Investigation of crushed rock material used in the frost protection layer (Norway)

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GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

ABSTRACT
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. Knowledge of thermal conductivity of all granular layers is required in order to calculate of frost penetration depth. This paper presents the results of field and laboratory investigations of crushed rock materials used in the frost protection layer. Field observations did not show direct connection of frost heave of the surface with the amount of fines content in the granular layers. Laboratory experiments on thermal conductivity revealed that increasing the water content from 0 to 7% increases thermal conductivity of granular materials from 1.5-2 to 4-7.5 W/mK in frozen and up to 3-6.2 W/mK in unfrozen states.

RÉSUMÉ
Les pratiques norvégiennes pour la construction des routes ont considérablement été changées au cours des 40 dernières années principalement en raison du remplacement des graviers par de la pierre concassée à titre de granulats pour les couches de fondation. La connaissance de la conductivité thermique de l'ensemble des couches granulaires est nécessaire afin de calculer la profondeur de pénétration du gel. Cet article présente les résultats d'investigations réalisées sur le terrain et en laboratoire sur des matériaux de pierres concassées utilisées dans la couche de protection contre le gel. Les observations de terrain ne montrent pas de connexion directe entre le soulèvement par le gel de la surface et la quantité de sols fins dans les couches granulaires. Des expériences en laboratoire sur la conductivité thermique ont révélé qu'une augmentation de la teneur en eau de 0 à 7 % augmente la conductivité thermique des matériaux granulaires de 1,5 à 7,5 W / mK pour les sols gelés et de 3 à 6,2 W / mK pour les sols non gelés.

1 INTRODUCTION

In all roads built in cold regions, the use of frost-susceptible granular materials in pavement construction gives increase to the possibility of frost heave damage (Bilodeau et al., 2008). Available free moisture in pavement layers, especially in the upper part, can lead to formation of ice lenses and existence of frost heave in the pavement section due to water movement towards the freezing front (Guthrie and Hermansson 2003).

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). Even though the average winter temperature increases, frost heave damage rises 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 to pavement deterioration (Konrad & Lemieux 2005). Frost action in the subbase granular layers, especially in the frost protection layer, is often ignored, because these materials are usually not considered to be frost susceptible. This may not necessarily be the case because the presence of fines 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} and of degree of saturation S_r. It is shown that conduction is the dominant 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 principal 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 version of 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 well-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.
As it was 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 the coarse material used in the upper layers and frost protection layers. The grain-size distribution of pavement base-course materials typically ranges from 0 to 20 mm, for frost protection layer from 0 to 500 mm. 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 coarse materials should be different from that of the well-documented sands and fine grained soils (Cote and Kondrad 2005).
Nowadays the formula which is 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 some published data it is not necessarily 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.
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 particles <0.063 mm together with increasing of water content in the frost protection layer, will 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. 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.

2 MATERIALS AND METHODS

2.1 Study area

Norway is located in an area of seasonal freezing and thawing referred to as an area of wet freezing.
Materials for laboratory investigations of thermal conductivity and frost heave were collected from the quarry in Vassfjellet, located 30 km from Trondheim (Sør-Trondelag) (Figure 1). Field investigations were held on two county roads: Fv26 in Tverrelvadalen (Alta, Finnmark) and FV452 in Meløy (Bodo, Nordland) (Figure 2). The laboratory and field testing was done in parallel for two different purposes and was not directly connected.
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.

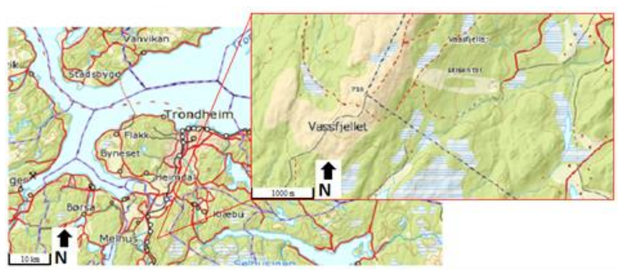

Figure 1. Geographical location of Vasfjellet (Sør-Trondelag) (Kartverket 2014)

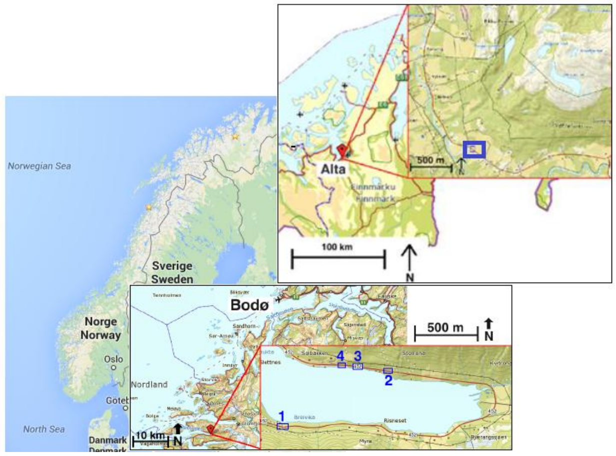

Figure 2. Geographical location of Meløy (Bodo, Nordland) and Tverrelvadalen (Alta, Finnmark) (Kartverket 2014)

2.2 Materials

2.2.1 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 (CR– crushed rock)

Place	Material analysed	
	Frost protection layer	Sub-soils
Meløy	CR 1	Moraine 1
	CR 2	Moraine 2
	CR 3	Moraine 3
	CR 4	-
Alta	CR Alta	Clay Alta

3.2.2 Samples used for laboratory investigations

Laboratory experiments on 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, subbase and subgrade layers in roads and railways in the area. The material is of average strength (in Norway) and represents a typical material for this purpose. It has been used for research intention for many years and the 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 the 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, we prepared 10 samples with different fines content (5% and 15%) and initial water content (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. The grain-size distribution is shown in Figure 3. Samples were prepared by compacting samples of desired grading using Standard Proctor compaction tests on aggregate mixtures with 5% and 15% fines.

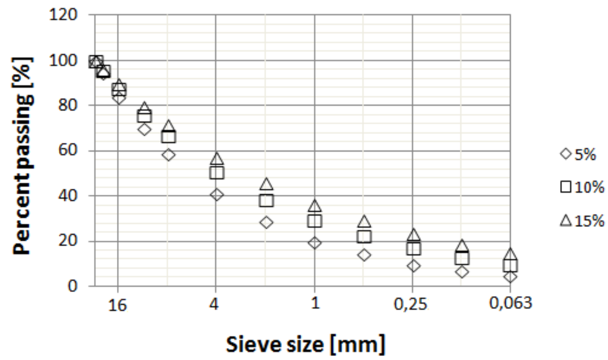

Figure 3. Grain size distribution of samples tested

2.3 Methods

2.3.1 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. This method comprises a thermal conductivity cell surrounded inside a freezing cabinet maintained at a relatively constant temperature of 4°C below the mean temperature into the sample. The sample and the mold are placed between two disks Heraeus HQQ310 with a diameter of 110 mm and a height of 10 mm. Heraeus HQQ310 is manufactured by fusion of natural quartz crystals in an electronically heated furnace. These discs have extremely low coefficient of thermal expansion, and low thermal conductivity variation: 1.37-1.38 W/mK (from -10 to +10^{o}C).
Each disk is instrumented with two thermistors inserted in the center. The heat exchanger's temperature is changed by a system of cryogenic machine through cooling liquid. A load was applied to keep the good contact between the heat exchangers, the quartz plates and the sample. The system was tightly surrounded by 50 mm polystyrene to minimize the radial heat losses. The heat flux, in the thermal conductivity cell, was measured through the quartz disk. The temperatures at top and bottom of each sample were recorded every 5 minutes through a data acquisition system and plotted as a function of time. When the temperature became constant with time, steady-state heat flow is established.
The tests were carried out at a mean temperature of about 5±1°C for the unfrozen conditions 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%. With regard to the imperfect contact between the quartz disk and the sample, it has been discussed by Brich and Clark (1940). They expressed the reported contact resistance as an equivalent thickness. In this paper, this aspect can be neglected because of the small thickness of the sample.

3 RESULTS AND DISCUSSIONS

3.1 Analyses of grain size distribution, fines and water content

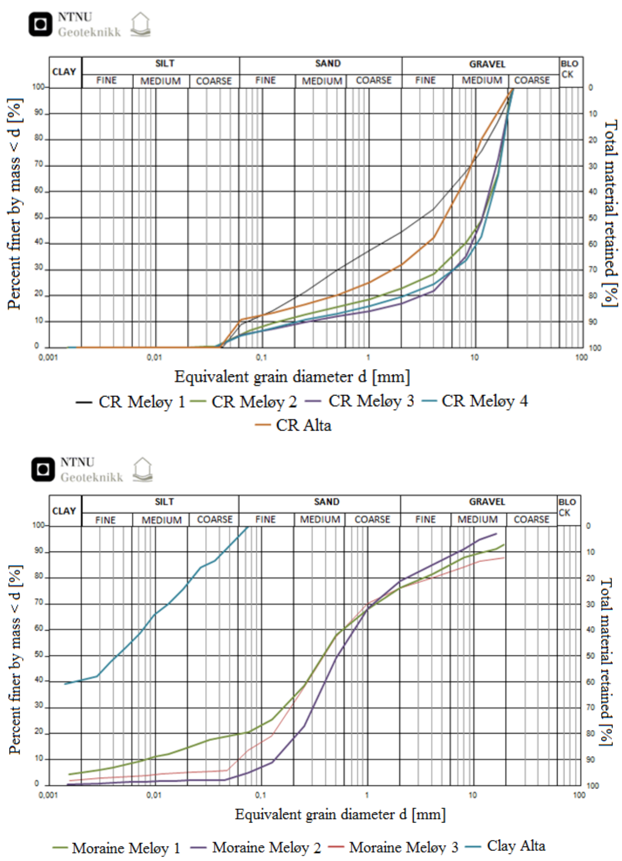

Figure 4. Grain size distribution of crushed rock materials (CR 1-5) and subgrade soils (moraines and clay) collected at the field

According the grain size distribution presented on Figure 4, all crushed rock materials CR 1-5 and moraine 2 are non-frost susceptible (class T1), moraine 3 is low frost susceptible, moraine 1 and clay are medium frost susceptible (class T3) (Handbook N200, 2014).

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, 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			
		Frosty protection layer		Sub-soils	
		Fine content (%)	Water content (%)	Fine content (%)	Water content (%)
	CR 1	9	9	23.5	17
Meløy	CR 2	6.5	-	4.9	6.2
	CR 3	4.9	5.9	5.6	10.4
	CR 4	4.6	-	-	-
Alta	CR 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.

Table 3. Mineralogical composition of the fine fraction of the material collected in frost protection layers. Numbers refers to: 1 – quartz, 2 – plagioclase, 3 – mica, 4 – feldspar, 5 – chlorite, 6 – pyroxene, 7 – hornblende, 8 – calcite, 9 – laumontite, 10 – epidote)

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

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.

During field investigations it was observed that visible frost heave problems were detected along investigated area on Meløy road, but not on Alta where the pavement and subgrade soils were frozen few meters down. The reason of it can be found in the type of subgrade soils 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 has 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 (8%), a hydrated calcium-aluminum silicate, which belongs to zeolite group, and thus can have high 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. But more laboratory investigations are still required.

3.2 Thermal conductivity

The results of the thermal conductivity measurements are shown as a function of water content by weight in Figure 6 for unfrozen (λ_{th}), compacted crushed rock materials and in Figure 7 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.

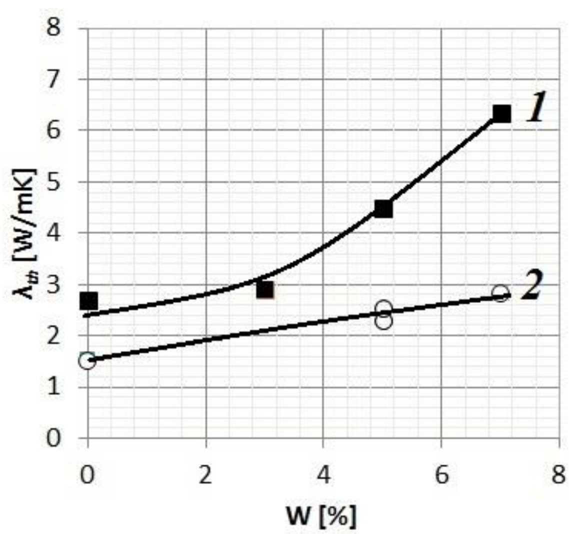

Figure 6. Thermal conductivity versus water content in unfrozen state (λ_{th}) for crushed rock material with: *1* – 15% fine content and dry density p_d = 2.67 kg/m^3, *2* – fine content 5% and dry density p_d = 2.4-2.7 kg/m^3

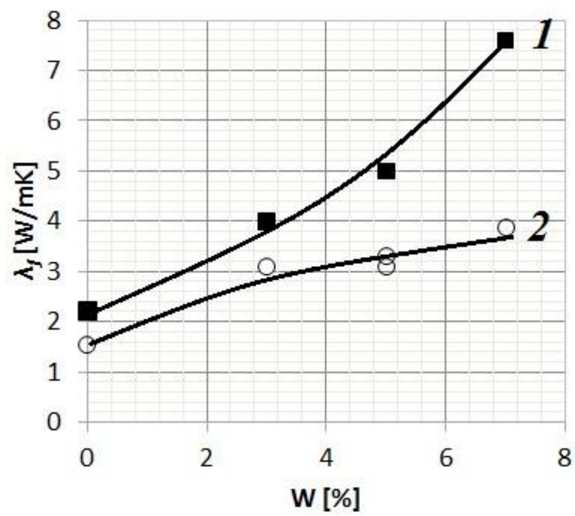

Figure 7. Thermal conductivity versus water content in frozen (λ_f) state for crushed rock material with: *1* – 15% fine content and dry density p_d = 2.67 kg/m^3, *2* – fine content 5% and dry density p_d = 2.4-2.7 kg/m^3

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

Comparison of data received in the lab and published data 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. The reason for it might be in the fact 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.

4 CONCLUSIONS

This paper presents results of field and laboratory investigations of crushed rock material used in the 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 – less than 15%.

2) There is no direct connection between amount of fines and water content for the sites investigated.

3) Frost heave of the surface is not connected directly with 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 trace of frost heave on the surface.

4) There can be connection between subgrade soil type and frost heaving. Under the pavement in Meløy, moraine deposits were found, while in Alta, it was clay with 100% of fine content. Clays have lower hydroconductivity than silt due to the size of the pores.

5) The XRD analyses showed slight difference between the mineralogical compositions of crushed rock materials.

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

1) 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.

2) 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 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.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the technical contribution of laboratory technicians NTNU/SINTEF: Bent Lervik, Jan Erick Molde, Lisbeth Johansen and Haris Brcic. Special thanks for Norwegian Public Road Administration (NPRA) for sponsoring field work. This research was partly supported by the Norwegian Research Council (NRC) under grant 246826/O70.

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