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Properties of the crushed rocks used as frost protection layer of the Norwegian roads: field and laboratory investigations

CONTENT

INTRODUCTION

Due to climate change, roads in regions that previously enjoyed stable winter conditions are now subject to several freeze-thaw cycles each winter (Grendstad et al., 2012). Frost heave damage increases and becomes more complex and more frequent.

Frost action mainly develops in the frost-susceptible subgrade soils, leading to ice lens formation, surface heave, and eventually, to pavement deterioration (Konrad & Lemieux, 2005). Frost action in the base and subbase granular layers is often ignored, because these materials are usually not considered to be frost susceptible. This may not necessarily be the case. The presence of fines in these layers can modify their frost susceptibility and cause severe degradations.

Heat transfer and frost action analyses in pavements require the knowledge of the thermal properties of each layer of the pavement structure including subgrade soils. Among various properties, thermal conductivity is one of the most important input parameters in heat transfer modelling. However, in gravel, cobbles, and boulders, other heat transfer mechanisms may be significant. Johansen (1975) established the limits of predominance for the different heat transfer mechanisms in soils, which are shown as a function of the effective particle diameter d_{10} (10% of the whole material mass has particles smaller than d_{10}) and of degree of saturation S_r. It is shown that conduction and is the governing heat transfer mechanism for the largest range of soil conditions (clays, silt, sands). However, in the materials with large particles and low degree of saturation, convection and radiation are predominant heat transfer mechanisms (Fillon et al., 2011).

Norwegian road construction practice has changed significantly during the last 40 years due to the replacement of gravel by crushed rock materials in the granular layers of the pavements. The use of non-processed rock materials from blasting was allowed in the subbase layer until 2012. This was a reason for a lot of problems with frost heaving due to inhomogeneity of this material, and in practice it was difficult to control the size of large stones. Since 2012 there is a requirement that rock materials for use in the subbase layer shall be crushed (Handbook N200, 2014).

During the spring of 2014, Norwegian Public Roads Administration introduced a new handbook with requirements for roads construction in Norway, including new specifications for the frost protection layer. When pavements are constructed over moist and/or frost susceptible soils in cold and humid environments, the frost protection layer also becomes a very important part of the road system. According to new specification; the size of large stones for this layer should be maximum 0.5 m (longest edge) or ½ layer thickness. And minimum 30% of stones should be less than 90 mm. Fines content (<0.063 mm) should be maximum 15% of the material less than 22.4 mm.

The idea behind increasing the fines content is that graded crushed rock material can keep some humidity and provide resistance against frost penetration by increasing the latent heat of fusion. On the other hand, the fines content cannot be so high that the material becomes frost-susceptible.

Analyzing these new requirements, several questions are arising. First of all how this materials size will affect heat exchange in the layer, secondly – if the allowable fines content will make the materials frost susceptible.

The study presented here is part of a larger research program to investigate the properties of crushed rock materials in relation to frost heaving in the frost protection layer. An important issue will be the resistivity for frost penetration due to presence of water and fine particles. Due to new requirements for allowed fines content, it's essential to investigate if increased amount of stones <0.063 mm together with increasing of water content in the frost protection layer, will not lead to more frost heave problems. At the same time investigation of the dominant heat transfer mechanisms is required.

Two county roads Fv26 close to Alta and Fv456 in Meløy in Northern Norway had experienced frost heave problems before they were restored in 2011/2012. Maintenance was partly successful and partly not. In March 2014, several excavations were done along the roads in order to investigate if frost protection layers fulfill the requirements, and to collect samples for further laboratory investigations. The grain size distribution, fines and water content of the collected samples were analyzed in the laboratory at NTNU.

At the same time two experiments were conducted to investigate the influence of fines content on frost susceptibility and thermal conductivity of crushed rock materials.

This paper presents the results of field and laboratory investigations. It is essential to understand the connection between fines and water content in frost protection layer and actual frost heave problems. At the same time, the knowledge of thermal conductivity of crushed rock materials is required in order to have adequate calculations of frost penetration depth.

BACKGROUND

It is generally accepted that in cold regions, the use of frost-susceptible granular materials in pavement construction gives rise to the potential for frost heave damage in roads (Bilodeau et al., 2008). When free moisture is available in subsurface pavement layers, its upward movement toward the freezing zone can lead to the formation of ice lenses and the occurrence of differential frost heave in the pavement section (Guthrie and Hermansson, 2003).

The use of non-processed rock materials from blasting was allowed in the sub-base layer in Norway until 2012. This was a reason for a lot of problems with frost heaving due to the heterogeneity of this material, and in practice it was difficult to control the size of large stones. Since 2012, it has been required that rock materials for use in the sub-base layer shall be crushed (Handbook N200, 2014). When pavements are constructed over moist and/or frost susceptible soils in cold and humid environments, the frost protection layer also becomes a very important part of the road system. Crushed rock materials are most commonly used in this layer, because it is easily available at most construction sites.

In a frost design method, the required parameter values of crushed rock aggregates are thermal conductivity, density and water content. The heat transfer during the freezing of natural soils is assumed proportional to thermal conductivity of the material. In a coarse-grained material with abundant pore space, convective heat transfer and radiation may be a considerable factor, sometimes even more significant than conduction.

As pointed out by Côté and Konrad (2003), mass transfer characteristics of pavement base-course materials were not systematically studied in the past. Unfortunately, the same applies to heat transfer characteristics of these base-course materials. This has resulted in a lack of experimental data to evaluate the reliability of existing thermal conductivity models and, if needed, to establish reliable empirical models for the prediction of thermal conductivity. The grain-size distribution of pavement base-course materials typically ranges from 0 to 20 mm, inclusively. This broad grading generally leads to high dry densities, ranging from 1800 up to 2350 kg/m^3. The fabric of soils, which refers to the size and arrangement of particles and the pore space distribution, has an undisputable influence on the thermal conductivity of soils. It is thus expected that prediction of the thermal conductivity of compacted base-course materials should be different from that of the well-documented sands and fine grained soils.

Recently, the formula used to calculate the frost penetration depth is according the standard NS-EN ISO 13793. It does require two thermal parameters of the soils: thermal conductivity and heat capacity. Currently, in calculations thermal conductivity for crushed rocks is taken as 1 W/mK, but according to some published data, it is not necessary the case. Experiments conducted by Côté and Konrad (2003) for several types of crushed rocks (granite, limestone, quartzite, syenite) show that in dry state thermal conductivity λ can be 0.5-1.5 W/mK, when water content W= 5-6%, λ_{th} = 1.1-3.7 W/mK in unfrozen state and λ_f = 1.2-4.4 W/mK in frozen state.

MATERIALS AND METHODS

STUDY AREA

Norway is located in an area of seasonal freezing and thawing referred to as an area of wet freezing.

Field investigations were held on two county roads: Fv26 in Tverrelvadalen (Alta, Finnmark) and FV452 in Meløy (Bodo, Nordland). Materials for laboratory tests of thermal conductivity and frost heave were collected from the quarry in Vassfjellet, located 30 km from Trondheim (Sør-Trondelag).

During the field investigations, it was observed that pavement in Meløy had experienced frost heave, but subgrade soils were not frozen. In Alta pavement and subgrade soils were fully frozen, and it was no trace of frost heaving.

MATERIALS

Samples collected in the field

A number of samples were collected during excavations along the roads in Tverrelvadalen (Alta, Finnmark) and in Meløy (Bodo, Nordland): 5 samples from frost protection layer and 4 samples from subgrade soils.

Table 1. Collected samples (“pukk” (norw.) – crushed stone)

Place	Material analyzed	
	Frost protection layer	Sub-soils
Meløy	Pukk 1	Moraine 1
	Pukk 2	Moraine 2
	Pukk 3	Moraine 3
	Pukk 4	-
Alta	Pukk Alta	Sub-soil Alta

Samples used for thermal conductivity measurements

Laboratory experiments on frost heave and thermal conductivity were performed on crushed greenstone rocks (methamorphic basaltic lava) from quarry in Vassfjellet, area of Sør-Trondelag. This material is commonly used for base, sub-base and subgrade layers in roads and railways in the area. The material is of average strength (in Norway), and can be taken as a typical material for this purpose. It has been used for research intention for many years, and its properties are well known.

Main characteristics:

- density of solid particles is 3,09 g/cm^3;
- resistance to fragmentation, determined in terms of Los Angeles coefficient, is 12.3;
- resistance to wear by abrasion, determined by Nordic Ball Mill test, is 9.2.

The mineralogy of fines of the samples was studied with X-ray diffraction method. The most common rock minerals are amphiboles (mainly hornblende), albite, epidote and chlorite.

To study the influence of fines and water content on the freezing characteristics of crushed aggregate, 10 samples were prepared with different fines contents (5% and 15%) and initial water contents (0 - 7.5%). The maximum stone size is 22.4 mm due to requirements for allowed percentage of the fraction <0,063 mm for the frost protection layer. Samples were prepared by compacting samples of desired grading using Standard Proctor compaction tests on aggregate mixtures with 5% and 15% fines.

METHODS

Thermal conductivity

In our investigation, the experimental setup described by Côté and Konrad (2005) for the measurement of thermal conductivity of crushed rock materials was applied. The tests were carried out at a mean temperature of about 5±1°C for the unfrozen and about -5±1°C for the frozen conditions. Analyzing the results, the errors connected to the position of the disk (±0,5 mm) and to the precision of the thermistors (±0,025°C) have to be considered. These factors cause a relative error on the thermal conductivity measurements less than ±5%. The imperfection of the contact between the quartz disk and the sample was discussed by Brich and Clark (1940). The contact resistance was expressed by them as an equivalent thickness. This case, the aspect mentioned can be neglected because of the small thickness of the sample.

Frost heave test

In the absence of a widely used standardized frost heave test method, the test arrangements were developed to meet the requirements of this research work as much as possible. Experimental setup is based on ASTM standard D5918 − 13, and modified for our laboratory conditions.

The data collected during the frost heave tests are:

- Frost heave (h) was measured during the test by a displacement sensor attached to the sample frame and connected with the NI Labview data acquisition system;
- Temperature sensors were set and connected with data loggers CR1000.

RESULTS AND DISCUSSIONS

ANALYSES OF GRAIN SIZE DISTRIBUTION, FINES AND WATER CONTENT

According the grain size distribution (Figure 1), all crushed rock materials PUKK 1-5 and moraine 2 are non-frost susceptible (T1), moraine 3 is low frost susceptible, moraine 1 and clay are medium frost susceptible (T3) (Handbook N200, 2014).

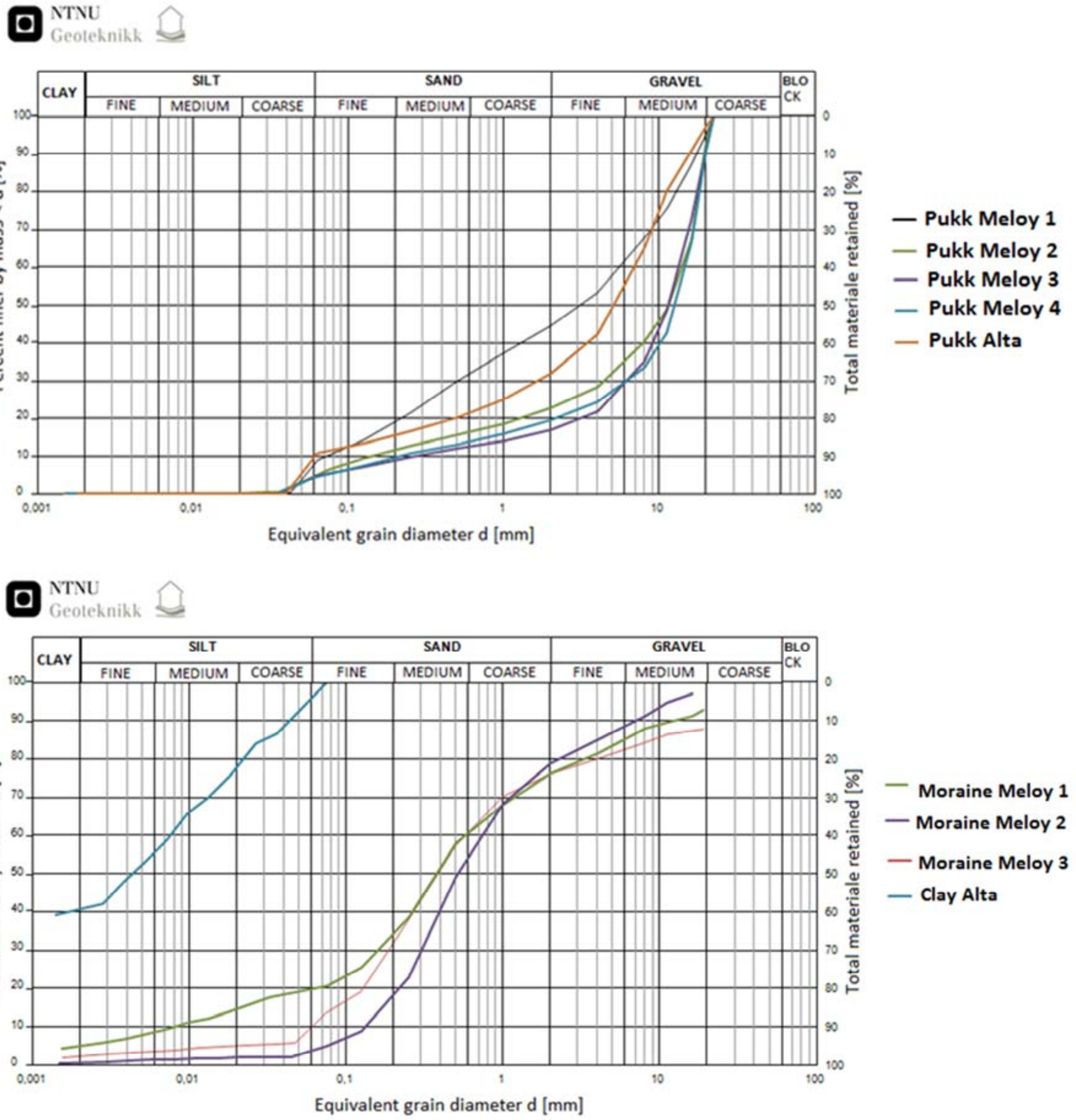

Figure 1: Grain size distribution of crushed rock materials (PUKK 1-5) and subgrade soils (moraines and clay) collected at the field

Table 2 presents the connection between fines and water content in crushed rock materials collected from the frost protection layer and from subgrade soils. In the sample with highest fines content, the water content was lowest. As mentioned in Introduction and Background, the idea behind increasing fines content in frost protection layer was increasing water content and thus, increasing latent heat of fusion during freezing process.

Table 2. Fines and water content in crushed rock materials collected from the frost protection layer and from subgrade soils

Place		Material analyzed			
		Frost protection layer		Sub-soils	
		Fine content, %	Water content, %	Fine content, %	Water content, %
Meløy	Pukk 1	9	9	23.5	17
	Pukk 2	6.5	-	4.9	6.2
	Pukk 3	4.9	5.9	5.6	10.4
	Pukk 4	4.6	-	-	-
Alta	Pukk 5	10.8	2.6	100	25.8

The results from the XRD analysis on bulk material < 20 µm are presented in Table 3. Quartz and feldspar are very strong and hard minerals, and not expected to accumulate in the fines. Mica however is a soft and more “lose” mineral, with weaker chemical bonds between the sheets of mica. Mica would therefore be expected to accumulate in the fines as it is more easily crushed than the other minerals.

Table 3. Mineralogical composition of the fine fraction of the material collected in frost protection layers

	1	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***
Pukk1 (Meløy)	19	31	15	16	4	5	8	-	2	-
Pukk2 (Meløy)	19	31	15	10	4	6	10	3	2	-
Pukk 3(Meløy)	17	22	15	11	6	5	7	14	3	-
Pukk 4 (Meløy)	20	26	15	12	6	5	9	5	2	-
Pukk 5 (Alta)	6	18	6	1	22	1	26	12	-	8
Moraine 1 (Meløy)	15	37	18	23	2	2	3	-	-	-
Moraine 2 (Meløy)	25	24	22	11	4	3	11	-	-	-
Moraine 3 (Meløy)	23	31	18	16		5	7			
Clay (Alta)	19	36	8	8	7	2	17		1	2

Materials: *1* – quartz, *2* – plagioclase, *3* – mica, *4* – feldspar, *5* – chlorite, *6* – pyroxene, *7* – hornblende, *8* – calcite, *9* – laumontite, *10* – epidote)

During field investigations, visible frost heave problems were detected along investigated area on Meløy road, but not on Alta where the pavement and subgrade soils were frozen in a depth of several meters. The reason of it can be found in the type of subgrade soil below the pavement. Clay had 100% of fines but moraine only 4.9 - 23.5%. Silt has higher hydro conductivity and water permeability than clay, thus, silt provides better conditions to let water move to freezing front and for segregation ice development.

Other reason can be found in mineralogical composition of the rocks and subgrade soils (Table 3). Crushed rocks and moraine from Meløy has higher mica content than crushed rock and clay from Alta. At the same time, crushed rock samples from Meløy contain laumonite, a hydrated calcium-aluminum silicate in zeolite group, and thus it can have good adsorption properties. Based on mineralogical analyses, it can be concluded that crushed rock material and subgrade soils from Miløy have larger potential for segregation ice development and frost heaving. However, additional laboratory investigations are still required.

FROST SUSCEPTIBILITY

Several parameters derived from the measurement results can be used to describe the frost susceptibility. All parameters are dependent on freezing time that is why reference parameters have to correspond to a certain time point (Nurmikolu, 2005).

Frost heave (h) is a distinct parameter derived from the displacement measurement. Frost heave produced after one and four days of freezing (h_{24h} and h_{96h}) were selected as parameters of the test results.

Figure 2 shows the relationships between displacement due to frost heave versus fine content (<0,063 mm) for open and closed systems in 24 and 96 hours. There is a close correlation between the fines content of the crushed rock aggregates and frost susceptibility in 24 hours. For frost heave in 96 hours, there is indirect correlation for open system which is connected with problems with water supply.

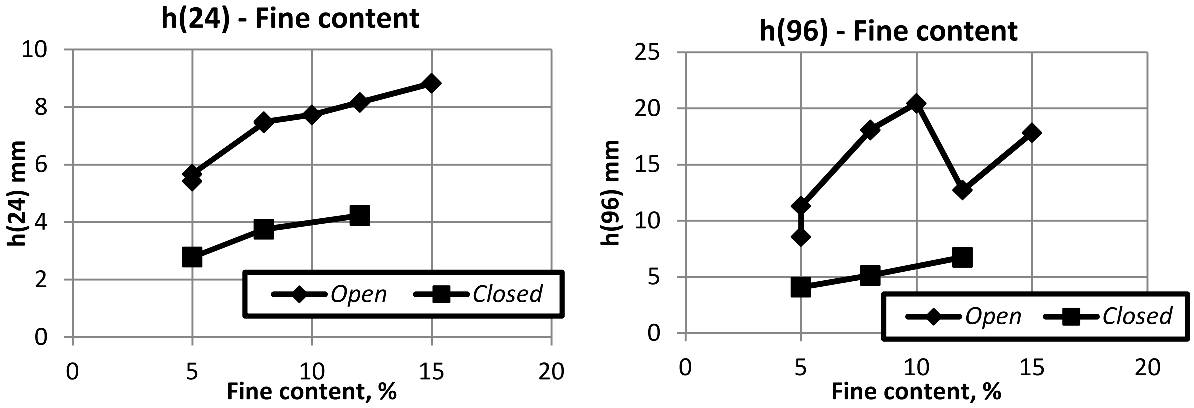

Figure 2: Curves of frost heave displacement vs. fines content for open and closed systems in 24 and 96 hours (Ilaria Miranda's data)

It can be seen that water supply greatly influences the frost heave ratio. The frost heave under open system is almost twice of that under a closed system. While the ratio between frost heaves for 5 and 15% of fine contents is about 1.5.

THERMAL CONDUCTIVITY

The bulk results of the thermal conductivity measurements are shown as a function of water content by weight in Figure 3 for unfrozen (λ_{th}), compacted crushed rock materials and as a function of ice content by weight for the frozen state (λ_f). Since water content and ice content by weight are equal, the symbol W and the term water content are used for both unfrozen and frozen states.

Lines combines data for: *1* – fine content 15% and dry density p_d = 2.67 kg/m^3, *2* – fine content 5% and dry density p_d = 2.4-2.7 kg/m^3. In dry state (W=0%) thermal conductivity is 1.5 W/mK for samples with 5% fine content and p_d = 2.4 kg/m^3 dry density and 2.0 W/mK for 15% fine content and p_d = 2.7 kg/m^3.

When sample has higher percentage of fine content, the dry density is also higher due to better compaction leading to higher thermal conductivity.

Comparison of data received in the lab and the data published for crushed rock materials shows that results for 5% fine content is within the range of data presented by Cote and Kondrad (2005), but for 15%, it is a little bit higher. Its reason might be that the density of solid particles for Vasfjellet materials is quite high (3.09 g/cm^3), and it means that materials more likely contain dense minerals with high thermal conductivity.

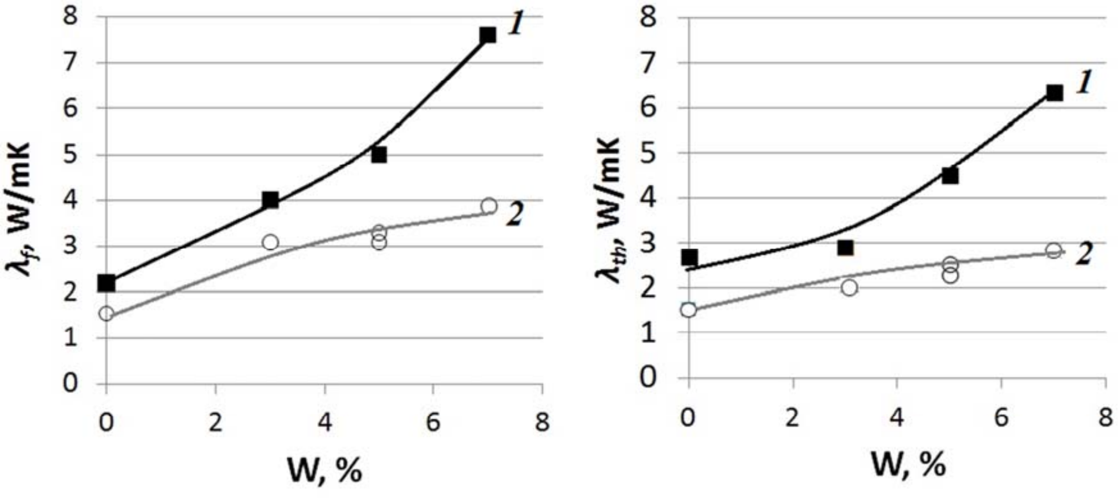

Figure 3: Thermal conductivity versus water content in frozen and unfrozen state for crushed rock material with: 1 – 15% fine content and dry density p_d = 2.67 kg/m^3, 2 – fine content 5% and dry density p_d = 2.4-2.7 kg/m^3 (Marta Marcheselli's data)

CONCLUSIONS

The paper presents results of field and laboratory tests of crushed rock material used in frost protection layer in Norway.

The main findings and conclusions from field investigations are:

1) The amount of fine content (<0.063 mm) in the frost protection layer fulfils the requirements of below 15%.
2) There is no direct connection between amount of fines and water content.
3) Frost heave of the surface is not connected directly to the amount of fines content, for example, in Alta the fines content in frost protection layer was higher than in Meløy, but there were no sign of frost heave on the surface.
4) There exists a connection between subgrade soil type and frost heaving. Under the pavement in Meløy, moraine deposits was found, while in Alta, it was clay with 100% of fine content. Clays have lower hydro conductivity than silts have due to the size of the pores.
5) The XRD analyses showed a slight difference between the mineralogical compositions of crushed rock materials but each of them fulfils the relevant requirements.

The main findings and conclusions from laboratory investigations on crushed rock material collected in Vasfjellet quarry are:

1) Frost heave in an open system (with access of water) is almost 2 times higher than in a closed system.
2) Frost heave in 96 hours 1.5-2.0 times higher than in 24 hours
3) Increasing the water content from 0 to 7%, thermal conductivity also increases from 1.5-2 to 4-7.5 W/mK in frozen and up to 3-6.2 W/mK in unfrozen states
4) The material investigated has quite high thermal conductivity due to the fact that particles are quite heavy (3.09 g/cm^3), and they contain dense minerals with higher thermal conductivity.

Furthermore, for future research, it might be very useful to make frost heave experiments with different aggregate types collected from different parts of Norway and using different amount of fines content in an open drainage system. It would help to learn more information on material behaviour in real situations since water can enter every civil engineering structure. More work is still needed to measure thermal conductivity of different crushed rock materials with different water contents and dry densities.

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