Monitoring and Classifying Spring Thaw Weakening on Low Volume Roads in Northern Periphery

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ABSTRACT: The ROADEX II Project is a co-operation aimed at developing ways for interactive and innovative management of low traffic volume roads in the Northern Periphery Area in Europe. The goal for subproject 2.3 “Spring Thaw Weakening” was to collect information regarding one of the most difficult challenges in low volume road condition management in cold climate areas, managing road condition during the spring thaw weakening period in a way that minimizes the impact of transportation problems on local livelihoods without destroying road structures or reducing the service level of the road for the rest of the year. The survey has followed the Roadex II Project phase II theme of “understanding and analysis” by using new technologies to monitor spring thaw problems and then analysing the problem sections so as to better understand the processes behind the problems. Data collection for monitoring the seasonal changes and spring thaw weakening was done at five test sites in Scotland, Sweden and Finland. This paper presents a summary of the field tests and, based on these results, proposes a new classification for spring thaw weakening periods and typical spring thaw damages that can happen during these periods. This helps engineers to better focus on the problems and find more economical and sustainable solutions in managing spring thaw problems in their low volume road networks.

KEY WORDS: Roadex, low volume roads, spring thaw weakening, dielectric value, DCP test.

1 GENERAL

In Scandinavia spring thaw weakening damage is the biggest problem on “unbuilt” gravel roads. In Finland, for instance, almost one half of the country’s 28.000 km gravel road network suffers some form of thaw damage. According to the annual Finnish spring thaw structural damage inventory results from 1998-2002 an average of 1020 km of road with severe visual spring thaw damage was observed. This represents 3.5 % of the gravel road network. There are major area differences with respect to the appearance of spring thaw problems in gravel roads. The changes can be related to changes in soil conditions but also to the development history of the low volume road network as well as how heavy transports use these roads.

Spring thaw weakening and seasonal changes are also major problems on paved roads and especially on weak roads with surface dressing pavement, a good example being the weak single track roads in Scotland. The difference between gravel roads and paved roads is that spring thaw damage in gravel roads is much easier and cheaper to repair; the problems can often be fixed with a grader.

In this paper, the term, "spring thaw weakening", refers to both the weakening and the resulting damage due to traffic loads. Launonen et al. (1995) listed the following factors as being necessary for the appearance of spring thaw weakening:

- road and/or subgrade soil freezes
- the material is frost susceptible
- freezing front has enough water available
- during the thawing period the water, released by the melting segregation ice, stays in road structures or subgrade soils, thus weakening the structure
- road is subject to loads during the thawing period

If any one of these factors is absent there is no risk for spring thaw damage. The processes behind spring thaw weakening are described in more detail in the report: "Managing Spring Thaw Weakening on Low Volume Roads", written by Saarenketo & Aho (2005).

2 ROADEX FIELD TEST RESULTS

2.1 Roadex test sites

The goal for the field tests in the Roadex II project was, through the use of modern survey and monitoring techniques, to collect and analyze data from sites which are representative of typical spring thaw or freeze-thaw cycle problems. Figure 1 presents the location of these sites in Scotland, Sweden and Finland. Two of the sites were paved roads (Garvault, Koskenkylä) and three were gravel roads (Kuorevesi, Ängesby, Kemijärvi). A detailed description of the test sites is given in the report "Managing Spring Thaw Weakening on Low Volume Roads", written by Saarenketo & Aho (2005).

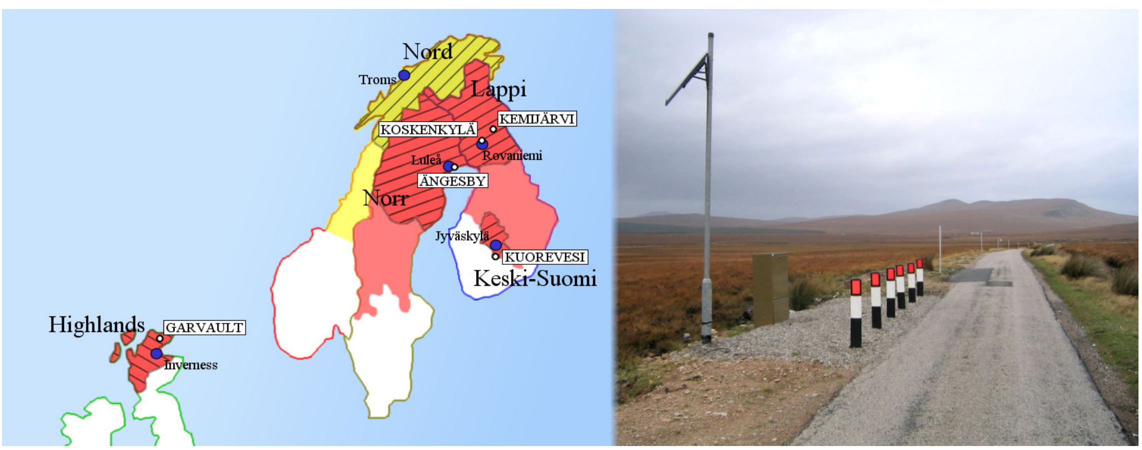

Figure 1: Location of Roadex II test sites and a photo of Garvault test site with Percostation at B871 in Sutherland, Highlands.

The test methods were: 1) Percostation technique to monitor frost and changes in moisture content at different depths in the road structures and subgrade soils, 2) frost heave and thaw settlement monitoring, 3) bearing capacity surveys using FWD and DCP techniques and 4) visual evaluation. Test section structures were studied in detail using the GPR technique. In addition, full scale loading tests using maintenance trucks were done at some stations.

The Roadex II project has collected an extensive amount of data from the project test sites and reports, and detailed analyses will be published in scientific symposiums and publications. Data is also available on the Roadex web pages www.roadex.org.

2.2 Frost depth and moisture monitoring results

The Percostation measuring technique, used at the Roadex II test sites, is based on dielectric value, electrical conductivity and temperature measuring techniques developed by the Estonian company Adek Ltd. The Percometer technique was first used to estimate the frost susceptibility of roads' subgrade soils and later to measure the water susceptibility of base aggregates (Saarenketo 1995).

The Percostation offers the option of measuring the dielectric value, electrical conductivity and temperature through a maximum of eight channels. The measurements are normally repeated at 2 hour intervals and the results are saved in the station's memory where they can be read via wireless modem. Normally the Percostation uses solar panels to generate its' power supply (see Figure 1).

Figure 2 presents an example of frost depth and moisture monitoring results from the Kuorevesi test site during the spring thaw period in 2003. The thawing phases are described in detail in chapter 3.

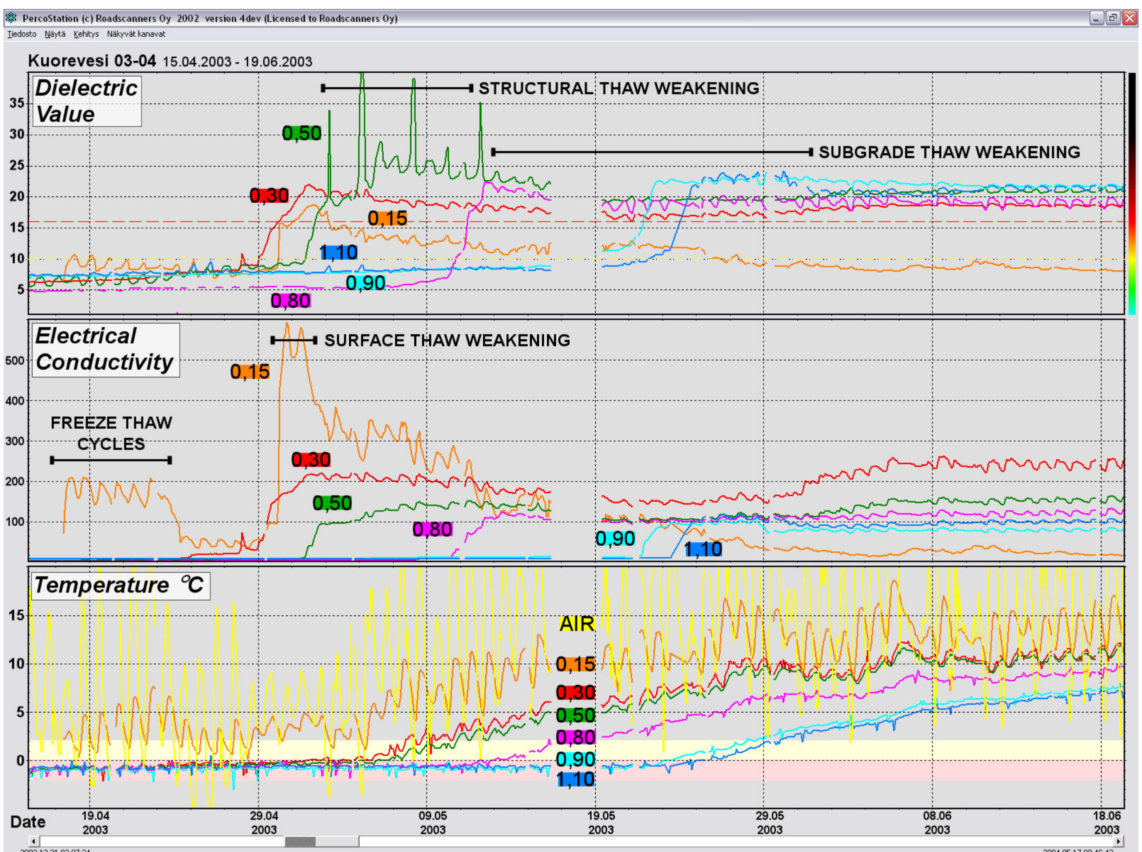

Figure 2: Frost thawing and moisture monitoring results from the Kuorevesi test site during the spring thaw period in 2003. Two topmost probes (0.15 m and 0.30 m) were installed in road structures and probes 0.50 m to 1.10 m were installed in silty subgrade soil. Different spring thaw weakening phases are also presented in the figure.

A good example of the combined effect of freeze-thaw cycles and rainfall on the critical moisture content and risk of permanent deformation in the unbound base course is presented in Figure 3 from the Garvault Percotation in Scotland. The figure presents dielectric value measured from the base course just below the pavement (0.12 m) together with base course temperature, air temperature and daily rainfall data measured at the nearest weather station. The figure shows that dielectric values exceeded the critical level of 16 after the third freeze-thaw cycle and when heavy rains followed the cycle. Following this peak, the base course material dried quickly but dielectric value (moisture content) always increased about a day after the air temperature had gone below 0^oC. If these freeze-thaw cycles were followed by rainy days, the values were even higher. The critical period on road B871 in Scotland was from mid December to mid February and after that there were still some frost nights but the days were so warm that cryo suction did not develop in the base course.

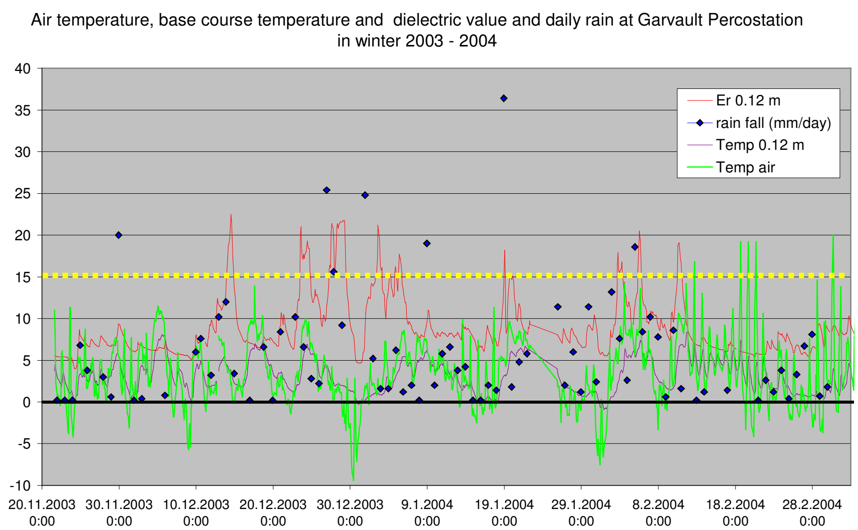

Figure 3. Base course moisture and temperature, air temperature and rainfall monitoring results from the Garvault test site on B871 in Scotland in winter 2003 – 2004. The critical dielectric value for the base course was 16.

2.3 Frost heave and thaw settlement

Frost heave and thaw settlement was monitored on the gravel road test sections by means of levelling. The measurements covered a selected area around the Percostation sites so that road surface readings were taken from both the road centre and road shoulders.

The results from frost heave survey were quite surprising and further served to illustrate the complex nature of the frost heave process. In Ängesby, the highest frost heave was measured in the road shoulders, while in Kuorevesi the frost heave was greatest in the road centre and in Kemijärvi the road structures were acting like a piston, pushing up and down through the road shoulders during the frost heave and thaw period. There were also quite major changes in the maximum frost heave values in Kemijärvi (350 mm), Kuorevesi (250 mm) and Ängesby (160 mm) even though the subgrade soils was basically the same. These differences can be explained in that in Ängesby the ground water level was higher than in Kemijärvi. In Koskenkylä, a paved road, almost all of the ice lenses, causing 40 – 60 mm frost heave, developed in the frost susceptible sub base and not in the subgrade. It is also worth noting that in every gravel road test section the frost heave in the road structures was about 50 – 60 mm and the greatest part of segregation ice formed in the subgrade soil just below of the road structures.

Frost thaw settlement surveys clearly showed the effects of solar radiation during the spring. Thaw settlement always started on the southern side of the road or in a place exposed to sunshine. This places stress on paved roads especially because differential thaw settlement on the cross section causes extra strain on the pavement.

2.4 Bearing capacity

Bearing capacity surveys were made with three different test methods: Falling Weight Deflectometer (FWD), Dynamic Cone Penetrometer (DCP) and full scale loading tests.

In order to monitor the road structures' response to different axle loads each survey point was measured using 1250 N, 2750 N, 4000 N and 5000 N loads. In addition, measurements using 1250 N and 5000 N loads were repeated at 0.3 – 0.5 m intervals. This was done in order to monitor if deflections were different if a different load was used and/or if loading was repeated at the same point. Any noticeable effect on the shape of deflection bowls could not be detected and the deflection values correlated quite well with the load levels.

Figure 4 presents deflection bowls under a 5000 N load measured in spring 2003 at the Ängesby and Kemijärvi test sites in the right wheel paths. When the Ängesby deflection bowls are compared with the Kemijärvi deflection bowls, major differences between the deflections of the outermost geophones can be observed. In Kemijärvi they remained very small, even in summer, while at Ängesby they increased when the frost in the subgrade thawed. In the summer, the outermost deflection values from Ängesby were as high as 500 µm indicating that the subgrade was very weak. Even if the subgrade at the Ängesby test site is much weaker than at the Kemijärvi test site, the maximum deflections from both test sites were basically the same (about 2000 µm in spring). This shows that the Ängesby road structures spread the load over a much wider area than at Kemijärvi. This could be the result of a base course treatment done in 2002 using MESA, an industrial byproduct from pulp mills.

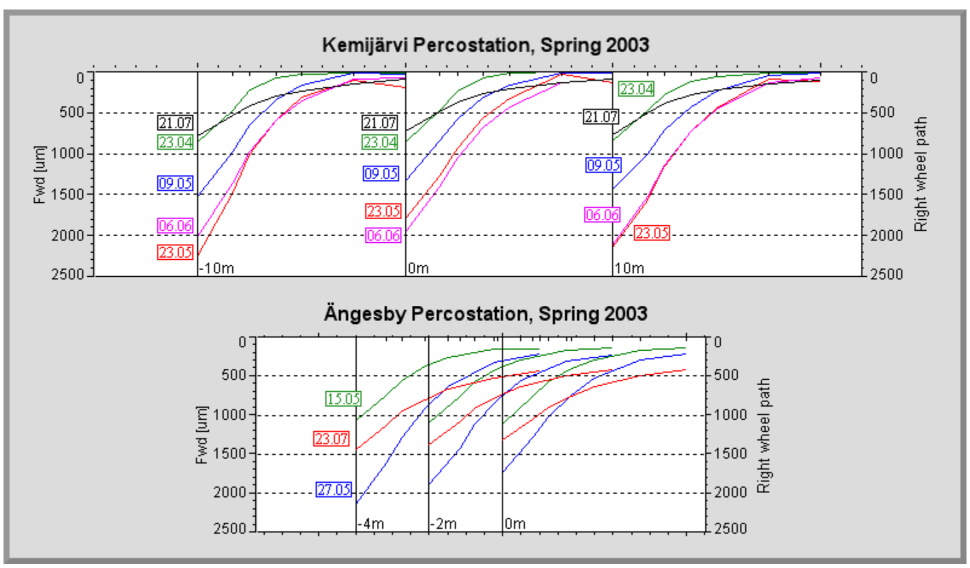

Figure 4: FWD deflection bowls measured at a 5000 N load level on the right wheel path at Kemijärvi and Ängesby test site sections in spring and summer 2003.

The DCP results can be used to measure the depth of structural interfaces in road structures and subgrade soils and in addition it is also a good tool for measuring thawing frost line. The DCP results have been related to strength and deformation properties of materials in a number of studies. In this survey the DCP results were used to calculate modulus values using a formula used by the Norwegian Road Administration (Roadex CD-ROM).

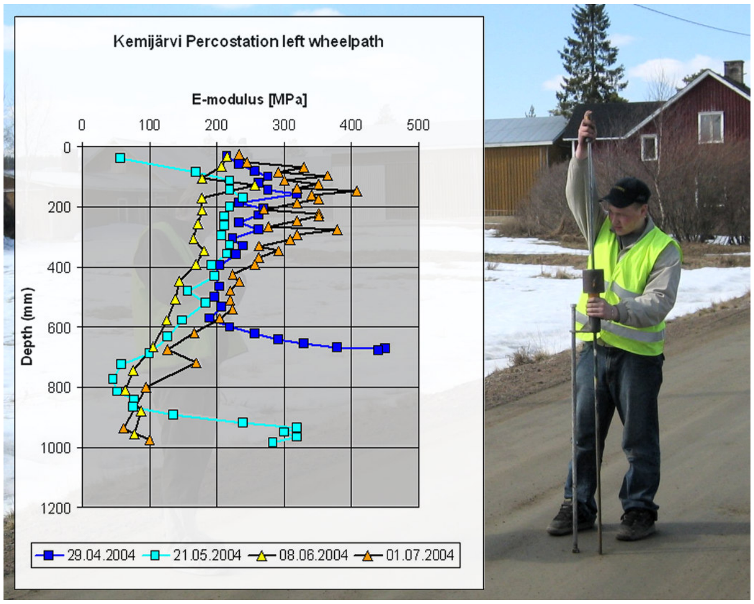

Figure 5: DCP profiles from the Kemijärvi test site's left wheel path in spring and summer 2004.

The DCP test results allowed the monitoring of the thawing process during the spring thaw period as Figure 5 shows. The survey data collected from the left wheel path of the Kemijärvi test section shows that on April 29th 2004 the frost depth was at a level of 600 mm and on May 21st 2004 the frost depth was at a level of 900 mm (higher E-module values). It should be kept in mind that DCP tests were calculated from a road surface which was settling and the greatest part of the total frost settlement of about 400 mm took place during May 2004. Due to water released from the ice lenses, the layers just above the frost level were always the weakest as can be seen in Figure 5.

The DCP results, as well as FWD deflection analysis results from the gravel road sections confirmed the fact that the bearing capacity of the road was worst shortly after the frost had completely thawed (see deflection bowls measured 23.5., 6.6. and 27.5. in Figure 4 and DCP profile in June 8th in Figure 5). The DCP method also clearly revealed the weakness of the road shoulders during the spring thaw period. The DCP tests done at the Kemijärvi test site also showed how much faster the frost thawed on the southern shoulder (left side in Figure 6) of a gravel road in an open area.

The greatest benefit of using the DCP technique to monitor spring thaw weakening is that it is possible to evaluate if the top structures are stiff enough to carry a truck load and, in that case, restrictions can be removed even though the subgrade is still very weak. Figure 6 provides a comparison of the modulus values, back calculated from the FWD data, and a contour map of the DCP results measured at the Kemijärvi test site on May 25th. The figure illustrates well that even though the absolute values may not be on the same level the trend is the same and that the road is much weaker on the left side than on the right side. This can be explained in that the frost thaws faster on the left side, which is the southern side of the road, and also that there are far more fully loaded trucks using the left side.

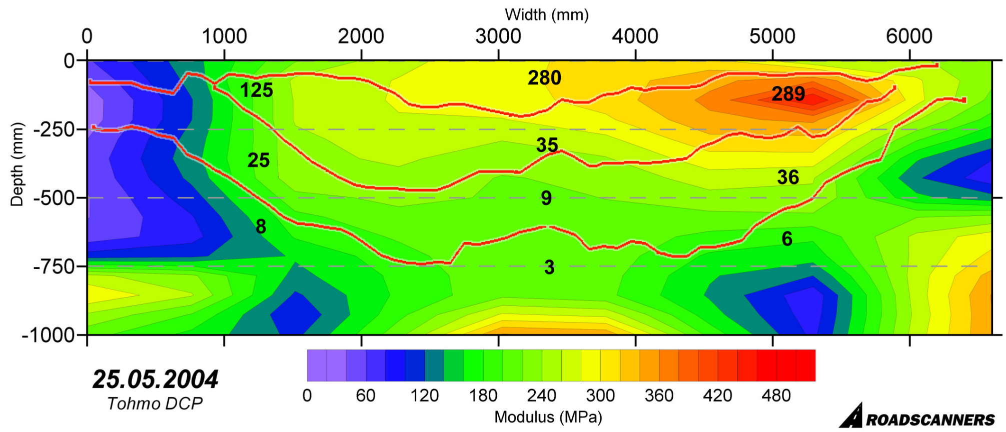

Figure 6: Comparison of modulus values calculated from the DCP results obtained 25.05.2004 with the modulus values calculated from the FWD data (50 kN load level) measured on 25.05.2004. Note the lower stiffness on the left side (Southern side) of the road which heavy trucks are using.

Full scale loading tests were conducted on the Kemijärvi and Kuorevesi test sections, in spring 2003, using maintenance trucks owned by the Finnish Road Enterprise. The trucks were loaded with water tanks in order to obtain the maximum axle weights allowed in Finland. In Kuorevesi, the changes in dielectric value and electrical conductivity were monitored during each truck pass using a high speed data logger owned by the Tampere Technical University. In Kemijärvi the changes were only monitored visually from the Percostation central unit.

Full scale loading tests on the gravel road test sites showed that, during the early phases of the subgrade thawing period, water being squeezed to the road surface and severe deformation and cracking could be found in the road surface even after just ten standard truck passes. Dielectric value and electrical conductivity measurements indicated that a single standard axle has a measurable effect on pore water to a depth of 50 cm.

One interesting observation from the full scale tests done earlier at the Koskenkylä test site was that slower truck speeds, which amount to longer periods of loading, caused higher pore water pressure in materials susceptible to permanent deformation while with good quality unbound aggregates the length of the loading period did not affect the response.

According to the authors, the tests related to electrical conductivity indicate that colloids released from clay mineral surfaces into the pore water can have a great effect on the forces between the mineral particles during the thawing period. Authors suggest that this is one of the main mechanisms of permanent deformation and more research should be devoted to this subject. This characteristic could play a key role in the future development of new sensor techniques for real time road condition monitoring.

3 A NEW PROPOSAL FOR SPRING THAW WEAKENING PHASES

The Roadex II spring thaw monitoring results showed four altogether different time phases for spring thaw weakening which have such unique features that they should be classified separately. They occur in a chronological order but the need for load restrictions, for instance, in each phase is strongly dependent on the increase, or lack thereof, in moisture content and stiffness of the road during the previous period. The four phases (see also figure 2) presented here are the 1) freeze-thaw cycles phase, 2) surface thaw weakening phase, 3) structural thaw weakening phase and 4) subgrade thaw weakening phase. A common factor in all of these phases is cryo suction. A potential fifth category with similar bearing capacity problems could be the autumn heavy rain season, although during this season, freezing is not a factor in the weakening process.

3.1 Freeze-thaw cycles phase

The first phase affecting spring thaw weakening is the phase of freeze-thaw cycles in late autumn, when the road surface freezes during the night or for a few days and thaws when the air temperature becomes warmer. Several freeze-thaw cycles in a short period of time during autumn can cause major problems in Scandinavia. The force of cryo suction during a repeated freeze-thaw process causes water to flow within the structure close to the road surface. Continuous freeze-thaw cycles act as a pumping mechanism ending in a situation where the wearing course becomes plastic or, in the case of paved roads, the base course under the pavement becomes saturated with water and, as such, susceptible to permanent deformation. One factor affecting the severity of the following spring thaw weakening is the number of freeze-thaw cycles that occurred during the autumn and how shortly after these cycles the road begins its final freezing process. In the spring, freeze thaw cycles can also take place but at that time the extra water in the structure comes from thawing snow and ice.

In Scotland, the main problem is not spring thaw weakening but repeated freeze-thaw cycles during the winter. A good example of this freeze-thaw mechanism can be found in the Percostation test data from the Roadex test site at Garvault where after each freeze-thaw cycle the moisture exceeded the critical level at which permanent deformations to occur under heavy truck loads (see Figure 3).

3.2 Surface thaw weakening phase

Following winter, the first phase, after random freeze-thaw cycles, is the “surface thaw weakening phase”. Its severity depends on the road’s condition before winter, but above all on the weather and traffic conditions when the road surface starts to thaw.

This phase could be identified through high electrical conductivity values measured at the Percostation sites. The authors suggest that the high electrical conductivity values are a consequence of the colloids releasing into the pore water from the clay mineral surfaces, which easily causes material to become plastic. This critical phase normally takes from 6 – 14 days and after that the road surface will become dry if there are no heavy rains.

The phase can be very critical for paved roads and especially for weak roads with surface dressing pavement which can easily disintegrate. Load restrictions should be considered if the base below the pavement has segregation ice or if it is wet due heavy rains. If the weather is dry, load restrictions are not normally needed on gravel roads during this phase. Continuous rainfall prevents the gravel road surface from drying and so it remains wet, slippery and plastic and in such a case the forecast for the next phase of the spring thaw weakening will be bad.

However freeze-thaw cycles do not always have a damaging effect on road structures. Especially on gravel roads, during the spring thaw weakening season, cryo suction during frost nights causes water to flow towards the road surface and because frost nights are generally followed by sunny days, solar radiation causes evaporation and thus the surface part of the road structure dries fast.

3.3 Structural thaw weakening phase

The second phase is “structural thaw weakening”, which starts when the upper frost line has thawed deeper than 15-20 cm but has not yet reached the subgrade soil. The moisture content in a road depends on rainfall and how well the drainage functions. During this phase a great part of the thaw settlement occurs if the road structure has frost susceptible material. If there is a significant amount of heavy traffic, the excess water, under repeated wheel loads, surges towards the road surface producing conditions with a high likelihood of causing plastic deformation of the road structure.

The structural thaw weakening phase can be the most critical phase of the spring for some roads. The data collected from the Koskenkylä site revealed a 20 cm layer of poor quality unbound material at a depth of 45 – 65 cm to be the only source of bearing capacity problems during the spring thaw period. The survey results from the Roadex gravel road test sites also indicated that a relatively large part of the frost heave occurred in the road structure itself (40 – 60 mm) and thus weakened the road during the thawing period.

The need for load restrictions during the structural thawing period depends primarily on the condition of the road when this phase begins. If the road surface is soft after the surface thaw period, restrictions are needed, but if the surface is stiff and there are not too many heavy vehicles using the road then it remain open to heavy vehicles.

3.4 Subgrade thaw weakening phase

The subgrade thaw weakening phase begins when the upper frost line reaches the subgrade soil. The severity of this phase is dependent, on the one hand, on the amount of maximum frost heave due to segregation ice in the subgrade soils and, on the other hand, on the stiffness of the road structures when subgrade thawing begins. A third, and equally important, factor is the weight of heavy vehicles and frequency of these loads since they determine the recovery time.

When the subgrade thaw weakening phase begins, load restrictions should finally be implemented especially on gravel roads known to have spring thaw problems and roads with weak subgrade soils. This is especially the case if the road structures are not dry and stiff enough. Load restrictions should be applied to paved roads only if the increase in rutting has been exceptionally high.

Figure 7 presents a typical GPR cross section profile measured during the early part of the subgrade thaw weakening phase at the Kemijärvi test site. At that time, about 20 cm of the subgrade had thawed and the melting ice lenses, in combination with the embankment load and heavy vehicles, cause high pore water pressure in the soil which, in turn, causes it to become plastic. The wet soil is squeezed out from under the road structure onto the roadsides and road shoulders and into the middle if structures are thin. All of these aforementioned processes cause the road to widen.

In Scandinavia load restrictions are removed much before the frost has completely thawed because the road structures above the subgrade are thick enough and become dry enough during the earlier thawing periods. However if the road structures are wet and there are many heavy vehicles using the road at close intervals severe pavement damage may appear.

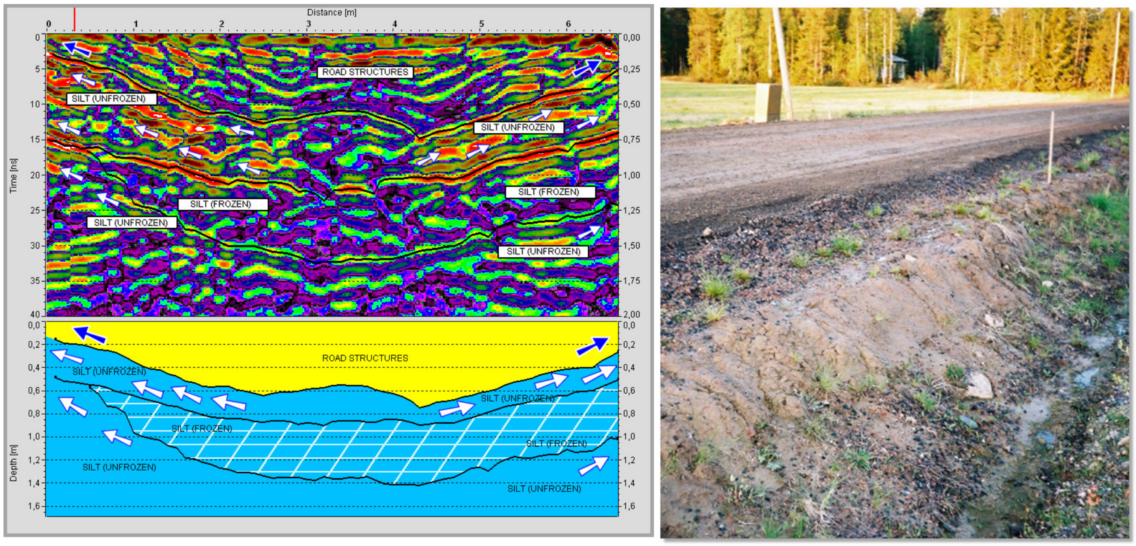

Figure 4: GPR cross section measured at Kemijärvi test site in early May 2004. The GPR profile reveals very wet silty material between the road structure and frozen ground. The GPR data also indicates plastic flow towards the road shoulders. Wet silty material can also be found under the frozen soil.

4 SUMMARY

Even though the springs of 2003 and 2004 in Scandinavia and Scotland were quite “easy” in terms of spring thaw weakening the Roadex II project monitoring results in each test site showed the same phases during the spring thaw period. In terms of bearing capacity measured with deflection values the road was weakest after the frost had completely thawed. This was in contradiction with the fact that the load restrictions have always been removed in both Finland and Sweden before the frost had completely thawed. But if road authorities had waited until the period of highest deflections was over there would still have been load restrictions in mid July in Northern Scandinavia. So more important than the actual deflection values is the stiffness of the upper road structures and their ability to carry loads and how long a recovery time the road has after each truck passes. A weak low volume road is like a relatively stiff mattress floating, on a layer of water created by melting ice, and at the same time settling. The risk for failure then depends on how dry and stiff the road remains thanks to weather conditions and how much time the road has to recover from an intrusion of water into the structures caused by a passing truck.

The Roadex II survey results on seasonal changes and spring thaw weakening gave valuable information regarding the processes behind road damage and the complexity of these processes. Test results indicated that standard truckloads can easily break the road during the weakest phases in spring incurring major costs to road owners as well as an unpleasant ride for other road users during the rest of the year. On the other hand it can be estimated that in Finland, for instance, every day of load restrictions results in more than one million euro extra cost for the forest industry. The results also reveal that the critical weakening phase is often quite short and that is why good monitoring systems with better spring thaw weakening models will allow major savings for the haulage companies using low volume roads. Other promising solutions that should be studied further are the recovery times after a truck passes and the use of CTI (central tyre inflation) techniques to reduce the risk of damaging roads during the spring thaw.

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