Thaw weakening of subgrades in Finland

Ramollissement des sous-sols lors du degel a Finlande

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ABSTRACT: In Finland, in late 90'ies, studies to limit and solve the thaw-deformation problem of pavements were carried out. One problem was to determine the start of thaw-weakening and the end of thaw in time. Another problem was to describe the development of effective stresses in a thawing and thawed subgrade with reference to development of resilient stiffness of the subgrade. Further, testing on development of irreversible deformations (surface rutting) was carried out and analysed. Further, measurement data on development of subgrade modulus during thaw on a road line over more than 10 years was collected and analysed.

The resilient stiffness of the pavement can be used for estimating the cracking of the asphalt surface. Knowing the ratio between irreversible and reversible deformations, the rate of rutting can be estimated, too. These can be applied in life-cycle analysis of a pavement structure on thawing, frost-susceptible subgrades.

RESUME: En Finlande, au bout des années 1990, on a passé des épreuves pour limiter et résoudre le problème de la déformation lors du dégel des chaussées. Un des problèmes a était déterminer le début du ramollissement lors du dégel aussi que le fin a la longue. Autre problème était décrire le développement des pressions efficaces dans une sous-sol avec la référence au développement de la rigidité résilié de la sous-sol dégelée. En plus on avait expérimenté et analysé le développement des déformations irréversibles. En plus, on avait collectionné et analysé information sur le développement des modules de réaction d'une sous-sol de chaussée quand il y a dégelée dans la chaussée pendant une période de plus de 10 ans. On peut utiliser la rigidité résilié de la chaussée pour estimer la rupture de la surface d'asphalte. En savant la relation ce qu'an a entre les déformations réversibles et irréversibles, on peut aussi estimer la vélocité d'orniérage. Ceux ci on peut utiliser dans une analyse de vie entière de la chaussée par relation à le gel.

1 INTRODUCTION

Freezing and thawing of soils is a common phenomenon in areas of cold climate. Freezing causes in frost-susceptible soils expansion and heaving of structures above, due to ice segregation in freezing soil. As the frozen, ice-rich soil thaws, water is released causing high pore pressures, and thawing soil consolidates and causes settlements. Due to decreasing effective stresses, the strength of thawing soil is reduced, and response to deformations, modulus is lowered below stable summer values. This forms a limit state for pavement design in cold areas.

2 FREEZING AND FROST HEAVING OF PAVEMENTS

2.1 *Climate and frost penetration*

The pavement starts to freeze, as the surface temperature is lowered under 0°C. Frost penetration continues until the surface temperature rises again above freezing point. The rate of freezing is proportional to the cooling heat flow through the frozen layer (the thermal conductivity of the frozen layer, Temperature gradient at the freezing front), latent heat of the freezing soil, frost heaving susceptibility of the freezing soil, and the ground heat flow to the freezing front.

The maximum frost penetration at the end of the freezing season is related to the freezing index at the location.

2.2 *Frost penetration and frost heaving*

Frost heaving of the pavement surface results from ice lensing (ice segregation) in the freezing soil and from in-situ expansion of pore water in the freezing, saturated soil. Heaving is strongly reduced, if the degree of saturation is lower than, say, 80%.

The expansion of freezing pore water is about 9% of the water volume. The expansion due to ice segregation is related to the flow of water to the freezing front that is proportional, i.e. frost heave coefficient (segregation potential) of the freezing soil.

In long-term observations at some sites in Finland (Saarelainen 1992), it was found that the frost heaving and frost penetration were proportional to the square root of the air-freezing index. So it could be concluded that the ratio between frost heave and frost penetration (the frost heave ratio) was somewhat constant.

2.3 *Increase of moisture content during freezing*

The water content of a frost-susceptible soil increases during freezing due to ice lensing. The increase of moisture content is related to the increase of porosity, which consists of in-situ expansion of pore water, and expansion due to ice lensing. It is related to the frost heave ratio (Saarelainen 1992).

3 THAWING OF PAVEMENTS AND ICE-RICH SUBGRADES

3.1 *Climate and thaw penetration*

Thaw penetration starts as the surface temperature rises above 0°C. Thawing ends as thaw penetration reaches the lower frost front. Thawing has been found to develop also from below due to ground heat. Thawing from below is normally less than 1/3 of the maximum frost penetration. The rate of thaw penetration is related to the temperature gradient at the thaw front, the thermal conductivity of the thawed material, and latent heat of thawing.

Thaw penetration can be related to the cumulative thaw index

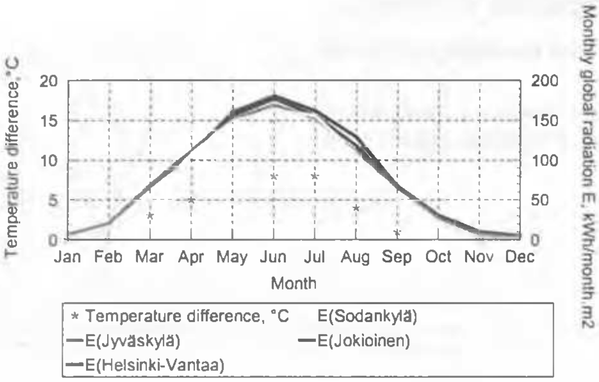

Fig. 1. Monthly difference between air and pavement temperature and monthly global radiation in years 1997-98 in Finland (Saarelainen 2000).

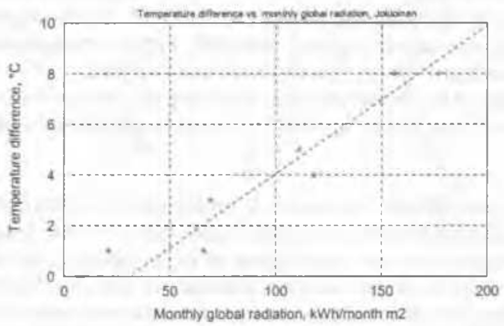

Fig. 2. Temperature difference between pavement surface and air vs. monthly global radiation at Jokioinen climate station (Saarelainen 2000).

at the pavement surface. The surface thaw index is the sum of air-thawing index and the heating effect of global radiation (sum of solar radiation and disperse radiation) during thaw (Saarelainen 1998). The heating effect of global radiation, estimated from road climate station network in Finland in years 1997-98 is illustrated in Fig. 1.

The variation of monthly temperature difference and global radiation are syncronously varied at different locations in Finland, and a linear relationship was found (Fig.2).

Thus, the thaw index on the pavement surface can be estimated adding to the local air thaw index the cumulative radiation influence (monthly temperature difference multiplied with hours of the moth).

3.2 *Estimation of thaw penetration*

Thaw penetration is related to the square root of thaw index at the pavement surface.

$$z_t = k_t \sqrt{F_t} \tag{1}$$

where

z_t is thaw penetration
k_t koefficient of proportionality
F_t thaw index on pavement surface

An example, describing the development of pavement thaw index, and estimated vs. observed thaw penetration on a gravel road site in Central Finland, is illustrated in Fig. 3.

3.3 *Thaw settlement*

Thaw settlement is reverse phenomenon to frost heave. It is developed along with the thaw penetration in the heaved, ice-rich subgrade. Thaw settlement is delayed due to the flow resis-

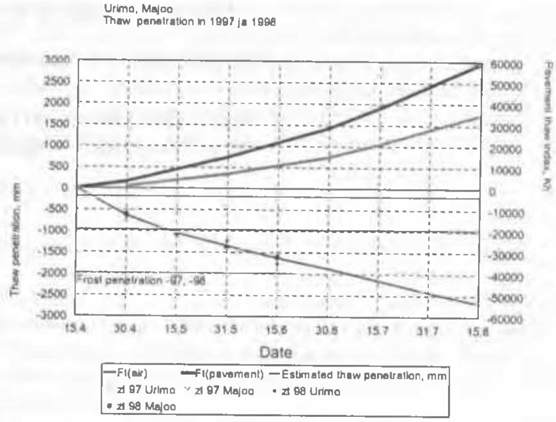

Fig. 3. Urimo. Central Finland. Thaw index in air and on pavement, and estimated and observed thaw penetration in the springs of 1997 and 1998 (Saarelainen 2000).

tance of the thawed layer. Resulting thaw consolidation causes a delay to the settlement rate. Settlements are continuing as post-thaw consolidation after thaw end.

4 DEVELOPMENT OF PORE PRESSURE AND EFFECTIVE STRESS DURING AND AFTER THAW

4.1 *Thaw compression and pore pressure development under overburden stress*

Pore pressure developed during thaw is proportional to thaw factor (Morgenstern & Nixon, 1971):

$$R = \frac{\alpha}{2\sqrt{c_v}} \tag{2}$$

where

α is coefficient ($z_t = \alpha\, t^{0,5}$)
c_v thaw consolidation coefficient

The pore pressure ratio under overburden stress is

$$\frac{u}{\gamma' z} = \frac{1}{\frac{1}{2R^2}+1} \tag{3}$$

where

u is pore pressure
γ' effective unit weight of thawed layer
z thickness of thawed layer

The pore pressure ratio according (3) is illustrated in Fig. 4.

4.2 *Release of pore water pressure after thaw*

The pore pressure at the end of active thaw is the initial condition for post-consolidation after thaw. The excess pore pressure is decreasing, and it is controlled by the thickness of thawed layer and thaw consolidation coefficient.

4.3 *Development of effective stress*

The stress state in the thawing and thawed soil depends on the pore pressure development in time and place. It can be estimated by determining total stresses and pore pressures in sublayers of thawed subgrade.

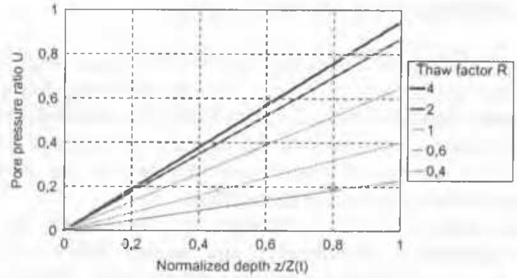

Fig. 4. Pore pressure ratio vs. normalized depth of thaw, assuming different values of thaw factor R (Knutsson 1983).

5 LOWERING OF PAVEMENT RESPONSE DURING AND AFTER THAW

5.1 *Lowering of the resilient modulus in the thawing subgrade*

The resilient modulus of the subgrade influences on the deformations resulting from stresses from the pavement loading. The subgrade modulus is (effective) stress dependent. Thus, lowering effective stress in the subgrade results in lowering resilient modulus. Estimates of in situ-values have been determined using loading tests like falling weight deflectometer tests (FWD). Laboratory testing of these relations is scarce

5.2 *Influence of the increasing thickness of thawed subgrade on the surface response*

According to rough evaluation, the surface modulus of thawed subgrade depends on the resilient (elastic) modulus of the subgrade soil and the thickness of the thawed layer. The former is during active thaw somewhat constant, as to the thaw penetration increases with time. The surface modulus is thus lowered with time, until the minimum response is reached at the end of thaw.

5.3 *Regain of surface response*

After thaw, the surface modulus is increased due to increasing effective stress, until a "stable" summer value is regained, as the moisture state is stabilised.

6 ESTIMATION OF THE SEASONAL VARIATION OF PAVEMENT RESPONSE

6.1 *Division in seasons*

Pavement response varies within different times of a year. At least three seasons can be pointed, when the pavement response on a frost susceptible subgrade is totally different with each other: winter (frozen), spring (thawing/thawed) and summer/autumn (response recovered after thaw).

6.2 *Development of surface response during thaw*

The surface response is lowered when the thickness of thawed layer is increasing. The minimum value of pavement response occurs normally, when the subgrade is totally thawed.

6.3 *Development of surface response after thaw*

After thaw, the surface modulus increases gradually as the released water dissipates from the thawed ice-rich subgrade. It seems that the time for total recovery of surface modulus after thaw takes somewhat longer than the consolidation of subgrade.

7 ESTIMATION OF PERMANENT DEFORMATIONS DURING THAW

7.1 *Development of rutting under traffic loading*

The permanent deformation due to impact stresses is proportional to the resilient deformation in the subgrade. This ratio between permanent and resilient deformations is a fundamental soil characteristics in the pavement design. It can be also explained in terms of strength and stresses. It can be determined using full-scale testing of pavement structures in the first place, and also, in principle, with triaxial testing of subgrade soil specimens in the laboratory.

7.2 *Application of rutting models in the design*

To estimate cumulative rutting of the pavement surface, the input parameters are thicknesses and resilient moduli of the pavement layers and subgrade. The stresses and deformations in different layers can be estimated using quasi-elastic element analysis. Using the ratio between permanent and resilient deformation in different layer materials, a unit increase of surface settlement can be estimated. According to the amount of overpasses of loaded wheels, the cumulated surface deflection, the rut depth can be estimated. In the design, the pavement structure can be formed so that the rutting according to the design traffic is allowable during the design period of the pavement.

8 OBSERVED PAVEMENT RESPONSE AND ESTIMATED LAYER MODULI AT TATTARA, SW-FINLAND

8.1 *Observed pavement response and frost heave*

Pavement response measurements with Falling Weight Deflectometer (KUAB) have been done more than one thousand within last thirteen years (1988-2000) at Tattara regional road in Southwestern Finland near the city of Pori (Gustavsson 2000). The superstructure of the road is 400-600mm, paved with soft "oil-gravel". The subgrade in Tattara is very frost susceptible silty clay. The FWD-measurements have been done using 50 kN load. In Fig. 5 measured pavement response from spring 1999 (10th and 31st of May) as well as minimum spring response and average summer response from 1988-1998 is presented. Minimum spring response varies from 70-90 MPa in Tattara test road. Normal summer response is about 140 MPa, excluding the culvert area (1000-1200), where frost heave is smaller and pavement response higher than other points. The relation with smallest spring response and average summer pavement response is about 0,50.

Some connection with freezing index (F) of winter and pavement response in spring can be seen from the test results: usually after a severe winter the pavement response is lower and it appears later, as the thawed, soft subgrade layer is thicker and the total thaw also appears later. Figure 6 shows the observed maximum frost heaves in 1998 (F=15800Kh), 1999 (F=9800Kh) and 2000 (F=6900Kh). Frost heave and pavement response can be noticed to be related to each other: at points, where the amount of frost heave is high the pavement response in spring is low. Also the frost heave can be noticed to be proportional to the air-freezing index.

8.2 *Estimated subgrade response and layer modulus*

Subgrade response and layer modulus was estimated using numerical calculation methods. FEM-based software (Plaxis 7.1.) was used to simulate the observed FWD-basins, assuming

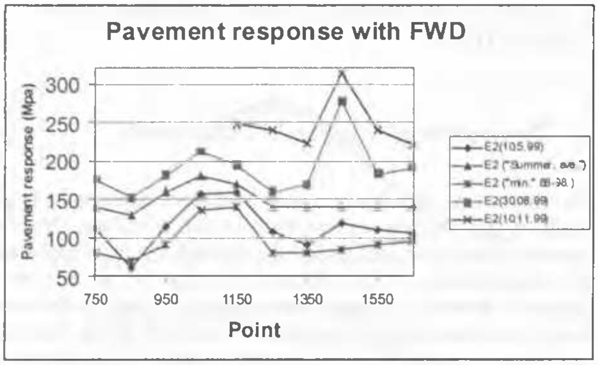

Figure 5. Pavement response test results using FWD. Minimum response in spring as well as average summer response is shown. Results at 30.08.99 and 10.11.99 are after the renovation of the road (Gustavsson 2000).

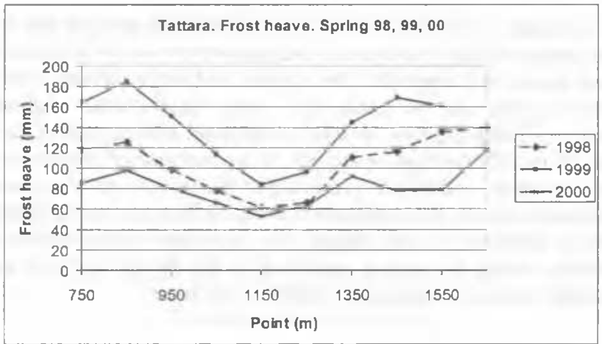

Figure 6. Observed maximum frost heaves in 1998,1999 and 2000 at Tattara test road.

Table 1. Calculated layer modi, Point 1450

Layer	Thick-ness (mm)	E-modulus (MPa) Spring	E-modulus (MPa) Summer
Gravel	200	350	350
Sand	400	95	150
Dry-crust clay	600	15	45
Soft clay	2000	20	20

the behaviour of the road linear-elastic and using 50 kN axi-symmetric load, 150 mm in radius. The estimation for point 1450 was made for a 4-layer structure: 200mm of gravel/crushed rock (including the broken pavement), 400mm of sand, 600mm dry-crust clay and below that a 2000mm layer of natural soft clay. The total layer thickness (1200mm) over the natural soft clay is the same as the frost depth of the winter 1997-1998 sub-tracted with observed frost heave. Poisson's factors used were 0,3 for gravel and sand layers and 0,35 for both clay layers. Simulations were done by changing the E-modulus for different layers, to achieve similar basins as observed in spring and summer. The E-moduli achieved with calculations are shown in Table 1.

As can be seen from the results, the E-modulus for the upper non-frost-susceptible gravel layer was constant as well as for the natural clay layer below the maximum frost depth. Most extensive change in E-modulus value seemed to exist in the highly frost-susceptible clay layer, from 15 MPa in spring to 45 MPa in summer. Also the reduction in E-modulus of the sandy filter layer in spring was considerable.

The "oil gravel" pavement of the road was in very heavily damaged because of low pavement response and high frost heave values. In autumn 1999, it was renovated with different stabilisation techniques. The pavement response after the renovation work was somewhat improved, especially at point 1450, where composite stabilization (cement+bitumen) was used (Fig. 5).

9 DISCUSSION AND CONCLUSIONS

The main purpose of designing pavements for thaw weakening is to control the pavement damage during the design life period. One of the damage components is rutting, that is caused by permanent shear deformations in the pavement layers and the subgrade. The damage is heavily concentrated to the period of weakest stiffness, occurring during thaw.

For design, the basic elements are the length of thaw-weakening period, rehabilitation, the resilient stiffness of pavement layers and thawed subgrade during thaw. These can be used to estimate the resilient deformations of the materials. To estimate the permanent deformations, ratio between permanent and resilient deformation is needed. Further, the amount of load repetitions determine the cumulated rut depth.

The damage starts with increasing rut depth, and leads to cracking of the asphalt, horizontal movements in the pavement (widening). Large shear deformations in the unbound layers may cause reduction in material stiffness of unbound layers.

The modulus of a frost susceptible subgrade layer may gain values of even three times bigger in summer than in spring. The lowest values of subgrade and pavement response are usually observed at time of total thaw.

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