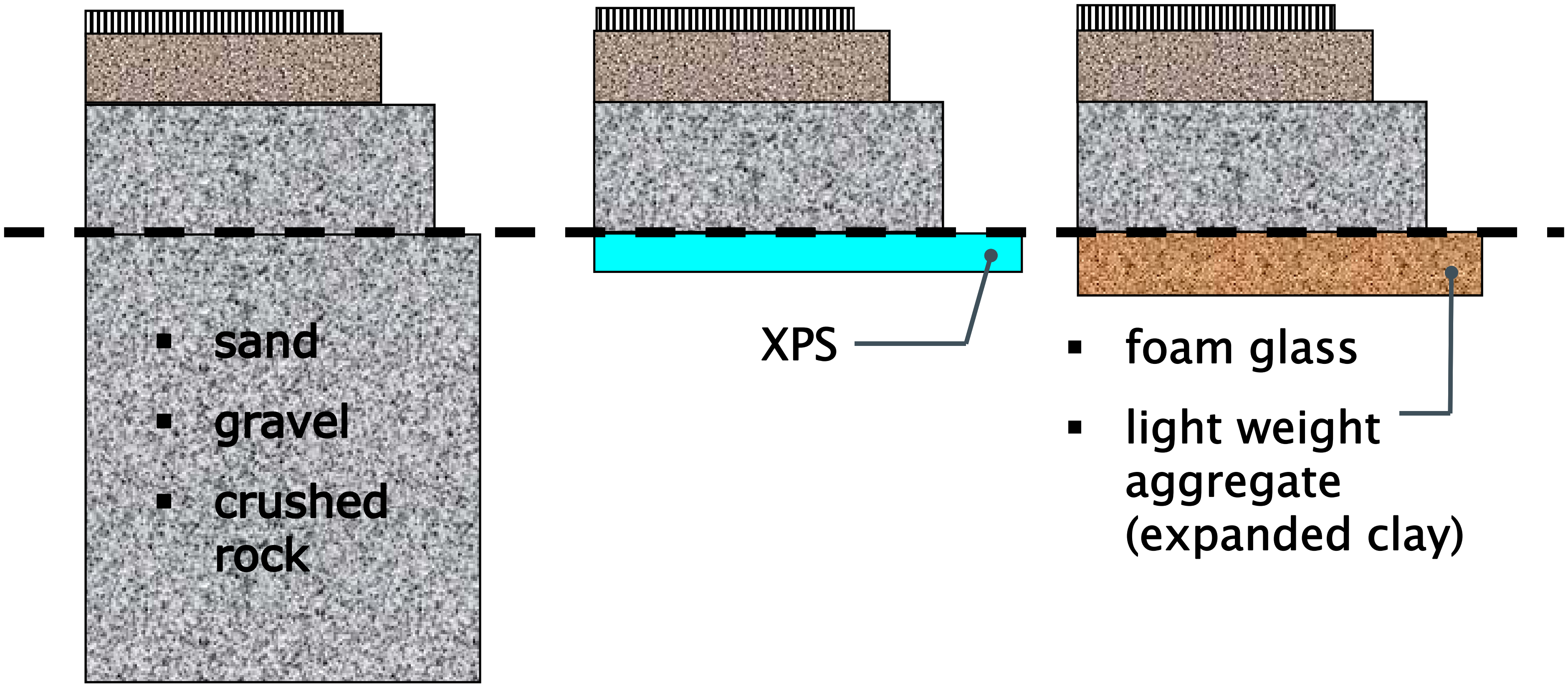
- F_d is the frost index (h°C)
- λ_f is the thermal conductivity of frozen ground (W/mK)
- L is the latent heat released when water freezes in the aggregates (J/m^3)
- C is the thermal capacity of unfrozen aggregates per unit volume (J/m^{3}K)
- θ_m is the annual average temperature (°C)

EXCEL – calculation of frost depth

Ann. avg. T	4
C	833

Layer no.	Type	Lay. thick. (m)	Density (kg/m3)	w-%	λf (W/mK)	R	Sum R	L + C* theta-m	Frost Index (hC)		Frost depht (m)
1	Asphalt	0,21	2400	0,5	1,7	0,12352941	0,12352941	4448		58	
2	Aggregate	0,1	1900	1	1	0,1	0,22352941	5099		88	
3	Aggregate	0,6	1800	1	1	0,6	0,82352941	5006		1572	
4	Insulation	0,3	333	15	0,15	2	2,82352941	7977		4364	
5	Frost pro. lay.	0,34	1900	6	1,6			13934	20000	13917	1,55
5	Frost pro. lay.	0,46	1900	6	1,6			13934	25000	18917	1,67
5	Frost pro. lay.	0,57	1900	6	1,6			13934	30000	23917	1,78

Materials used for frost protection in Norway



Thermal conductivity for soil materials

Besides the water content, the soils thermal conductivity is dependent on the degree of saturation and the particles thermal conductivity.

Soil particles thermal conductivity is dependent on the mineralogical composition. Quartz has especially high thermal conductivity and the quartz content in the particles is vital for the soils thermal conductivity.

Quartz content varies considerably in coarse material and makes it difficult to determine this input parameter.

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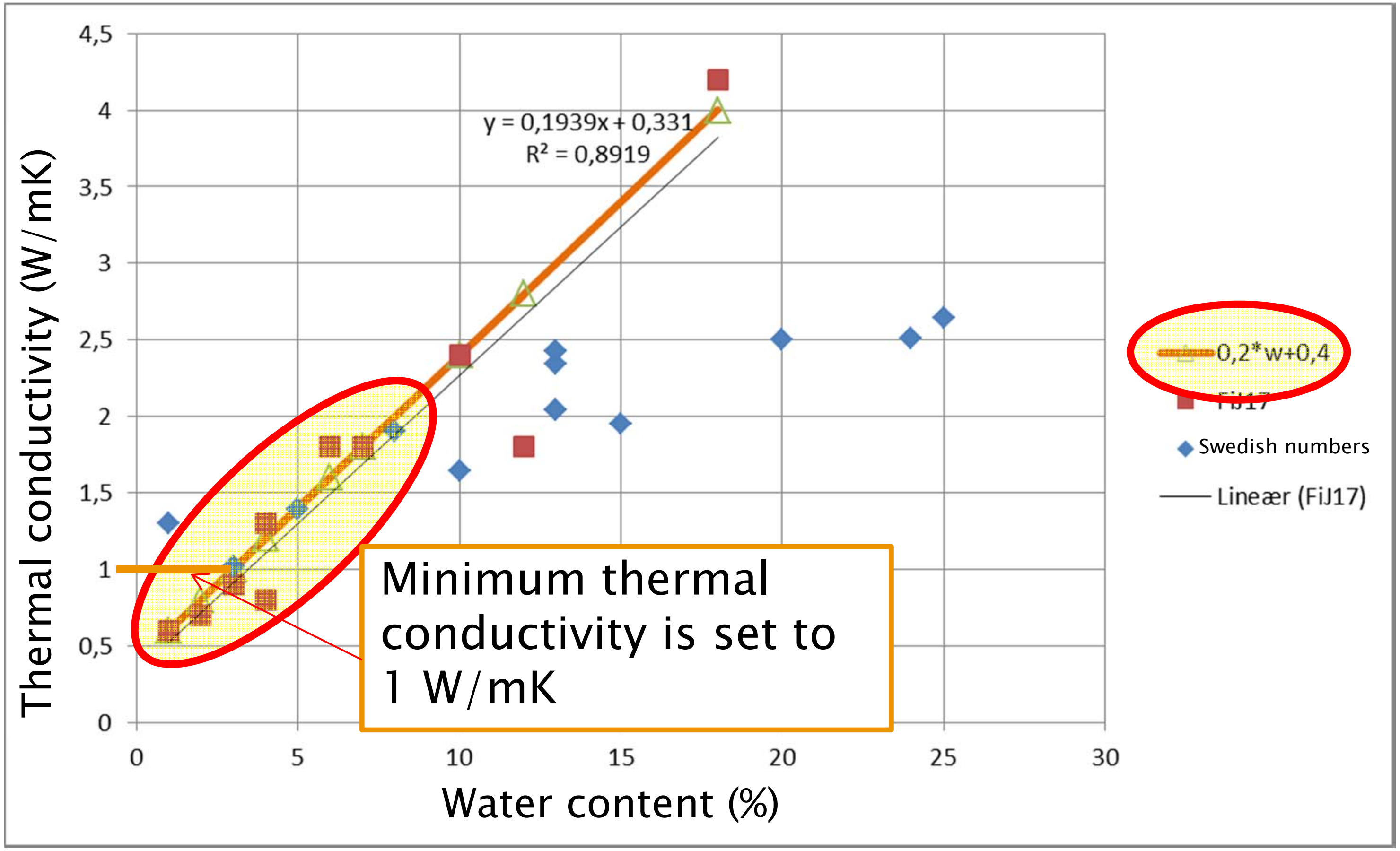
Thermal conductivity



Thermal conductivity for thermal insulation materials

- Foam glass/light weight aggregates
  - Varies by water content
  - Based on measurements in NPRA-project "Recycling Project" is the thermal conductivity set to 0,15 W/mK

- XPS - insulation board
  - Varies by water content
  - Value in CE Document: 0,039-0,04 W/mK for insulation board placed horizontally in the ground

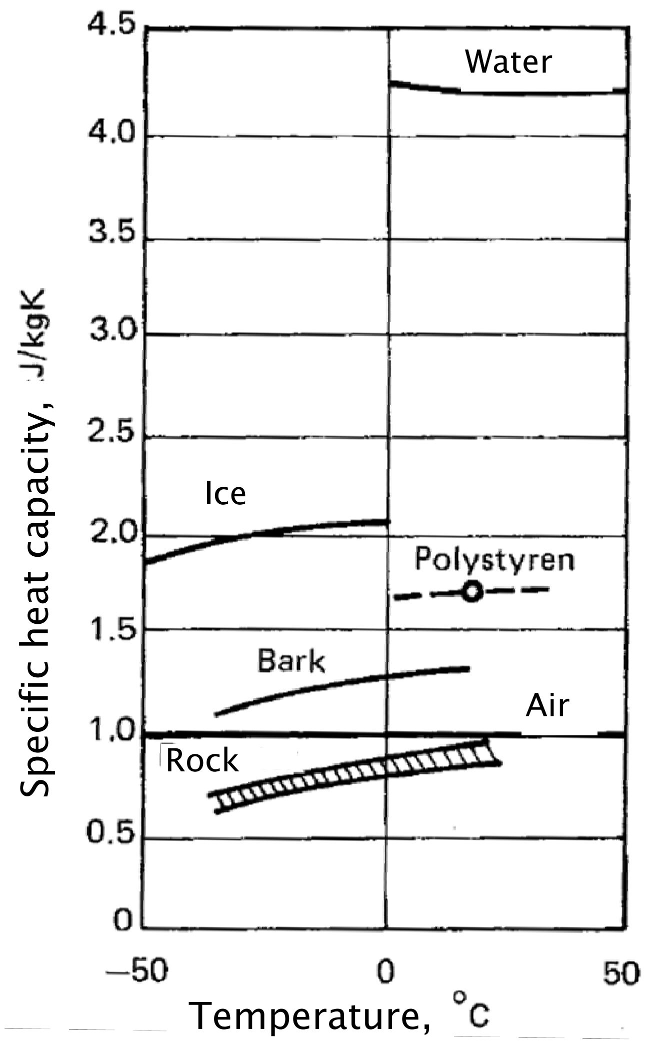
Thermal capacity

- C – volumetric thermal capacity. The amount of energy that rise (or reduce) the temperature in 1 m^3 soil by 1°C.
- c – specific heat capacity. The amount of energy that rise (or reduce) the temperature in 1 kg soil by 1°C.
- $C = \rho \cdot c$
  ρ – density

$c = 1{,}5$ kJ/kgK, $\rho = 2000$ kg/m^3

$\Downarrow$

$C = 3$ MJ/m^3K

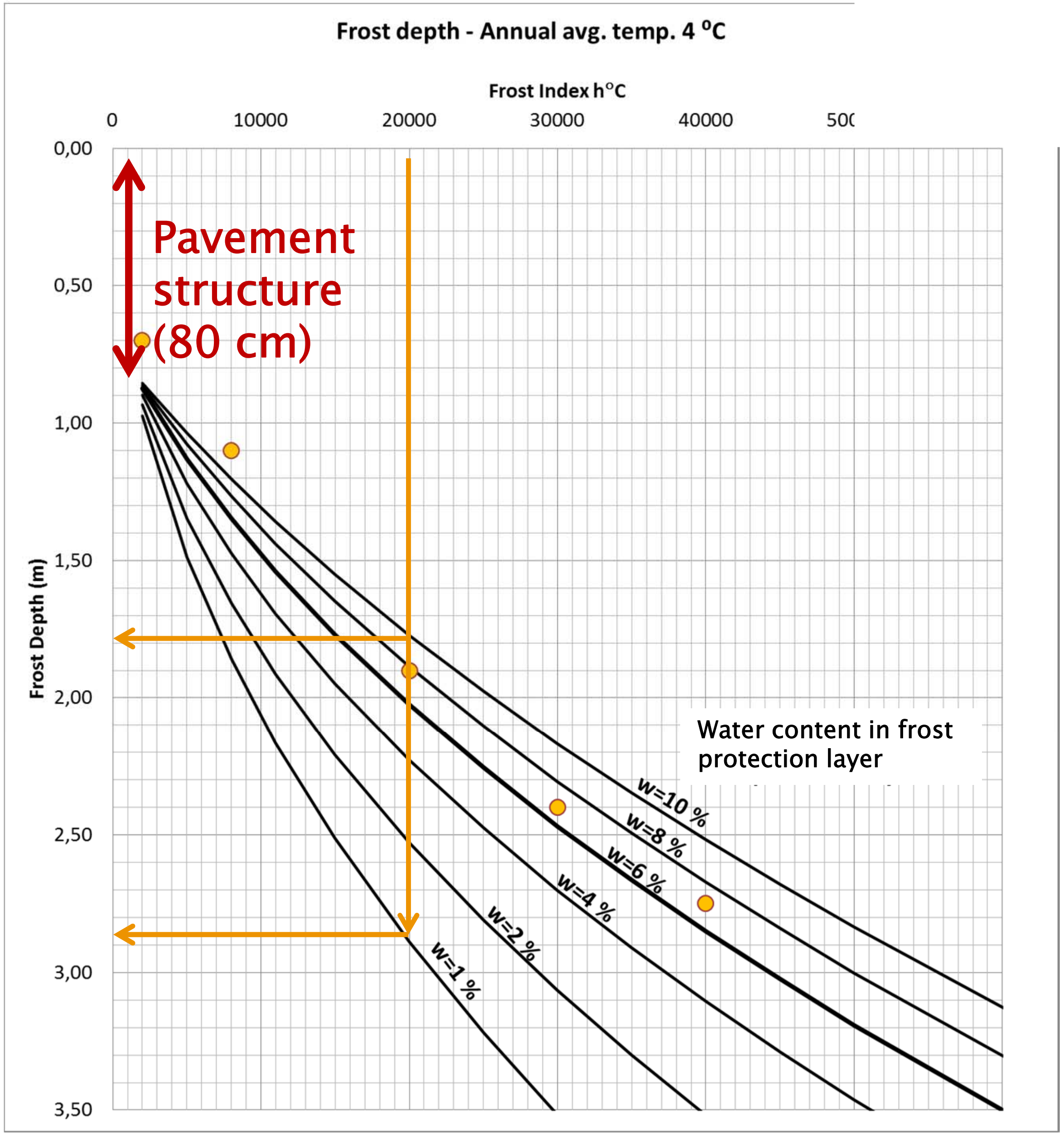


1 J = 1 Ws
1 MJ = 0,278 kWh

Frost protection design

- Have to be easy to use
- Need for simplifications
- Use of predefined thermal conductivity and thermal capacity

Frost depth – sand, gravel, crushed rock

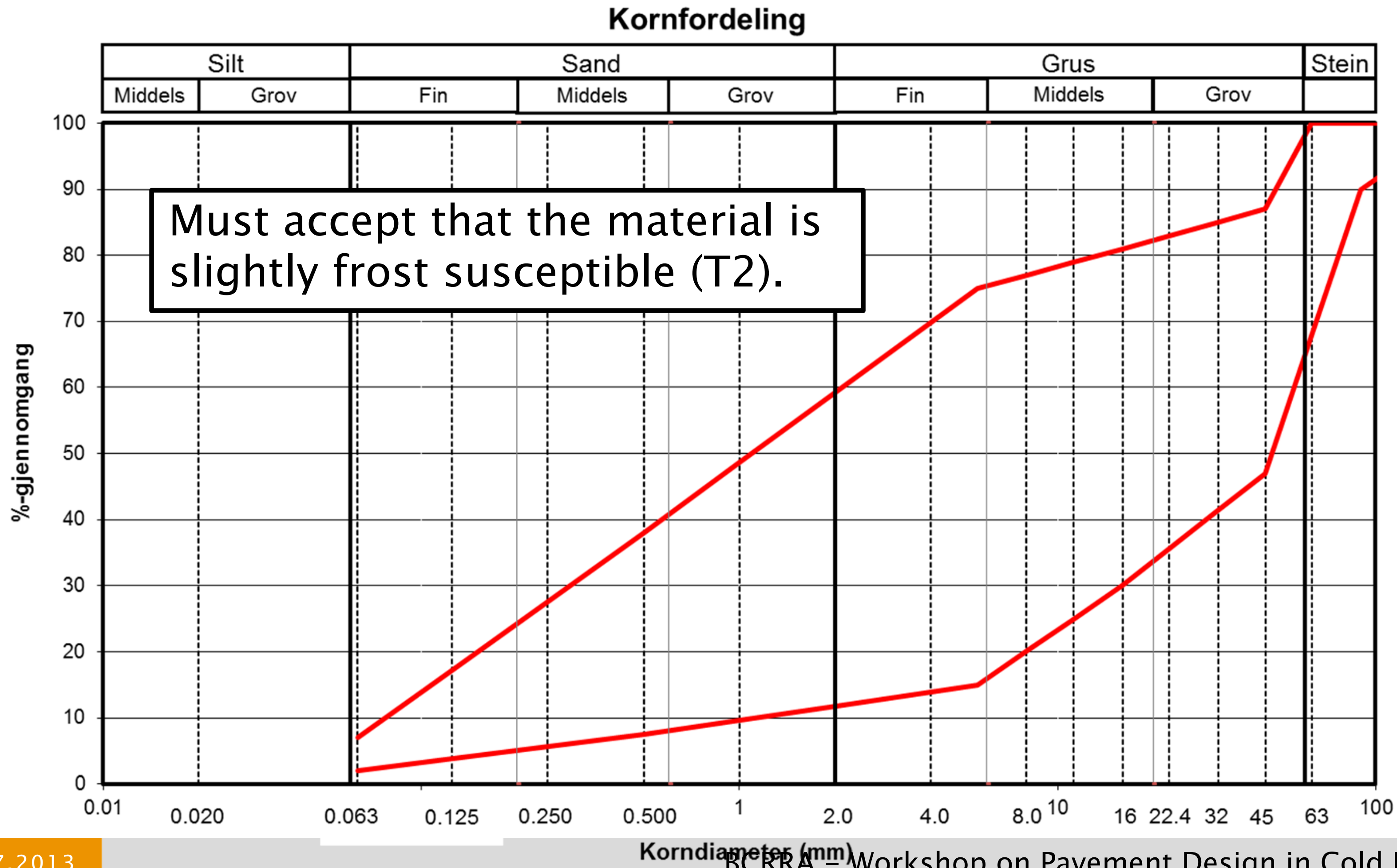


Is there a relationship between the content of fine particles and water content?

Frost protection layer – sand, gravel, crushed rock

- Must be homogeneous
- An advantage if the material contains some water (... provides greater frost resistance)
- Limitations to largest stone size

Proposal for grain size distribution curve. Frost protection layer for the portion of the material <90 mm



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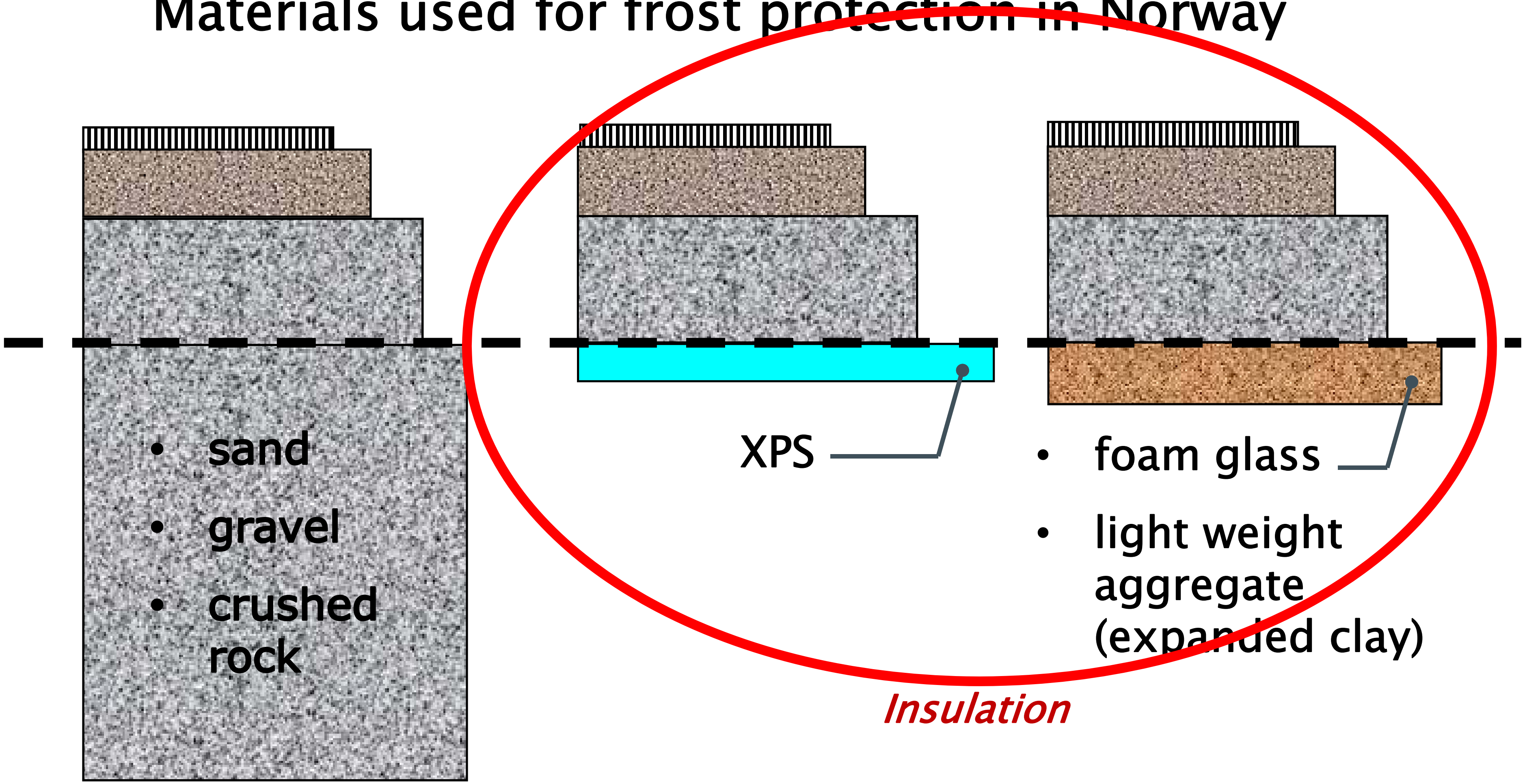


Why thermal insulation?

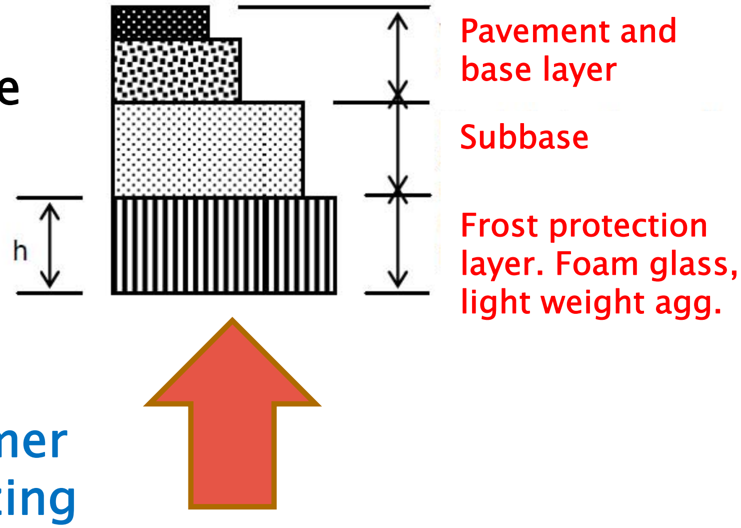
- *We want to keep the heat in the house*
- *Stop the heat loss*

Why insulation?

Wikipedia:

Thermal insulation *is the reduction of [heat transfer] (the transfer of [thermal energy] between objects of differing temperature) between objects in thermal contact or in range of radiative influence.*

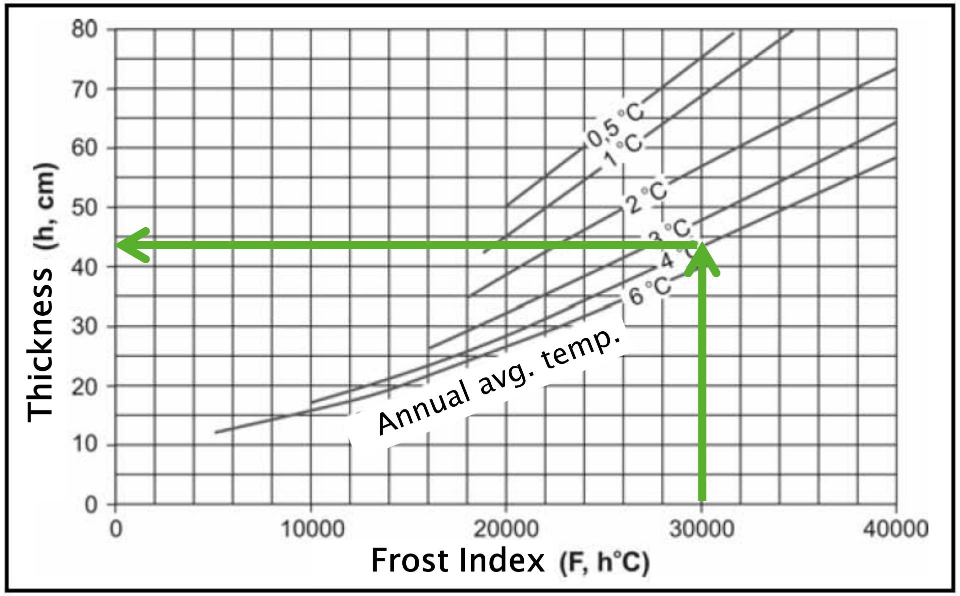
or:
increase the heat flow resistance

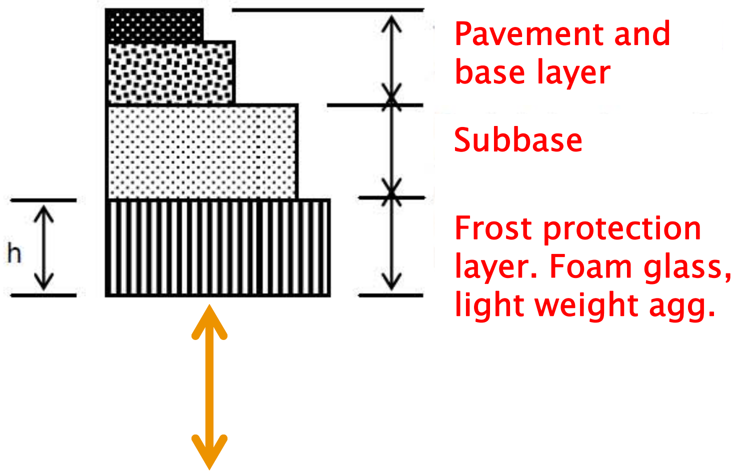


Heat flow from:

- accumulated heat from last summer
- heat released when water is freezing

Frost protection layer – Insulation





Assume that the frost pene-tration stops at the bottom of the insulation layer.
No requirements for the agg-regate under the insulation layer.

...but then we are talking about a frost accumulating layer...

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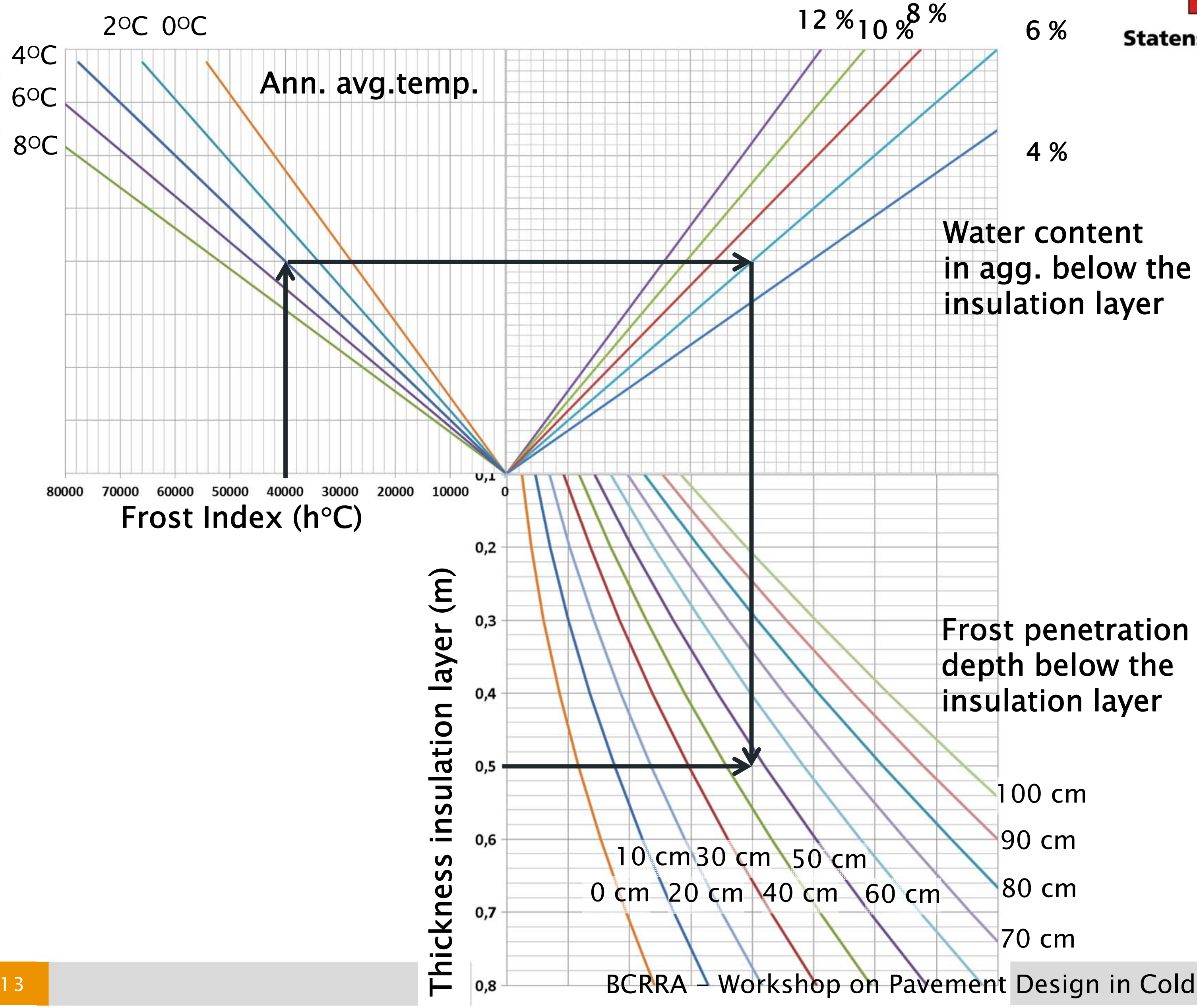
Thermal insulation

- low thermal capacity -> low frost accumulation capacity
- the frost has to penetrate the insulation layer (if not it is cheaper and easier to use aggregates)

to avoid frost heave problems requirements are needed for the aggregates below the insulation layer!



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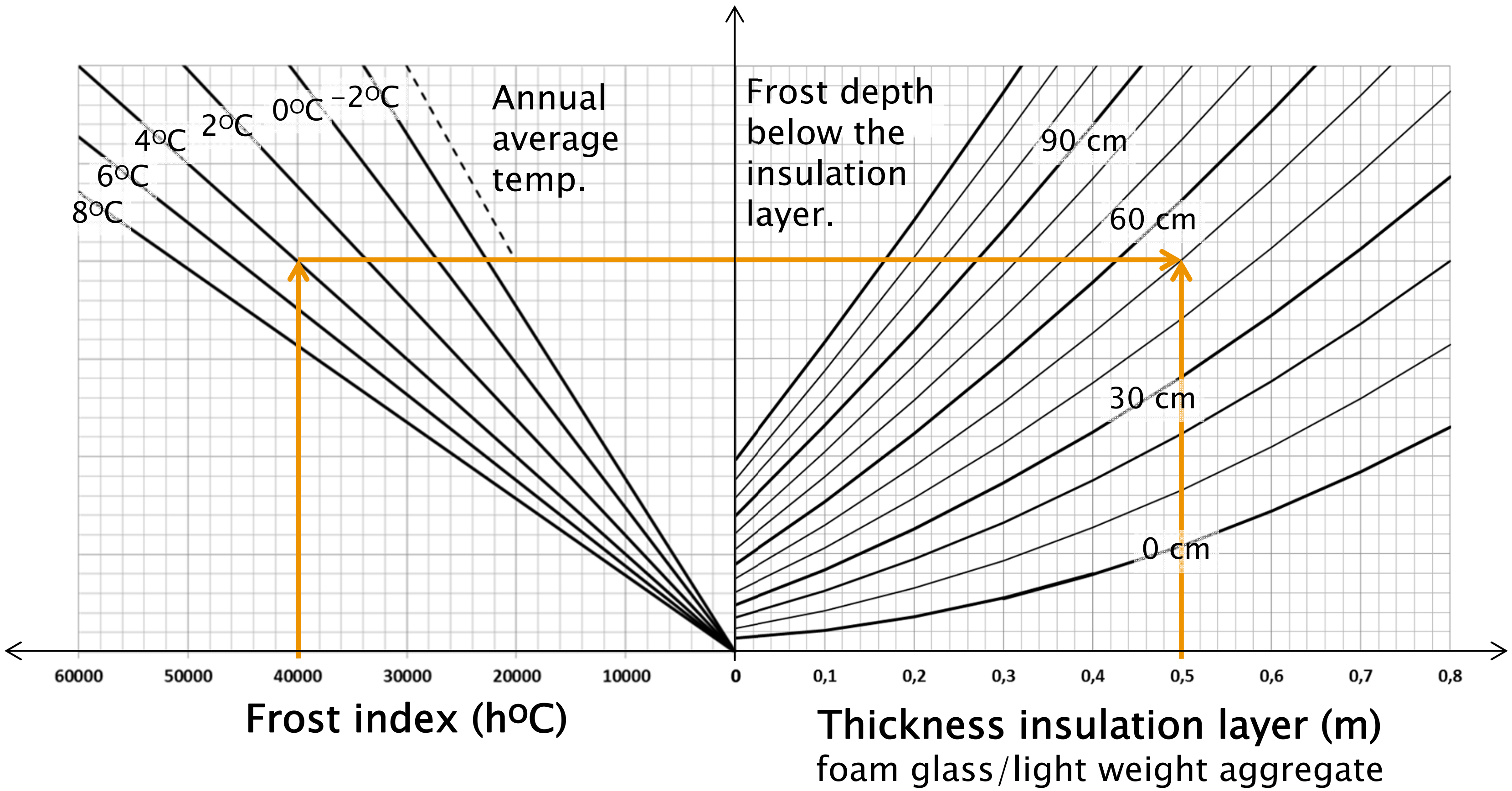
To difficult!!!

- Difficult to know the input parameters as thermal conductivity, thermal capacity, density and water content.

- water content is fluctuating with time; the other are constant or changes with the water content.

- To make the design easy to use and understand we must assume a value for the water content (and also the other input parameters)

Design chart – foam glass/light weight agg.



NB! ASSUMED w=6 % WATER CONTENT IN THE LAYER BELOW THE INSULATION LAYER!


Thank you!
Spring thaw in Finland.