Light-weight fill aggregates for insulation in roads-strength and stiffness properties

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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. SINTEF Civil and Environmental Engineering have performed a research project to investigate the possibility for using light weight expanded clay (Leca) as insulation of road pavements. Physical, thermal and mechanical properties of the Leca material have been investigated in the project, which includes laboratory testing, large-scale laboratory tests, full-scale field tests and theoretical analyses. The project shows 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 tests and an ongoing instrumented field tests seem to verify the results from laboratory tests and theoretical analyses. The performed project shows 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.

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 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. If the material should be used as a part of the pavement structure it will be subjected to considerable loads both during construction and the service lifetime. The material has to sustain these loads without being crushed or develop deformation that would result in damage of the pavement. The physical, mechanical and thermal properties of the material therefore had to be verified before Leca material could be taken into common use. 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.

2. LIGHT EXPANDED CLAY AGGRAGATE (LECA)

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.

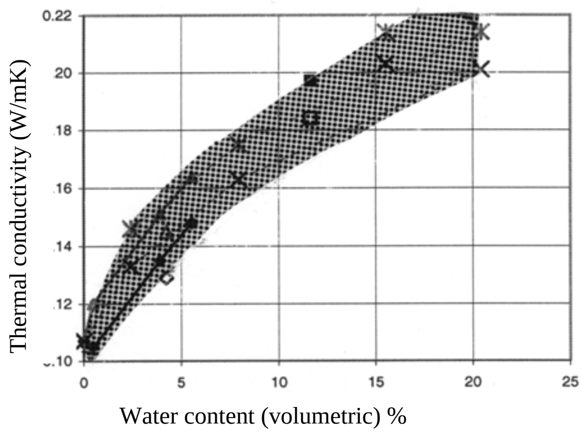


Figure 1 thermal conductivity of Leca-material

3. LABORATORY TESTING

Traditional tests for particle strength like the Los-Angeles test or the Micro-deval are not applicable for expanded clay because the particle strength is low compared to crushed rock or gravel. The stress levels in these tests are higher than what the expanded clay should be exposed to in service. For most materials the highest loads are experienced during construction and especially in the compaction process. Therefore we focused on crushing and deformations during installation and compaction. The laboratory programme includes:
-compaction testing (gyrator compaction, vibrating table)
-large scale oedometer tests
-cyclic triaxial testing

3.1 Compaction testing

The aim of the compaction testing was to investigate the amount of crushing and wear of the Leca grains that occur in the compaction procedure. The compaction testing also aimed at developing relevant methods for preparing samples for triaxial testing. The compaction testing showed that the crushing of the particles was generally low with vibration compaction and with gyrator compaction provided the stress levels were less than 100 - 150 kPa. With the gyrator procedure, which applies shear movement on the particles combined with vertical stress, considerable crushing could be observed at high stress levels. The compaction testing showed that a compaction of about 10-15% related to the loose density might be obtained on the material only by a reorganisation of the particles. More compaction could only be obtained by crushing of particles.

3.2 Oedometer tests

The oedometer tests were performed to investigate the resistance to deformations for static loading. The tests were especially focusing on determining the stress levels relevant for this type of material to avoid unacceptable deformations in the pavement, i.e. the stress level without crushing of the grains. The tests also focused on determining the material stiffness at these stress levels. The tests were performed in a large-scale oedometer with diameter 500 mm and height 580 mm. The dimensions of the oedometer reduce the influence of border conditions and thus gives reliable results for the static stiffness of the material.

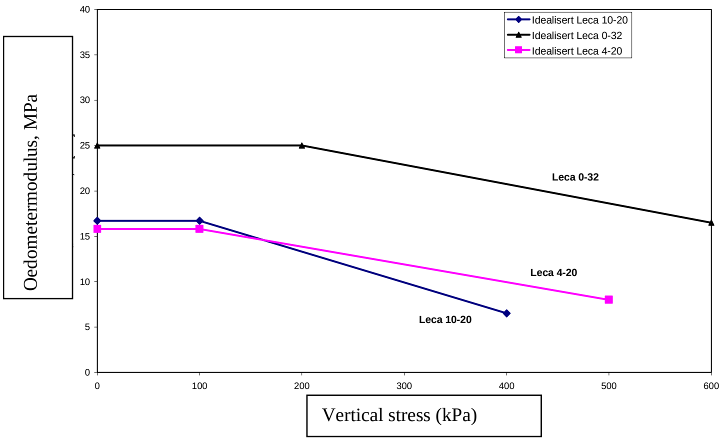


Figure 2 Idealised curves of oedometer modulus related to stress level for Leca materials

The testing were performed on the gradings 10-20, 4-40 and 0-32. The material was compacted by vibration in layers of 100 mm thickness. The compaction procedure gave an initial volume reduction of about 10-14 % related to the loose state. Visual inspection of the material and sieving after the compaction indicated almost no crushing of the material. Hence, the volume reduction during the compaction was assumed to be related to reorganisation of the grains.

Based on the results from the oedometer tests the stiffness of the material can be expressed by the oedometer modulus. Oedometer modulus related to the stress levels for the tested materials are presented in Figure 2.

This verifies that the Leca material has a relatively high compressive stiffness for static loading, provided the stress levels is not too high. The tests indicate that the crushing is not influencing the stiffness when the stress level is less than 100 kPa for the gradings 4-20 and 10-20 and about 200 kPa for the grading 0-32. At higher stress levels the stiffness is gradually decreasing.

3.3 Triaxial test

The material has been tested by a repeated load triaxial test equipment. The sample diameter was 150 mm and the height was 300 mm. The tests were performed with constant confining pressure and repeated sine function deviatoric load. Because of the low density of the material the top-platen had to be loaded with lead to balance the buoyancy force.

3.3.1 Sample preparation

The materials were compacted on a vibrating table in one to four layers with vibration time varied from 15 second to 4 minutes for each layer, to produce samples with different densities. The compaction was performed in a splittable steel mould with a latex membrane inside the mould. After the compaction vacuum was applied and the mould was removed. The sample was kept under constant vacuum until it was ready for testing and confining pressure could be applied.

3.3.2 Loading procedure

The loading procedure was designed to test the material for relevant stresses for use as lower part of a base coarse or as a sub-base coarse. We were interested in both the resilient stiffness and the resistance against permanent deformations.

The loading procedure is illustrated in Figure 3. As can be seen different number of load pulses will be applied depending on the sample strength. The maximal deviatoric stress applied for these test has been 300 kPa. The load is applied as a continuos haversine function with 10 Hz frequency. 3 000 load pulses were applied for each load step

Very little crushing/wear of particles was observed during the triaxial tests.

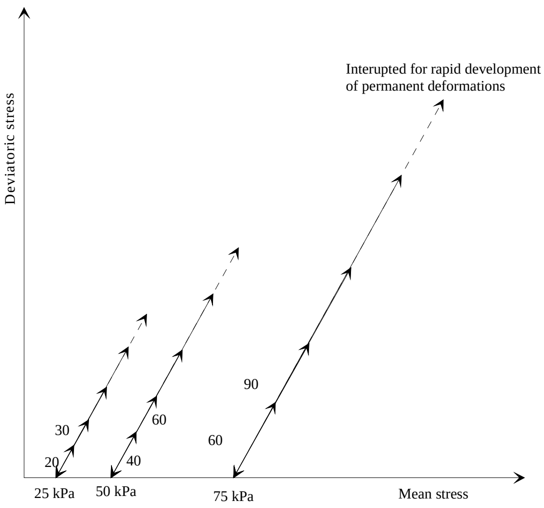


Figure 3 Loading procedure used for testing of Leca - material

3.3.3 Resilient stiffness

It is important that materials used in pavements have high enough resilient stiffness to avoid large deformations and fatigue cracking of the asphalt surfacing. Large deformation would also increase particle wear.

The resilient stiffness of unbound aggregates is generally highly influenced by the stress situation. Hence, the material has to be tested for a range of different stress situations that are relevant for use in pavements exposed to load from traffic. Figure 4 shows the resilient stiffness for different levels of mean stress.

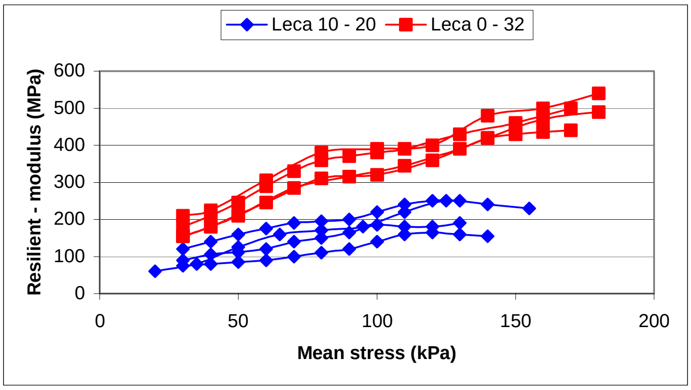


Figure 4 Resilient stiffness as a function of mean stress

As we can see is the 0 – 32 mm grading significantly stiffer than the open graded (10 – 20 mm) material. The stiffness is close to what might be expected from traditional pavement construction materials like gravel or crushed rock. Table 2 shows the resilient modulus compared to some results from testing of typical Norwegian gravel and crushed rock.

Table 2 Resilient stiffness for Leca materials compared to gravel and crushed rock

Mean stress (kPa)	Leca 10 – 20	Leca 0 - 32	Gravel (Hovinmoen 0 – 22)	Crushed rock (Åndalen 0 – 22)
50	110	250	110	290
100	200	350	160	350
150	210	450	210	410

3.3.4 Resistance against permanent deformation

Development of permanent deformations in unbound granular material is an important distress mechanism for low-volume roads with relatively thin asphalt layers and high stresses on the unbound layers. There are two important mechanisms for development of permanent deformations:

- Crushing of particles
- Rearrangement of particles

The Leca – grains are relatively weak compared to typical gravel or crushed rock materials. This means that care must be taken to avoid overloading these grains. This is especially important during construction and compaction. When the material is placed and compacted the governing mechanism for further development of permanent deformations depends on the stress situation.

If the material is exposed to high overall pressure crushing of particles is likely to be the problem. However, if the ratio between confining pressure and deviatoric load is high shear deformations with rearrangement of particles will govern the behaviour. This is illustrated in Figure 5.

The failure angle (ϕ_c) and the elastic limit angle ($\rho_{elastic}$) are determined from repeated load triaxial tests and characterises the materials resistance against permanent deformations. In theory these angles could have been used for design by comparing these values with calculated mobilised friction in the structure. Unfortunately the uncertainties in such a method will be too large for the time being. However, the limit angles are very useful to compare the resistance against permanent deformations for different materials. As can be seen from Table 3 the elastic limit angle is similar to gravel and crushed rock. The failure angles are, however, lower for the Leca-material.

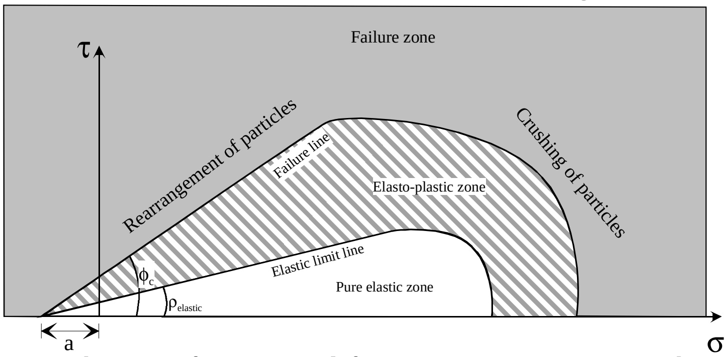


Figure 5 Development of permanent deformations in a Leca - material

Table 3 Elastic limit and failure angles for Leca – material compared to gravel and crushed rock

	Leca 10 – 20 mm	Leca 0 – 32 mm	Gravel, Hovinmoen 0 – 22 mm	Crushed rock, Åndalen 0 – 22 mm
Sin (ϕ)	0.31	0.42	0.41	0.6
Sin(ρ_{elast})	0.20	0.35	0.18	0.3

4. FULL SCALE LABORATORY TEST

To investigate how the material will behave in a real pavement structure a full-scale laboratory test was performed in the laboratory to simulate the behaviour under simulated traffic load. The intention was to study the behaviour of a structure with Leca as a major element during long-lasting repeated loading.

Load, deformations, stresses and temperature were continuously registered during the test. The load was transferred to the structure by a steel plate with diameter 30 cm. The load was applied with load steps of 30, 40 and 50 KN. A total of 4.8 million load pulses were applied. Figure 6 shows a sketch of the test rig.

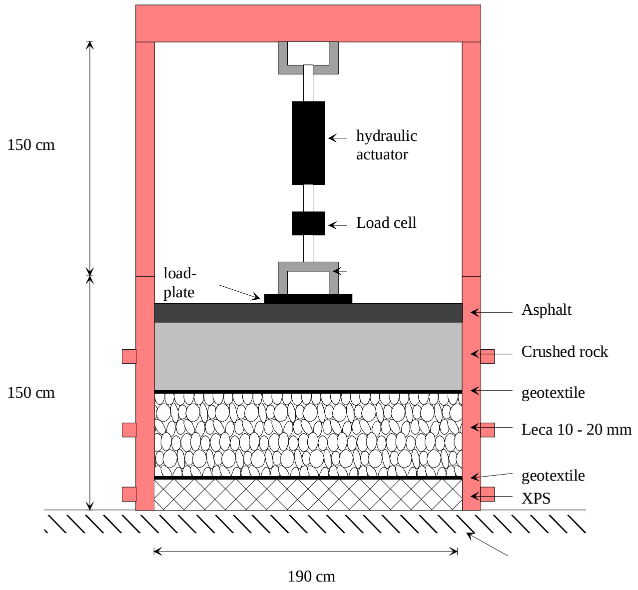


Figure 6 Sketch of the full-scale test with loading equipment

4.1 Test results

The tests verified that the Leca material has a stiffness and strength that makes it useable as a major part of a road structure. Figure 9 shows measured permanent deformations in the structure. Some plastic deformations of the Leca material are registered, but the deformations are small compared to the deformations in the other structure materials. The total deformations increase with the number of loading pulses, especially for the highest load amplitude. This behaviour could be a result from cracks in the asphalt around the steel plate.
Visible cracks could be observed in the asphalt layer at the completion of the test.

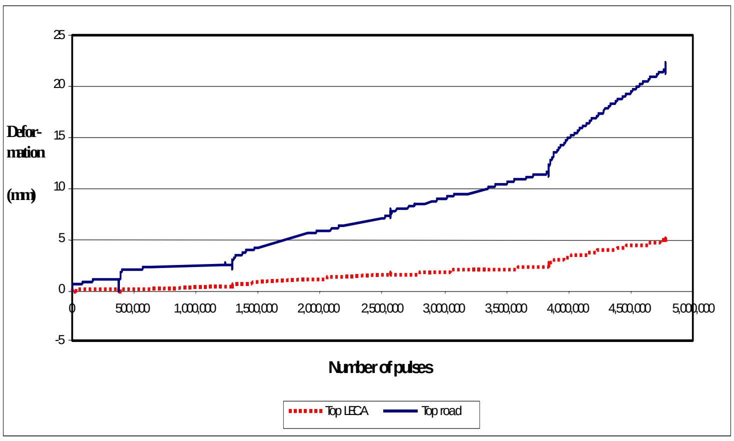
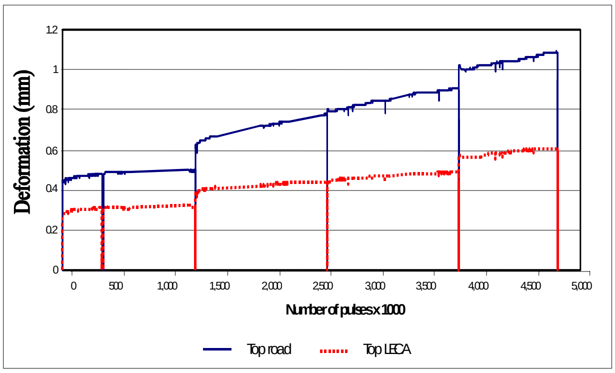


Figure 7 Permanent deformations

The examination of grains after the test showed little crushing. Previous laboratory tests showed lower stiffness and resistance to permanent deformations for the Leca fraction 10-20 mm than for the 0-32 mm and 4-20 mm fractions. The other Leca fractions are therefore believed to result in smaller permanent deformations.

The measured elastic deformations for the whole structure as well as for the Leca-layer is in the range as expected for a typical pavement structure. The increase in elastic deformations with number of pulses is almost the same in the Leca-layer as in the rest of the structure.



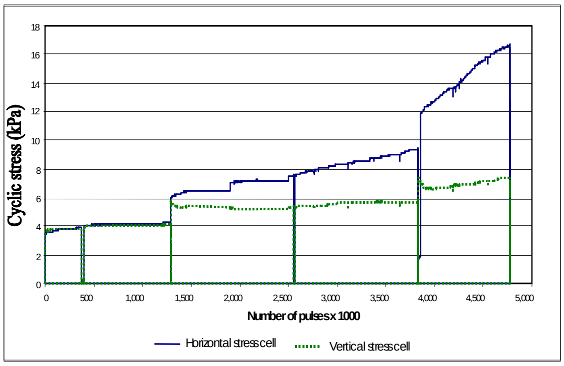


Figure 8 Elastic deformations

Figure 9 Cyclic stresses

Figure 8 shows measured cyclic stresses in the Leca-layer. The measurements show relatively high horizontal stresses in the Leca-layer. Sufficient lateral support is therefore crucial in structures with Leca aggregate.

4.2 FEM – analyses

The full-scale model was back-calculated using the finite element method to verify that the measured values were reasonable. Very good match between calculated and measured values was found for the vertical deformation on top of the asphalt and the Leca layer and for the vertical stress beneath the Leca - layer. The horizontal stress measured in the Leca layer was higher than what could be calculated with reasonable parameters for the different materials. This difference is believed to be caused by local differences in the stress field were the load cell was placed. Figure 10 show the calculated vertical stress in the Leca- layer.

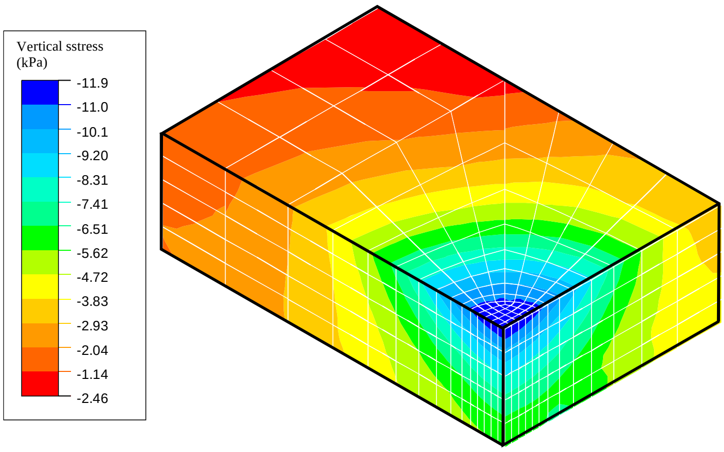


Figure 10 Vertical stress in the Leca – layer

5. INSTRUMENTED FIELD TEST

The full-scale laboratory test showed promising results for use of Leca-materials in pavement structures. To verify that the material also behaves satisfactory for real traffic load a field test has been built at Sandmoen in Trondheim. The field test is combined with another study made by the Norwegian University of Science and Technology to investigate the stress and strain distribution near the edge of roads. A total of four different sections were build whereof two was built using Leca as a frost insulation layer.

The first of the Leca section was instrumented with load cells for measuring vertical, transversal and longitudinal stresses in the Leca-layer and deformation transducers for measuring vertical and transversal deformation in the Leca and crushed rock layer. The temperature is also measured at eleven different depths of the structure. The layer thicknesses are shown the left part of Figure 11.

The second Leca - section was build to investigate how much was needed above the Leca-material to avoid development of permanent deformations and crushing of particles. Figure 11 shows how the section was build. At the weak end of the structure quite high stresses are applied on the Leca-layer and development of permanent deformations were expected.

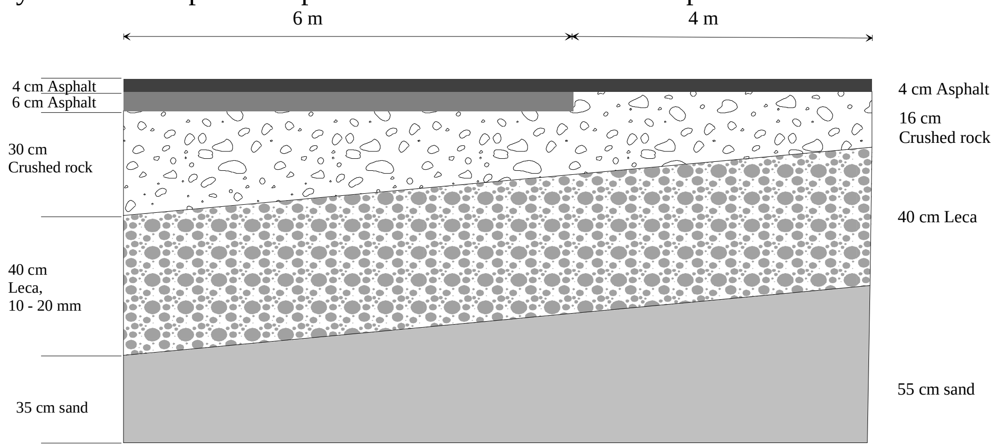


Figure 11 Layer thickness for the wedge-out section at Sandmoen field test.

The field was constructed during June 1999, and we are now working with analyses of measurements done both from ordinary traffic and controlled loading with FWD and trucks with known wheel loads. The results from measurements and conclusions from the field test will be published later.

6. CONCLUSIONS AND RECOMMENDATIONS

The research program that has been carried out has given valuable results as a basis for evaluation of the possible use of Leca materials for frost insulation in roads. The results verify that it can be easily installed and compacted by the use of common construction equipment on site. The material should be compacted by equipment with an applied pressure of maximum 50 kPa to avoid crushing of the grains. A volume reduction of 10-12 % can be expected during the compaction in the field.

The results clearly indicate that the stiffness and strength of the compacted material is sufficient to be used as part of the pavement structure, provided the stress level is kept low enough to avoid crushing of the grains. The elastic stiffness and resistance to plastic deformations for the Leca material is comparable to those found for conventional materials used for road construction (gravel and crushed rock).

The large-scale laboratory tests and the numerical analyses indicate that the Leca material has mechanical properties to be used in the road structure with an overlay thickness significantly less than previously recommended. The ongoing field tests are aiming at verifying the results obtained in the project so far. These tests and complementary evaluation of other aspects related to frost insulation are planned are included in a Nordic project including public authorities, Universities and research institutes in Finland, Sweden and Norway. This project is planned to be basis for assumed to give a basis for recommendations on use of Leca material for frost insulation in roads.

7. ACKNOWLEDGEMENTS

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