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Note

FROST – Frost Protection of Roads and Railways

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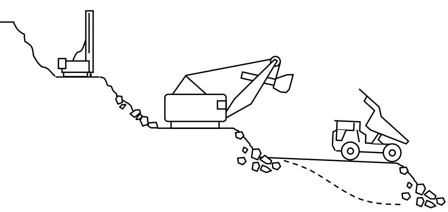
We are facing a changing climate and an increasing pressure on traditional aggregate resources. Road fundaments are being designed and built differently, with different materials – and not least; exposed differently than before. At the same time – research on frost exposure and protection has been absent in our country for decades. NTNU is now launching a major research project – "Frost protection of roads and railways", with the objective to up-date knowledge in this area and to propose new guidelines for design and materials selection.



1. INTRODUCTION

Presently, about 90% of the aggregate production in Europe comes from naturally occurring resources: quarries and pits, the rest is recycling materials. Due to the increased demand for sand and gravel for construction purposes, e.g. in road construction, the last decade has seen a significant trend towards the use of more crushed rock aggregates. This resource has been more and more preferred to sand and gravel thanks to the significant technological development of its process and use phase. 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 (Danielsen and Kuznetsova 2015). Today Norway is one of the European countries with the highest percentage of crushed aggregates.

Another challenge we are facing now is climate change, which leads to increasing winter temperatures and precipitation. And as a result, the areas, which before were enjoying stable winter conditions, now are facing frequent freeze-thaw cycles during winter months, which lead to severe frost heave problems. Frost action mainly develops in the frost-susceptible subgrade soils, leading to ice lens formation, surface heave, and to pavement deterioration (Konrad and 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 (Fillion, Côté and Konrad 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. However, most of the classifications (e.g. frost susceptibility, thermal conductivity) used in the current specifications are based on the research within the former project Frost i Jord (1970 - 1976). As mentioned before different materials were used in granular layers of the roads at that time (gravel instead of crushed rock). Complex approach is required to develop new design guidelines for pavements in cold climate conditions. There is a need to optimize the properties of crushed rock (gradation, water content, mineralogy) and to adapt existing design procedure to climate change. The research project “Frost protection of roads and railways” was initiated at NTNU with the objective to increase the understanding within this complex area and provide the scientific basis for new design guidelines.

2. CLIMATE CHANGE AND ROAD CONSTRUCTION

Infrastructures are traditionally designed to face with various stresses along their life, including extreme weather events as historically and currently experienced (Nemry and Demirel 2012). In Scandinavia, roads in regions that previously enjoyed stable winter conditions are now subject to several freeze-thaw cycles each winter. This will accelerate road deterioration and consequently increase maintenance costs. In general, cold climate countries have to cope with pavement deterioration effects, and in countries such as Norway this represents ~30% of the maintenance budget (PIARC Technical Committee 2010). The Norwegian Green Paper on Climate Change Adaptation, prepared for the government by a committee of experts (Ministry of the Environment 2010), offers detailed projections of future climate change in Norway, based on three scenarios. It shows that annual mean temperatures will increase by 2.3°C to 4.6°C by 2100, with the greatest increase during winter and the least during summer, and major regional differences – northern regions will warm the most, and western Norway the least. Annual precipitation could increase by 5% to 30%, with major seasonal and regional variations, and more frequent torrential rains and massive snowfalls. Transport infrastructure is one of the concerns, especially given existing inadequacies in maintenance and repairs. And the committee notes that because new infrastructure may have many decades of lifespan, climate considerations should be taken into account in planning for infrastructure and facilities.

The performance of the aggregates is generally evaluated depending on three main factors: the geological origin (mineral composition, texture, structure, degree of weathering), the aggregate processing (crushing, sieving, washing, storing) and the user technology for a specific area of use (e.g. road construction, asphalt binders). Nevertheless, climatic conditions should carefully be taken into account in application such as road construction. Large temperature gradients and high levels of humidity are known to significantly affect the performance of the material.

Higher precipitation, higher groundwater levels and more frequent freeze-thaw cycles affect the bearing capacity of roads (Grendstad 2012). Frozen layers in the sub-base of roads with poor drainage properties or made of frost susceptible materials prevent melt water or precipitation from draining away from the road structure when thaw sets in. In addition, melting ice lenses contributes to the excess water. This temporarily reduces the bearing capacity of the road. A higher content of fines due to sub-base wear will increase moisture in the structure and the risk of subsequent frost heave. Due to climate change, frost heave problems may become more frequent in areas that previously had stable winter conditions. In particular, surface layer problems during winter are more common because the period without freezing conditions has increased. Fluctuation around 0°C could give more frost heave depending on local conditions due to the fact that frost index for short term (2 or 5 years) – F2 or F5 – is decreasing, but for 100 years (F100) it could increase and lead to extreme cold winters occurring more frequently.

During the spring of 2014, the Norwegian Public Roads Administration introduced a new version of their pavement design guidelines (Statens Vegvesen 2014), including new specifications for the frost protection layer. When pavements are constructed over frost susceptible soils, the frost protection layer also becomes a very important part of the road system. According to new specifications; the size of large stones for this layer should be maximum 0.5 m along the longest edge (reduction from previous specifications) 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 moisture 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.

All existing requirements for frost susceptibility are based on the gradation only, and they were primarily developed for natural soils and gravel – not for crushed rocks.

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 characterized by more polymineral composition, and it will also much more depend on the local bedrock.

In order to reduce mass transport it is beneficial to use the local aggregates, but the geology of Norway is very diverse, which affects the quality of the aggregates. In road construction, there is a large attention on mechanical properties, but other properties are often ignored or given less focus. These are the properties, which include:

i. Heat exchange (convection, radiation, conduction)
ii. Thermal conductivity
iii. Frost susceptibility
iv. Segregation potential
v. Influence of mineralogy

3. FROST PROTECTION OF ROADS AND RAILWAYS

"Frost Protection of Roads and Railways" is an international research project, supported by the Norwegian Research Council (NRC), the Norwegian Public Roads Administration (NPRA) and Jernbaneverket (the Norwegian Railway Administration). The project started in 2015 and was designed to tie together knowledge from cold regions engineering, thermodynamics, geology and mineralogy, and bring together researchers from Norway and Canada. The primary objective of this project is to build new knowledge on behavior of crushed rock materials and subgrade soils, used in road and railway construction, under cold climate conditions. In addition, the design methods for frost protection layer of roads and railways in Norway and other cold region countries will be improved. Since the large research program “Frost i Jord” (Heiersted 1976) ended about 40 years ago, very little research has been done in Norway on frost related problems in granular layers of roads and railways.

Research is conducted based on three main aspects: laboratory investigations, field observations, and numerical analyses to simulate different climate conditions, thickness of structures and material combinations. The project includes two PhD projects, where one will focus mostly on frost susceptibility of subgrade soils and pavement materials, and the other one on the assessment of the frost protection layer. Both students will be co-supervised from NTNU and University of Laval and will spend some time at both universities to maximize the exchange of knowledge and use of experimental resources.

4. METHODOLOGY

Laboratory testing of coarse-grained materials is challenging because the equipment needs to be rather large to adequately simulate field conditions. This means that everything becomes both expensive and labor intensive. Laboratory investigations will include two main tasks. The first task will concentrate on investigation of heat transfer properties in rock materials, used in road construction. The second task will focus on frost susceptibility properties of subgrade soils and crushed rock material.

4.1 Frost susceptibility of construction materials

Laboratory frost heave tests are the most reliable method for assessment of frost susceptibility. The segregation potential of pavement subgrade materials is usually measured by freezing tests using step freezing conditions which simulate more closely the freezing conditions of pavement subgrade soils. Under these conditions, frost penetrates at the selected rate and tends to stabilize at a certain level in the soil.

It was found that the frost heave tests are very sensitive to the quality of the sample. The degree of compaction of the sample is of significant importance in order to comprehend the test. The estimation of frost heave criteria of materials can be performed and specified by using this test method together with variations of fine particles content.

4.2 Conduction, convection and radiation

The estimation of thermal conditions within the pavement system requires the use of basic thermal properties of soils and pavement materials. Measurement of heat transfer properties in rock materials is particularly challenging because of the need for large representative samples.

An experimental heat transfer cell with 1 m^3 sample size will be developed in order to measure the equivalent thermal conductivity (including conduction, convection and radiation heat transfer) of coarse crushed materials. The experimental configurations will aim at promoting heat convection within an experimental cell. Radiation heat transfer occurs in the form of electromagnetic waves travelling in air from a warm surface to a colder surface. Heat fluxes and thermal profiles will be measured in different parts of the specimen.

By using the heat transfer cell, we can measure either all three heat transfer mechanisms (conduction, radiation and convection), or only conduction and radiation, or just pure conduction. The experimental heat transfer cell should allow applying thermal gradients such that the different heat transfer mechanisms are stimulated:

- For measuring all three heat transfer mechanisms minimum temperature will be set at the top of the cell and maximum at the bottom.
- For inducing only conduction and radiation, the thermal gradient should be established in the way that minimum temperature is at the bottom and maximum is at the top.

For establishing pure conduction we should control d_{10} and keep maximum density of the material.

In both cases the important parameters and factors that should be considered and analyzed are:

- Influence of thermal gradient
- Influence of grain size distribution
- Influence of water content
- Influence of rock mineralogy

Obtained data will be compared with existing ones and used to validate or adapt existing models.

5. COMPLEX APPROACH FOR A HOLISTIC MODEL

The PhD topics conducted in the FROST project will be strongly connected with two other PhD topics, which are financed by the Norwegian Public Road Administration and dedicated to improve the use of local materials for road construction.

Figure 1 illustrates the four aspects to be covered by the research; frost, thermal properties, mechanical properties and geological characteristics of the materials. Combining these PhD studies we aim to create a holistic approach for a new understanding within this very complex area. An understanding, which in turn can lead to new and better design guidelines and selection criteria for road materials.

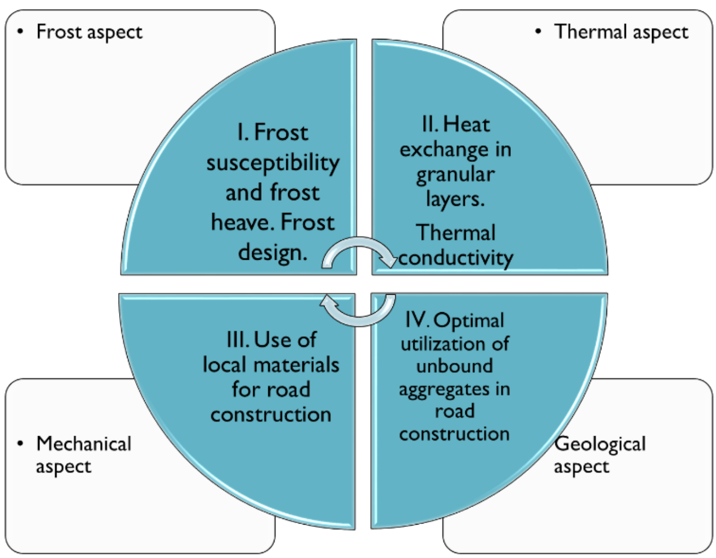


Figure 1. Four aspects and four PhD projects to study the use of crushed rock material in road construction.

Another area, which we have started to discuss with the industry, is how to exploit the smallest fractions of crushed stone production (0-4 mm). Since it is hard for producers to crush stones without producing pretty much of the finest materials, most quarries have a large surplus of fine-grained materials. Preliminary studies suggest that it would be beneficial to use a more dense gradation for better insulation capacity (to prevent possible convection). However, this will open a number of questions relating to how such materials will fulfill existing requirements.

Field and laboratory tests in cooperation with quarry companies are being discussed in order to establish relations between fines amount, fines gradation, mineral composition and the effect of these materials to insulation and convection. For the industry it would be of great benefit if part of a surplus problem this way could be turned into a valuable product.

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