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Crushed aggregates for roads and their properties for frost protection
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With natural (fluvial, glaciofluvial) sand/gravel resources being rapidly depleted in many countries, the last decade has seen a significant trend towards using more alternative materials for construction purpose. In Norway the development and implementation of crushed aggregate technology has been the most important way to get around the problem with increased resource scarcity. Today Norway is one the European countries with the highest percentage of crushed/manufactured aggregates. A crushed product will reveal a different particle size distribution, a sharper, more angular particle shape, and not least – a significantly different mineral composition. The latter may often be characterised by more polymineral composition, and it will also much more depend on the local bedrock. When handled with care and knowledge, these differences can give the user a lot of new opportunities relating to materials design.
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 2014 The 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 $\frac{1}{2}$ 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.
Analysing 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.
For calculations of frost protection layer thickness the knowledge of thermal conductivity of the aggregate layers is required. Handbook for geotechnical investigations of the soils provides this data for natural gravel which is limited by 0.7 – 1.3 W/mK. But when it comes to the crushed rocks, it can be significantly increased due to the higher conductivity of minerals (especially if they contain high amount of quartz), as well as due to higher effective conductivity. In rock-fill materials, i.e. materials with large particles and low degree of saturation, convection and radiation are the predominant heat transfer mechanisms. Convection and radiation can increase the effective conductivity by factor 2-10. Lebeau and Konrad (2007) showed that convection heat transfer could lead to the formation of undesirable permafrost conditions in toe drains of embankment dams located in Northern Quebec, i.e. in areas where there are no naturally occurring permafrost soils.
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.
Specifications used by pavement engineers in most countries are solely based on grain size distribution and allowable fines content. The presence of fines in these layers can modify their frost susceptibility and cause severe degradation, especially with recent trends in climate change leading to more freeze-thaw cycle events during the winter season (Konrad & Lemieux, 2005). A higher content of fines due to sub-base wear will increase moisture in the structure and the risk of subsequent frost heave.
Guthrie and Hermansson (2003) showed by laboratory tests in a closed drainage system that retained water in a soil sample was sufficient to feed the frost heave. Even though the most severe frost heave in real pavements occurs when the material is in contact with free water (open drainage system) we wanted to study freezing behaviour in

aggregate materials having initial water contents (closed drainage system).
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. The objective of the present study was to investigate the influence of fines on the freezing characteristics of well-graded crushed aggregate in a closed drainage system. The reason for it is the understanding of the behaviour of the aggregate material when there is no access for any other water resources besides existing in the pavement (ex., from rain-fall). At the same time we did some estimation of thermal conductivity and frost penetration depth for all tested material using different aggregate density and water content.
Experiments were made by using greenstones (methamorphic basaltic lava), collected in Vassfjellet, area of Sor-Trondelag, Norway. 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.
The influence of fines on the frost susceptibility of crushed rock aggregates in a closed drainage system was established by laboratory frost heave tests. A total of 10 samples with fines contents of 5%, 10% and 15% respectively were subjected to freezing in constant temperature. Also we made calculations for thermal conductivity by using Johansen's (1975) model.
The study led to the following results:
1. Even for a closed system, without access of water, frost heave can occur just from redistributing water if the following conditions are met: a) Fines content exceeds 10%, b) Water content is around 7%
2. As to frost susceptibility classification, the crushed rock aggregates with 5% and 10% of fine material, fraction less than 0.063 mm, show negligible and/or low frost susceptibility. Those with 15% show medium frost susceptibility
3. Dry thermal conductivity for crushed rock samples, estimated by using Johansen's model, showed that an increase of dry density of 15% led to an increase of thermal conductivity of 75%.
4. Latent heat of fusion for all samples shows significant dependence on the water content, and less on the density
5. Highest calculated frost penetration depth was observed for dry samples. For other samples no big variation was found between 4% and 7% water content.