ISSN 1893-1170 (online utgave)
ISSN 1893-1057 (trykt utgave)
Mineralproduksjon 8 (2018) B1-B7
MINERALPRODUKSJON
www.mineralproduksjon.no

Note

Heat Transfer Mechanisms of Crushed Rock Aggregates

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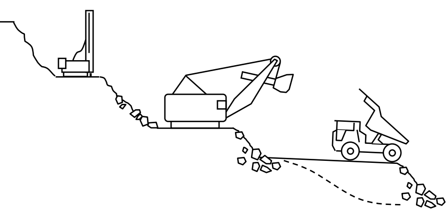
Crushed rock material is the principal constituent of road and railway structures in terms of volume and mass. The knowledge about material properties, both mechanical and thermal, can greatly influence the total necessary thickness of the road pavement and railway ballast and the total cost of construction. A research project have been initiated to gain more extensive knowledge about the main heat transfer mechanisms (conduction, convection and radiation) of crushed rock materials that greatly define the frost penetration depths of roads and railways.



1. BACKGROUND

During the last decades, road construction practice in Norway has undergone significant changes. During this time, deposits of natural mineral resources that were commonly used for road construction have now become unavailable. Regulations does not allow any more usage of such materials as gravel and sand for unbounded layers of roads and railways. These have now been substituted with crushed rock materials usually obtained from magmatic or metamorphic rocks, such as granite or gneiss.

The last large study regarding frost actions in the ground was conducted during the years 1970-76 under a project called Frost I Jord (Johansen et al., 1976). Still many requirements implemented in the road construction guidelines regarding the quality of materials are based on properties of gravel and sand that was research extensively during the Frost I Jord project. Yet, these two types of materials, gravel and crushed rock, have very different characteristics. Therefore more extensive knowledge is necessary for materials used today.

The winter of 2009/10 and 2010/11 were cold and gave some frost heave problems even for some newly built roads. This drew the public's attention with some articles in newspapers and gave a negative publicity to the national road authorities. As a following action, an expert group was given the task to find the causes of the problems and to propose changes in regulations regarding frost protection of roads to avoid future problems. The last reviewed and currently active version of N200 handbook was releast in 2014. A new revision is about to be finilazed by the end of 2017. The up to date version of N200 includes revision regarding material gradation used in frost protection layer. Although the revised guidelines have significant imporvement, few details still needs more scientific bacground and investigation.

Road and railway structures built in cold regions typically have thick unbound granular material layers. This is a design requirement due to combined effect of unstable subgrade conditions (mechanical) and deep frost penetrations (thermal). Consequently, these thick structures allows the use of coarser crushed rock materials, thus reducing the production costs and increasing mechanical stability. In Norway, it is typical to use aggregates with particle size up to 200 mm. In addition, the current active pavement design manual ''N200 – Vegbygging'' (Handbook N200, 2014) allows using particles with size up to 500 mm for frost protection layer.

Thermal conduction is the principal heat transfer within crushed rock material layers. However, for coarse material, with effective particle size (d_{10}) exceeding 10 mm, other heat transfer processes can give significant contribution or even become predominant heat transfer mechanisms. These include convection and radiation in particular. In seasonally freezing environment, this would give an adverse effect. The current specifications regarding the gradation of frost protection layer as well as subbase layer have a solid reason to be in this risk zone having excessive heat transfer properties.

Research project described in this paper is a part of a larger study on frost protection of roads and railways (Kuznetsova et al., 2017) with a focus on the main heat transfer mechanisms of crushed rock materials used in road and railway construction.

2. SCOPE

The primary focus of this research is on the heat transfer characteristics of unbound crushed rock materials used in frost protection layer with emphasis on their mineral composition. As a secondary focus, heat transfer in subbase and subballast materials is to be investigated. The research about heat transfer is limited only to the most important heat transfer modes, namely conduction, convection (free) and radiation.

This research also includes collaboration with two industry partners – producers of light weight aggregates (LWA) Leca® and Glasopor®. Materials form both companies is to be used in both full scale test site construction and large-scale laboratory experiments.

3. RESEARCH OBJECTIVES

The main objectives that are directly related to the project are as follows:

- acquire more consistent laboratory-tested data and develop knowledge for thermal conductivity of crushed rock materials used in road and railway construction in Norway;
- adapt or develop reliable model for calculation of thermal conductivity of crushed rock materials for full range of saturation;
- develop and improve knowledge for conditions, when convective and radiative heat transfer can yield a considerable contribution to heat extraction during cold periods;
- basis for improving the existing regulations for road and railway construction by defining more strict limits for material gradation to eliminate the risk of having excessive heat extraction during cold periods;
- improve the existing calculation methods of frost depth penetration by implementing the newly acquired knowledge regarding the heat transfer of crushed rock materials, paying enough respect to all possible heat transfer modes that have been covered within this study.

4. RESEARCH METHOD

The research has been initiated with a sophisticated literature review. This includes journal publications, conference papers, international book, etc. The current state of the art has been assessed and present knowledge gaps were determined. The literature review had a focus on three main topics: i) thermal conductivity of crushed rock materials and models for simple calculation; ii) convective and radiative heat transfer in coarse aggregates; iii) field test site construction with regards to investigation of thermal properties of materials.

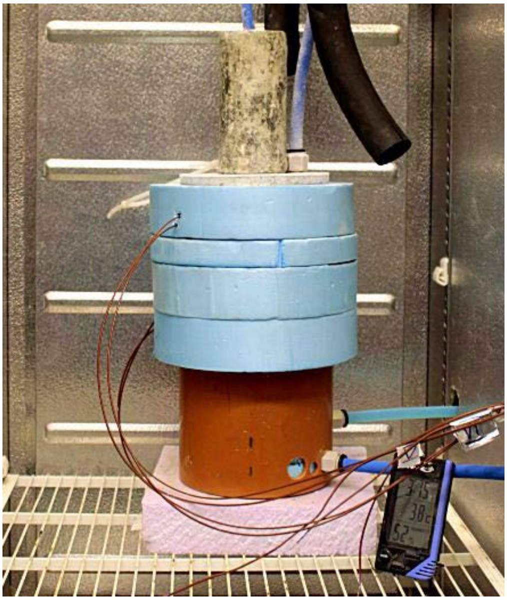


Figure 1. Small scale experiments.

Figure 2. Large scale experiment.

Figure 3. Full scale field test site.

Laboratory work consists of small and large-scale experiments. Small-scale laboratory experiments (Figure 1) implies testing various mineral materials for their thermal conductivity as a function of water content and dry density. The sample size is limited to 75 mm in height and 100 mm in diameter. This allows testing materials with particle size up to 16 mm. Materials with various mineralogy are tested at different degree of saturation in frozen and unfrozen state (Rieksts et al., 2017a). This can consequently give a good database on thermal conductivity of materials used in road construction.

Next step is development or adaptation of existing model (Côté et al., 2005a, 2005b) calculating thermal conductivity which is a simple tool to have a quick and good approximation of thermal conductivity without running laboratory tests based on mineral composition.

Large-scale laboratory test (Figure 2) is used to test thermal properties of crushed rock aggregates ranging between 0-200 mm. The setup allows testing material with a total volume of 1 m^3. By applying different temperature gradient, it is possible to perform the tests in two modes, imposing upward or downward heat flow (Rieksts et al., 2017b). By comparing heat flux from both modes, it is possible to assess the contribution of convection and radiation. Apart from testing coarse aggregates, large-scale experiments are used to assess the thermal properties of light weight aggregates (LWA). The total number of samples is very limited as these tests require considerable amount of time to prepare and run them.

During the fall of 2016 a full-scale field test site (Figure 3) has been constructed allowing to acquire temperature distribution throughout a year (Loranger et al., 2017). The test site includes six sections (6 m x 8 m) for roads and four sections for railways. Three road section have various gradations of material used for frost protection layer. This allows to assess the effect of particle distribution on the overall heat transfer rate. Three types of gradation are used - coarse open-graded, fine dense-graded and typical grading. These types of gradation are chosen in order to have the both possible extremities that the current regulations allows. The other three road sections have different layer of insulation material (Leca® or Glasopor®) while the frost protection layer have a fixed gradation. The four railway sections have a varying subballast layer constructed with two different gradations and mineralogy. All test sections are equipped with thermocouples placed in every layer of construction. In addition, test sections are equipped with moisture sensors and linear variable differential transformers (LVDT) to monitor frost heave actions.

The last part of the PhD study is dedicated to modelling heat transfer in crushed rock materials. This is done using data obtained from the large-scale laboratory experiments as well as data from the field test site. Upon successful modelling of the laboratory and field conditions, the model can allow varying the properties of materials that are used. Therefore, it will yield a tool for easy assessment of all possible heat transfer conditions within the pavement system.

5. EXPECTED RESULTS

It is expected that all the joint work during this PhD study will give results that could be directly used to improve the current regulations regarding the frost protection of roads and railways.

It is anticipated that small-scale laboratory results should give a reasonable database for thermal conductivity of crushed rock materials that are currently used in road construction. This knowledge leads to developing or adapting one of existing models for calculation of thermal conductivity and help to assess the data obtained from field test site. In addition, it should give a simple and fast tool for engineers to calculate the frost depth penetration.

At the same time, laboratory large-scale investigations gives a good insight into heat transfer mechanisms in coarse open-graded materials. This knowledge allows to set more strict limits regarding the use of such materials and minimizing the risk of having excessive heat extraction conditions during wintertime.

Modelling of laboratory small and large-scale experiments coupled with field test data gives a handy tool allowing to assessing heat extraction and frost depth penetration of various pavement structures.

6. PARTNERS AND COOPERATION

The current PhD study is a part of a larger research project called Frost Protection of Roads and Railways. The project is financed by The Research Council of Norway (under grant 246826/O70), Norwegian Public Roads Administration and Bane NOR (rail administration). In addition, the project involves collaboration with experts from SINTEF Byggforsk and Laval University, Canada. The PhD work is supervised by Professor Inge Hoff and Elena Kuznetsova from NTNU, and Professor Jean Côté from Laval University. The project has also established collaboration with two producers of light weight aggregates Leca® and Glasopor® and is also led by advisory board incorporating experts from public authorities and material producers. The current PhD study was initialized in 2015 and is planned to be finalized in 2018.

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