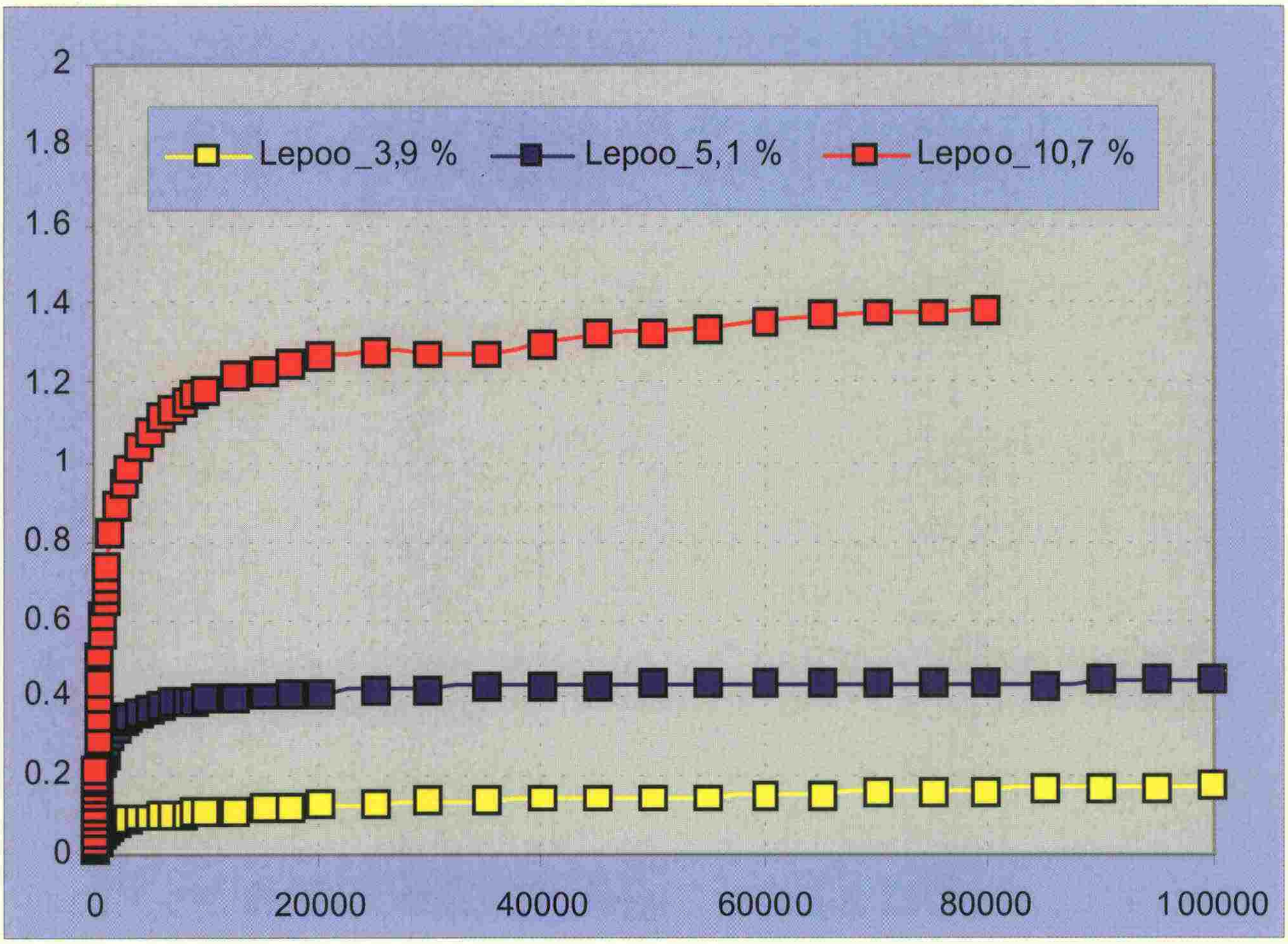
FINNISH ROAD ADMINISTRATION

Timo Saarenketo, Pauli Kolisoja, Nuutti Vuorimies, Seppo Ylitapio

Suction and deformation properties of base course aggregates

Finnra reports 10/2001



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Key words Base course aggregate, permanent deformation, resilient modulus, water content, dielectric value, suction, seasonal variation

ABSTRACT

On assignment from the Finnish National Road Administration (Finnra), a series of Research projects were carried out during 1996-2000 to examine strength and deformation properties of unbound and bound base course aggregates, as well as those mechanical, thermodynamic, electrical and chemical factors, which affect the seasonal variation of the mechanical behaviour of these materials.

A main part of the Research was done in the geotechnical laboratory at the Tampere University of Technology, where cyclic loading triaxial tests, frost heave test, and long lasting cyclic repeated loading tests were used to examine, for example the resilient modulus values and permanent deformations caused in the samples by cyclic loading. The tests were performed in situations simulating dry, moist, and post freeze-thaw cycle, seasonal conditions. In addition to the tests performed at TUT, Tube Suction tests were performed on the selected aggregates in the Lappi Region laboratory of Finnra, and chemical properties of the aggregates were examined at the University of Oulu.

The Research results show clearly that the most significant problem of Finnish base course aggregates is the Development of permanent deformations during frost thawing periods which can be caused by only a few passing heavy vehicles. Instead, the resilient properties of all tested aggregates were relatively good, and their resilient modulus values were not significantly lowered even during the thawing phase, which in the tests simulated the frost thawing period. The results suggest, that suction properties of aggregates have a very significant effect on the deformation properties. Suction properties, in turn, result foremost from the fines content, but also from chemical properties of the aggregate.

The Tube Suction test proved to function well in the identification of problematic aggregates and in defining appropriate binder types and their required amounts. Further, the results suggest that the properties of aggregates bound with emulsified bitumen are not necessarily improved when binder content is increased, but sufficient compaction of the aggregate is apparently significant in avoiding permanent deformations in stabilised layers.

FOREWORD

In the Lappi Region of the Finnish Road Administration, the Research and Development work on ground penetrating radar technology was started in the mid-1980's. A significant part of this work was, at first, to study how electrical properties of road aggregates and subgrade soils affect the radar signal. Later in the 1990's these electrical properties were also used to explain the mechanical properties of road aggregates. This Research was started in 1994-95 at the Texas Transportation Institute, where electrical and strength and deformation properties of Lapland and Texas aggregates were compared. The results of these studies formed the basis for the Research Program, which is presented in this report.

This publication presents a concise summary, of a series of separate Research projects started in the mid-1990's with the purpose of studying the mechanical, electrical, and thermodynamic factors and processes which affect the seasonal behaviour of unbound and bound base aggregates. The Research projects were carried out by Pauli Kolisoja and Nuutti Vuorimies at the Tampere University of Technology (TUT); by Teija Yliheikkilä at the Oulu University, and by Seppo Ylitapio in the central laboratory of Lappi Region of the Finnish National Road Administration (Finnra) as well as in the Oulu laboratory of Finnra Consulting. Timo Saarenketo from Roadscanners Oy, in co-operation with Pauli Kolisoja and Nuutti Vuorimies, has been responsible for the main part of result analysis and Research reports. The Lappi and Vaasa regions of Finnra have financed the Research project; the final phases of the programme have been co-financed by the Central Administration of the Finnish Road Administration.

This Research programme would not have been possible without the support of Lappi and Vaasa regions in the initial phase of the programme, for which the authors of this report express a special thanks to the leaders of these regions. The authors formed the project steering group, Arvo Lähde from Vaasa region, Tapani Lakkala from Lappi region, Irma Saariniemi from Rovaniemi unit of Finnra Consulting and Hannu Peltoniemi from Vaasa unit of Finnra Consulting. Hannu Peltoniemi has also given a valuable contribution as chairman of the steering group.

Teuvo Kasari from Finnra Consulting and Tom Scullion from the Texas Transportation Institute have participated in some steering group meetings. The final report of the project results was made possible by the support of Central Administration of the Finnish Road Administration, and Kari Lehtonen has given valuable advice to the authors of this report.

In Rovaniemi and Tampere, December 2000

Authors

Helsinki, March 2001

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1 INTRODUCTION

Thanks to a sizeable pavement Research programme the rutting of paved roads caused by studded tyres has been brought under control in Finland. Currently one of the most significant causes of rutting is permanent deformations in poor-quality unbound base course. The deformations can develop rapidly, when the base course is partly or entirely saturated with water. The situation is common in Finland, particularly in springtime, as the frost is thawing, but also during rainy autumns, roads with poor-quality base course have been observed to display damage in a short period of time.

A central factor in the Development of damages is excess pore water pressure in the aggregate, caused by dynamic axle loads, which decrease effective stresses between soil particles. Because the ability of the material to resist deformations under a wheel load depends on the effective stresses between soil particles, the increase in pore water pressure leads to deformations in the material. The bigger the loads, the larger is also the degree of permanent deformations.

The purpose of this project has been to determine strength and deformation properties of base course aggregates in conditions, which correspond to the seasonal variations in roads. In addition, the project aimed at developing methods for identification of problematic aggregates and for selecting proper binders and binder content needed to stabilise them. The Research concentrated on the examination of electrical properties of materials such as dielectricity, additionally chemical and thermodynamic properties and their relation to the mechanical properties were also studied. A connecting theory of the separate Research projects is the suction theory, which by using the variation of Gibbs' free energy explains the function of effective stress between soil particles, and the impact of water in the aggregate during different seasons.

Suction theory and preliminary results of this Research project has been published in the following publications: Carpenter and Lytton (1977), Fredlund and Rahardjo (1993), Saarenketo (1995), Saarenketo and Scullion (1996), Titus-Glover and Fernando (1997), Saarenketo, Scullion and Kolisoja (1998), Saarenketo (1999), Saarenketo et al. (2000a) and Saarenketo et al. (2000b).

2 AGGREGATES AND RESEARCH METHODS

In the first phase of the Research project in 1996-97, several crushed gravel and hard rock aggregates from Lapland and Vaasa districts were tested in Finnra's Lappi Region laboratory, at the Oulu University department of chemistry, and at the Tampere University of Technology. Materials selected for the test were those known to have performed well in road structures, or those which were known to have caused numerous problems. An example of a good quality aggregate was e.g. Tohmovaara granite aggregate from Kemijärvi, and an example of a poor-quality aggregate, Lampeltmossen granite and Vuorenmaa mica gneiss which came from Vaasa district. The aggregates were tested with a Tube Suction test, (TS-test), (Saarenketo and Scullion 1996, Scullion and Saarenketo 1997, Ylitapio 1997, Saarenketo 2000) with different fines contents using 200 mm high samples. At the Oulu University department of chemistry, < 2 mm fractions of the aggregate samples were analysed to ascertain their chemical and mineral composition. In addition, cation concentration and the presence and classification of colloids in the aggregates were analysed from extracted solutions (Yliheikkilä 1998).

In the cyclic loading triaxal tests performed at the Tampere University of Technology in 1997, the aggregate samples' resilient modulus values were examined using SHRP P46 method (Kolisoja 1997). The tests, using 400 mm high compacted samples, were performed after drying the samples for two weeks in 45° C, and then after allowing them to absorb water through the bottom of the sample for one week. This method aimed at defining the minimum and maximum modulus values of the aggregates for summer and autumn seasons.

In the test series carried out at TUT in 1998, a freeze-thaw cycle was added to the test procedures and frost heave was measured in the samples during the cycle. After thawing, a cyclic loading triaxial test was performed on the samples, as well as an additional 10^5 cyclic axial loading test series, which aimed at simulating the deformations which occur in the aggregate during the frost thawing phase. This time, Lepoo crushed intermediary volcanite, Vuorenmaa mica gneiss and Lädesglo crushed granite aggregate from Vaasa district, as well as Vuontisrova amfibolite and Tohmovaara crushed granite aggregate from Lappi district were selected for the tests. In the test series the fines content of these aggregates was varied.

In a new test series in 1999-2000, the TS tests and TUT test series were performed using Lädesglo and Lepoo aggregate samples. These samples were identified in 1998 tests to present problematic performers. In the new test series, these aggregates were stabilised using different amounts of emulsified bitumen. The target of the tests was to determine the amount of bitumen needed to prevent the problems previously observed in these aggregates. In addition, the test series of 1999-2000 aimed at examining the effect of axial stress level on the Development of permanent deformations after a freeze-thaw cycle, as well as to study changes in the dielectric value of the material during deformation.

The tested materials and test methods are described in more detail in the Research reports of Tampere University of Technology (Saarenketo et al. 2000 a and Saarenketo et al. 2000b).

3 TEST RESULTS

The key results of the project, regarding the TS tests and the test series carried out in the Geotechnical Laborotory of TUT in 1998 and 1999 are presented with following figures. The Figures 1-3 present results of the TS tests conducted with crushed rock and gravel aggregates having different grain size distribution. The effect of fines content and voids ratio on the moisture content and on the dielectric value measured from the sample are illustrated in the figures. Figure 1 also presents moisture content after TS test of Lepoo and Lädesglo aggregates stabilised with differing bitumen content.

Figures 4 and 5 present the resilient modulus values of aggregates samples based on cyclic loading triaxial tests carried out a) for a dry sample, b) for a sample which has absorbed water, c) for a sample, which has gone through a freeze-thaw cycle. The variable in these graphics is the fines content. Figure 6 presents likewise the relationship between fines content and frost heave measured during the frost cycle in unbound and bitumen bound samples

Figures 7 and 8 present the effect of the fines content and axial load level on permanent deformation values measured during a cyclic loading test series performed after a thawing phase. Figure 7 also presents the permanent deformation values measured from bitumen bound samples after 100.000 cyclic load repetitions. The relationship between dielectric value of test sample surface and permanent deformation is presented in Figure 9.

Figures 10-13 present the results of the tests conducted with emulsion bitumen stabilised samples. The figures study the effect of bitumen content on the voids content of samples compacted using different methods, on the absorbed water in the sample, and on the permanent deformations measured in the samples.

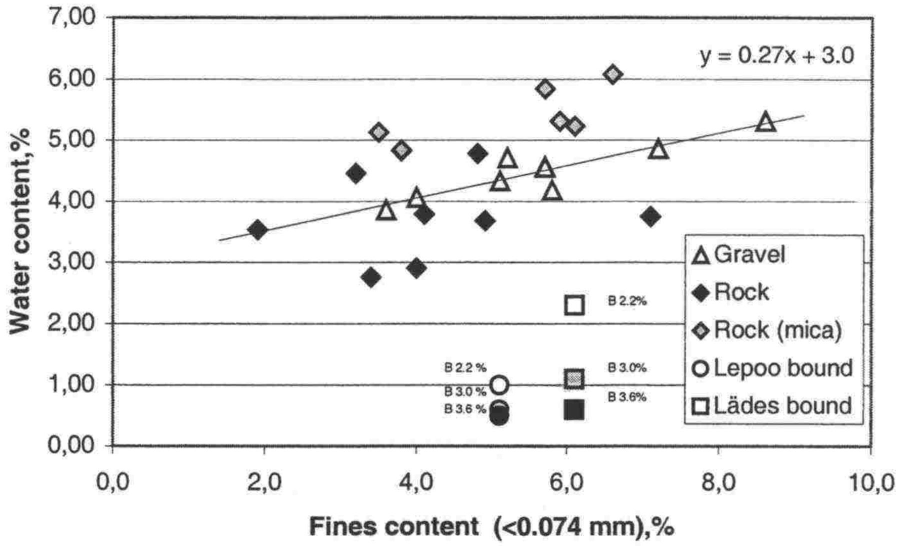

*Figure 1. The relation between fines content (<0.074 mm) and water content in the crushed gravel and rock aggregate samples tested with TS tests. The figure shows, that absorbed moisture content may vary approximately 2 %-unit for samples of the same fines content. For gravel aggregates, the variation is smaller and their water content can be roughly evaluated with the formula: 0,27 * fines content + 3,0 %. For crushed rock aggregates, the moisture content may be lower or higher than for the gravel aggregates with corresponding fines content, depending on pore volume and the level of osmotic suction in the rock material. Mica rich hard rock aggregates adsorbed greatest amount of water. Figure also presents the effect of bitumen content on the amount of water adsorbed during the TS-test in Lepoo and Lädesglo hard rock aggregates. Figure shows that for a Lepoo base aggregate having 5 % fines content only 2 % bitumen content is enough to prevent water adsorption in the specimen. The corresponding value with Lädesglo base aggregate is greater than 3 %.*

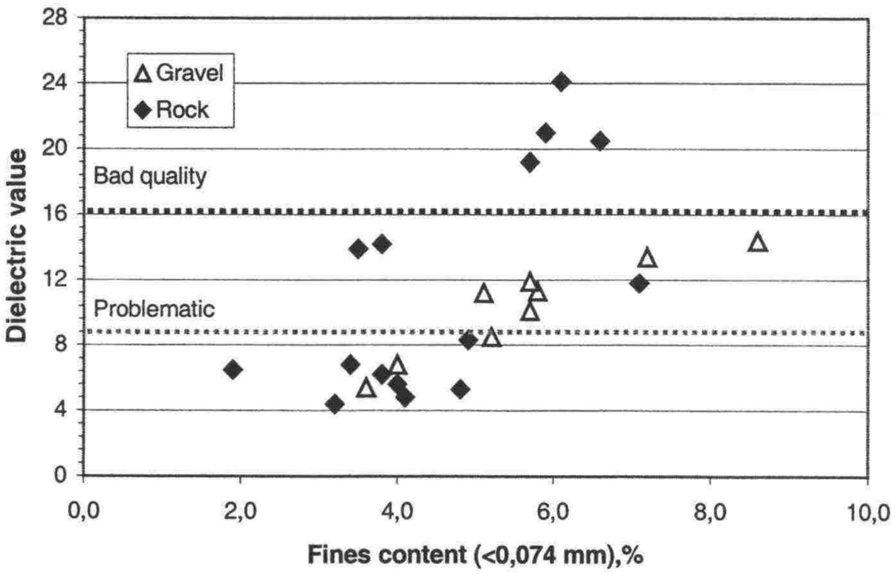

Figure 2. The relationship between fines content and dielectric value measured from examined gravel and hard rock aggregates in the TS test. The figure shows that as the fines content of the examined aggregates exceeds 5%, the aggregate absorbs so much water that the dielectric limit value of 9 determined for problematic aggregates is exceeded. For bad quality rock aggregates, the limit value can be exceeded even at a fines content less than 4%.

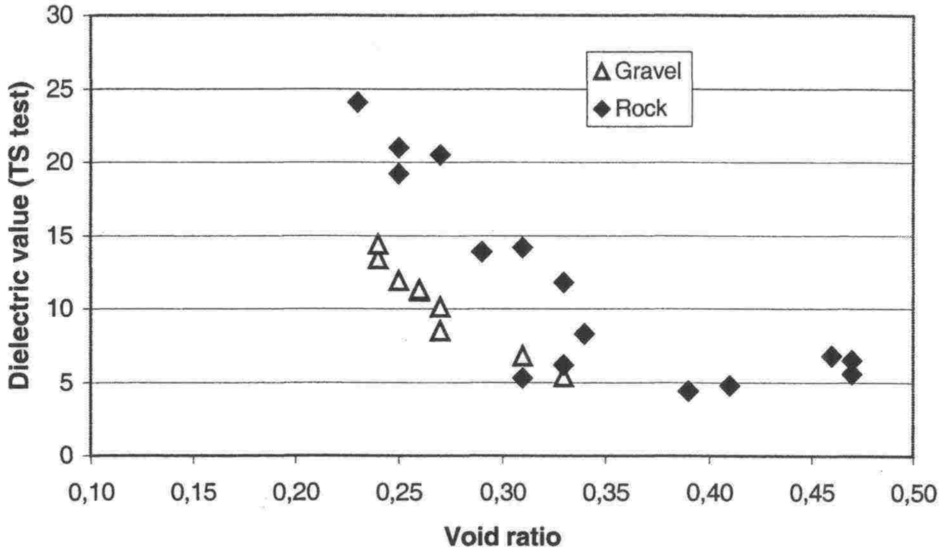

Figure 3. *The relation between dielectric value measured in the TS test and void ratio of the examined gravel and hard rock aggregate samples. The figure shows that in a well compacted sample, the capillary forces are increased, which is clearly indicated by the increase of the dielectric value which corresponds to volumetric water content in material. Gravel aggregate samples absorbed water at different voids content clearly less than most rock aggregates, in which the chemical processes on newly crushed grain surfaces caused an increase in osmotic suction.*

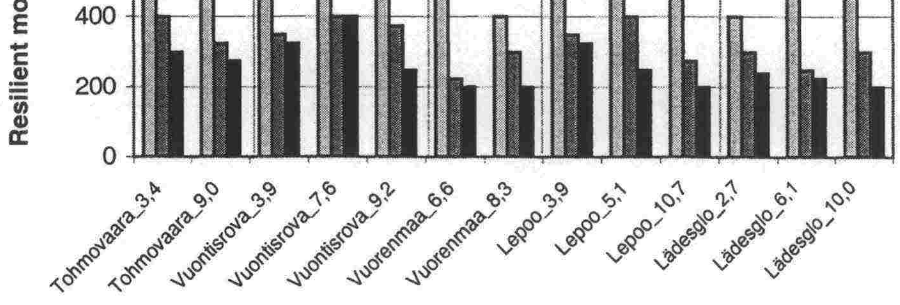

Figure 4. *Results of cyclic loading triaxial tests from 1998. The tests with Lädesglo sample which had 2.7 % fines content were repeated in 1999. The figure shows, that except for the Vuorenmaa sample, the modulus values of dry samples increase as the fines content increases. In samples which have absorbed water or those which have gone through a freeze-thaw cycle, the modulus values instead tend to decrease as the fines content increases.*

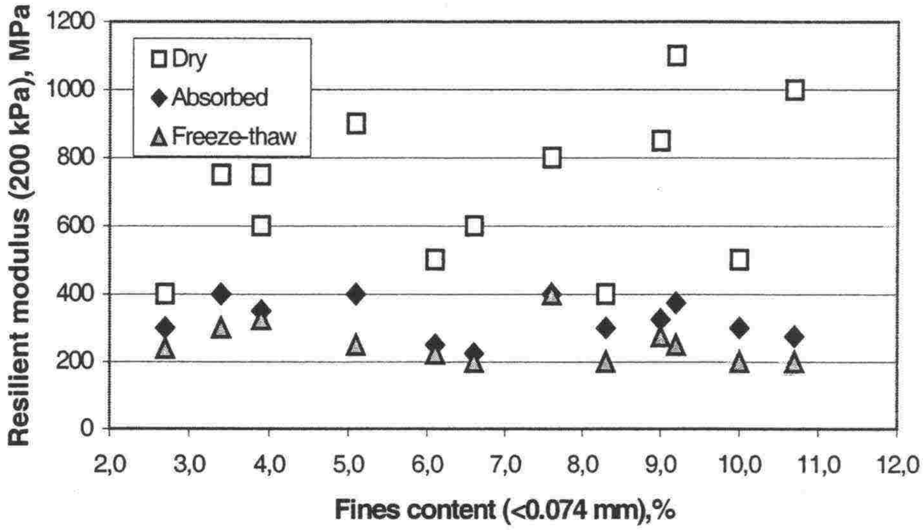

Figure 5. The effect of fines content on resilient modulus values measured at 200 kPa stress level in dry aggregate samples and samples which have absorbed water or which have gone through a freeze-thaw cycle. All examined samples are crushed rock aggregates.

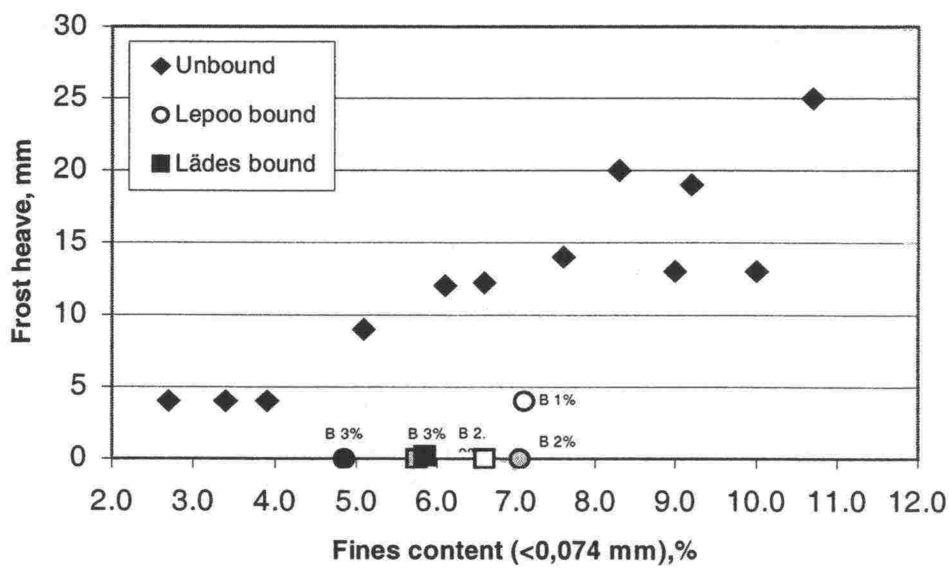

Figure 6. Relation between fines content and frost heave measured in the sample during the freeze test. A clear frost heave was already measured in samples with over 5% fines content and the fines content seemed to have a clear correlation to the height of measured frost heave. Figure also shows that mixing bitumen binder to the sample prevents the frost heave almost completely.

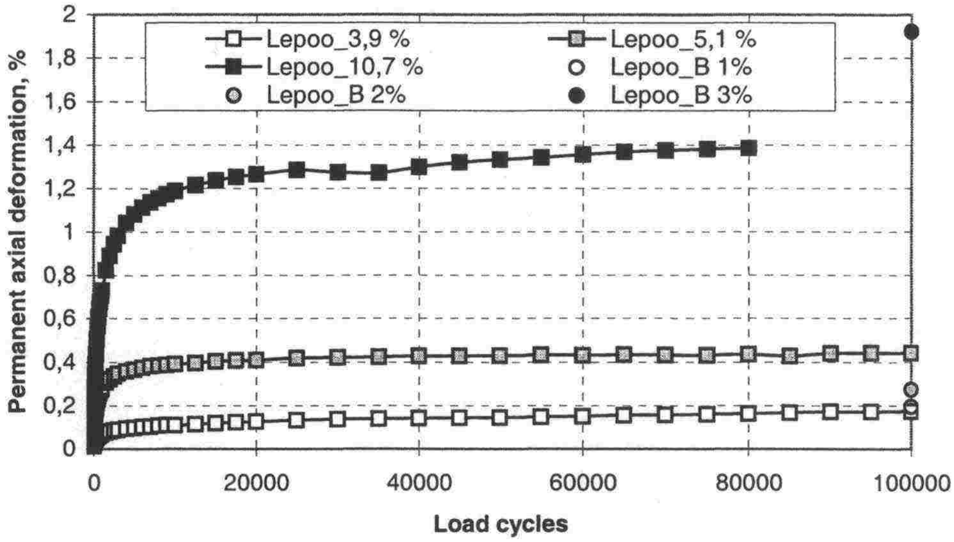

Figure 7. The effect of the fines content, in Lepoo crushed rock aggregate on permanent deformations measured during a cyclic loading triaxial test. A rise in the fines content clearly increases the amount of measured deformations. Figure also shows the measured permanent deformation values of bitumen bound samples after 100.000 load repetitions. The greatest deformation values were measured from a sample having 3 % bitumen, which was not compacted properly (see also figure 12). The cell pressure in the test was 50 kPa and axial stress 300 kPa.

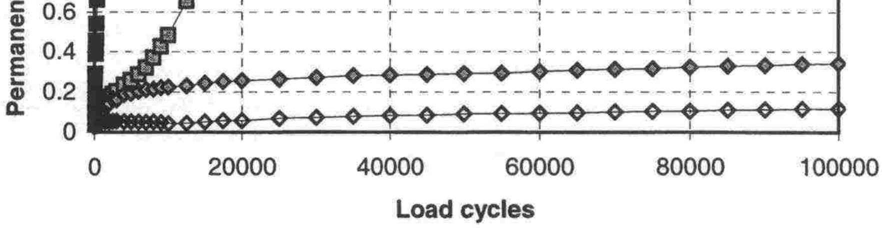

Figure 8. Permanent deformations measured in Vuorenmaa aggregate of normal grain size distribution during cyclic loading triaxial test performed using different load levels after a freeze-thaw cycle. The results clearly show that load level in the material have a significant role in the measured permanent deformation values. In the case of Vuorenmaa base aggregate, at least 200 mm of bound layers over the aggregate would be required to ensure the elimination of permanent deformations in this material.

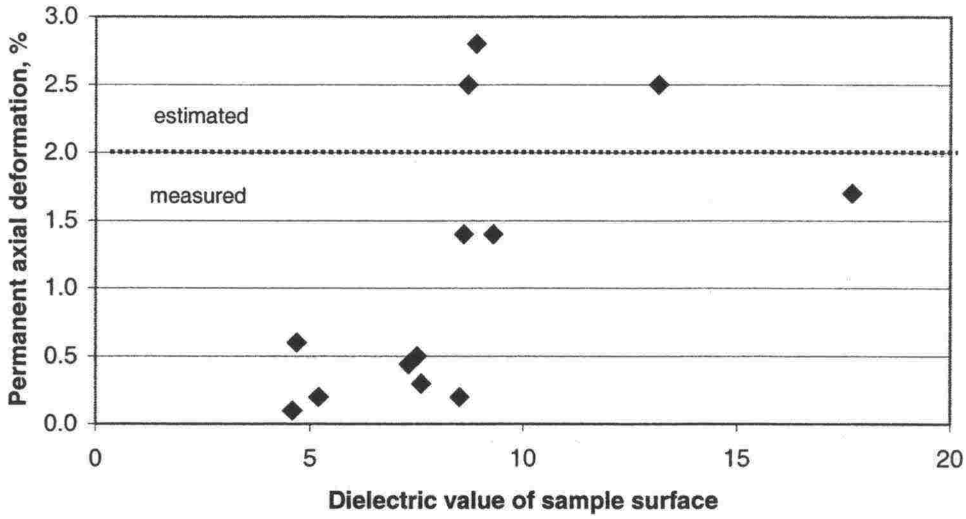

Figure 9. The relationship between dielectric value of sample surface after water suction and permanent deformation measured after freeze-thaw cycle in TUT test. Deformation values more than 2 % have been estimated. Results show that higher permanent deformation values were measured in samples with dielectric value higher than 8. The measured dielectric values in TUT tests were slightly lower than corresponding values in TS-tests because the thickness of the sample in TUT test is 400 mm compared with the 200 mm thick samples used in TS-test.

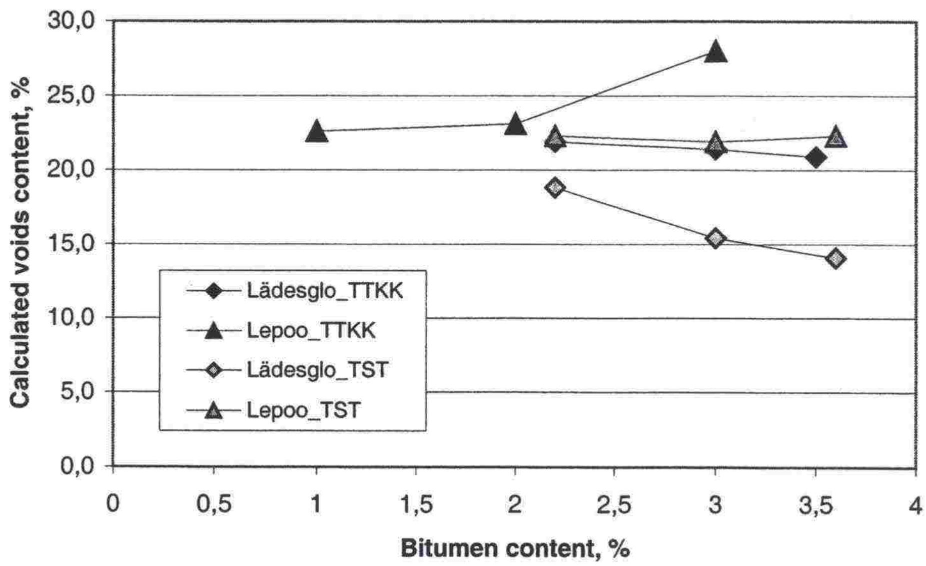

Figure 10. The relationship between bitumen content and voids content of emulsion bitumen stabilised aggregates in samples compacted at 60°C using a gyratory compactor (used in TST sample preparation) or at 20°C using vibratory compactor (TTKK, TUT). The figure shows, that the voids content of samples compacted with gyratory compactor in higher temperature are 1-5 % lower than in the samples compacted in TUT laboratory in room temperature. The figure also shows, how an increase in the bitumen content lowers voids content for Lädesglo aggregate, but for Lepoo aggregate the voids content increases at higher bitumen content with both compaction methods.

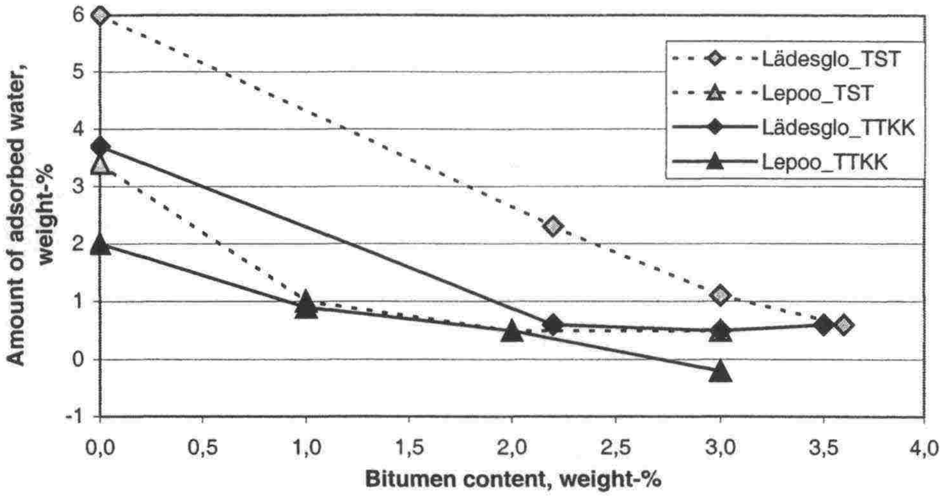

Figure 11. The effect of bitumen content on the absorbed water content measured during the TS test and on the amount of adsorbed water measured during absorption phase in TUT test. In the TS test, water absorption in the Lepoo aggregate sample was completely obstructed at 2,5-3,0% bitumen content, whereas the Lädesglo aggregate required at least 3,5% bitumen to completely prevent water absorption. Otherwise, in the TUT tests with Lädesglo aggregate there was no significant difference in the amount of adsorbed water when the bitumen content was increased from 2,2 % to 3,0 %. Water content was decreasing as the bitumen content was increasing and it was totally obstructed at a 3 % bitumen content.

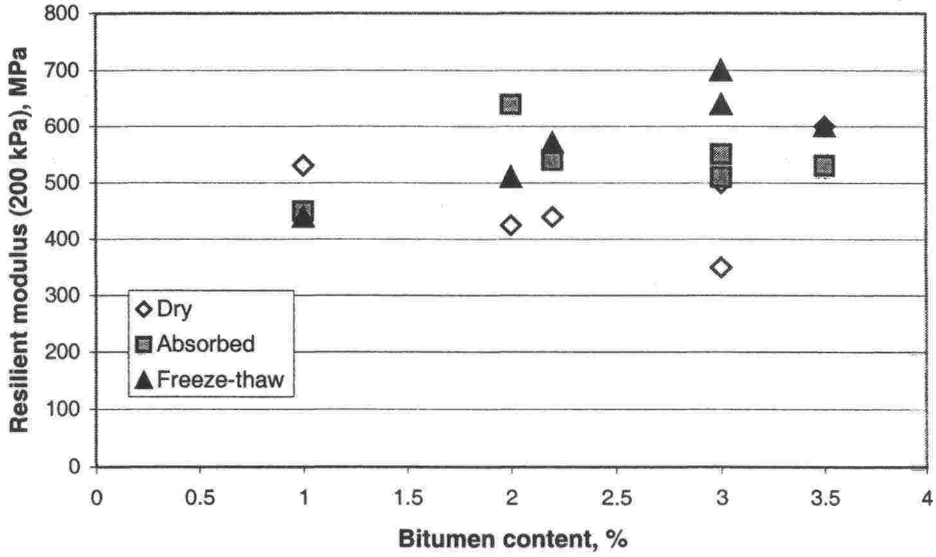

Figure 12. The effect of bitumen content on the resilient modulus values of tested dry and water adsorbed bitumen stabilised base aggregates and after the samples have gone through a freeze-thaw cycle.

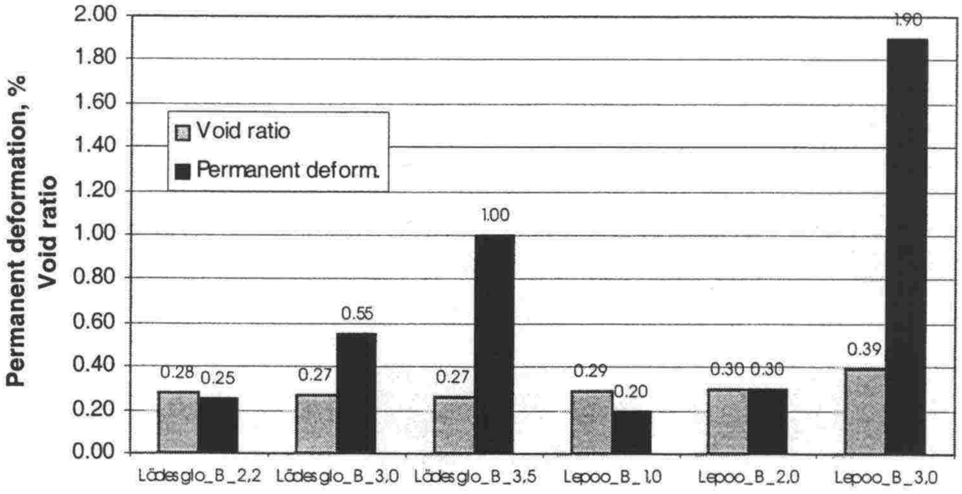

Figure 13. Void ratio and permanent deformations of emulsion bitumen stabilised Lepoo and Lädesglo aggregate samples measured after 10^5 load cycles using 300 kPa axial loading pulse and 50kPa cell pressure. The figure shows, that permanent deformation values increase in both aggregate samples when their bitumen content is increased. The significantly larger permanent deformations in the Lepoo aggregate with 3% bitumen are explained by poor compaction of the sample (void ratio 0,39).

4 CONCLUSIONS

The results of this Research project clearly show, that the problems with Finnish aggregates are not their resilient properties and their seasonal variations, but the permanent deformations which develop in the base course mainly in springtime as the frost is thawing. The results also support the assumption that permanent deformation originates from excess pore water pressure caused by dynamic axle loads in the aggregate which has absorbed water during the freezing phase in autumn and winter. This pore water pressure decreases effective stress between soil particles and may thus lead to plastic deformations only after a few dozen axle load cycles. This is why significant deformations may occur in the base course during the critical time in spring even from just a few passing heavy vehicles.

The degree of permanent deformation in an aggregate sample is clearly controlled by suction properties of the sample, which in turn are mainly a function of the fines content, but are also influenced by chemical properties of the material. In the chemical tests conducted during this project it was found, that problematic aggregates contained various mineral and amorphous colloid compounds; however, their role in the Development of permanent deformations could not be examined in this phase. Another factor affecting the degree of permanent deformation is the stress level in the sample and the project produced new information about critical stress levels above which significant permanent deformation may take place. This information can be applied in evaluating the thickness of bound layers needed overlaying problem base aggregates.

The Research project also showed, that frost heave can occur in unbound base course aggregates and that the degree of frost heave correlates with the fines content. Frost heave was measured in samples having as low as 5% fines content. The amount of frost heave does not however directly correlate with the permanent deformations that take place in the aggregate during the cyclic loading test performed after the freeze-thaw cycle; more critical is whether or not the excess water leaves the aggregate during the thawing phase.

The resilient modulus values measured in dry samples, representing summer conditions, increased clearly in function of fines content. In the moist samples, representing autumn conditions, and in the samples simulating spring conditions after a freeze-thaw cycle, the modulus values decreased instead as the fines content increased. The results confirm previous observations that measuring bearing capacity values during dry summer months may not be sensible, as the modulus values of poor quality aggregates are also high at the time. When interpreting bearing capacity measurement results, one should remember that when the bearing capacity is low, there are always problems in the road structure, but if bearing capacity results are good, the unbound materials in the road may be good, or very bad as well.

The results of the Research project showed, that the Tube Suction Test (TST) developed for the identification of problematic aggregates works well. With the help of this test it is possible to estimate if an aggregate with a given grain size distribution is frost susceptible and if it is susceptible to permanent deformation. The test can also help to evaluate how the grain size distribution of a crushed aggregate should be changed, so that the aggregate would be suitable for unbound pavement layers. If the aggregate needs to be stabilised, the TST can be used to estimate the effectiveness of binder type and amount of binder required. Results of the TST also show, that gravel aggregates, on average, absorb less water than rock aggregates, which have more newly exposed surfaces which are susceptible to reactions with water.

The tests conducted during the project on samples stabilised with emulsified bitumen also provided interesting results. The most surprising result was, that an increase in the bitumen content does not always improve the properties of stabilised aggregates; for example with Lädesglo rock aggregate the situation was the opposite: the smallest deformations were measured in the lowest bitumen content, 2,2%, and the resilient modulus of this sample was not lower than in the samples with higher bitumen contents. The test results suggest, that if base course aggregate is stabilised in low temperatures, special attention must be given to the compaction of the layer, and if there is uncertainty about the result of the compaction, for example, because of low bearing capacity of the subgrade, the bitumen content should not be increased "just in case". If there is enough bitumen in the sample, so that water absorption in the aggregate is prevented and the workability of the mass is preserved, there are no short-term benefits from increasing the bitumen content.

The results of the completed Research programme clearly show, that the most critical factor in Finland, regarding the function of base course aggregates is the amount of free water. When the absorption of water to the base course is prevented, this should prevent the Development of large permanent deformations in the layer. The results also suggest, that in the future, dimensioning, of at least middle and low class roads, should not be done using only elastic models, but that the visco-elastic and visco-plastic behaviour of the material should also be taken into consideration.

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