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Frost protection of roads

The use of crushed rock aggregates in a frost protection layer

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Preface

This master thesis was conducted at the Norwegian University of Science and Technology (NTNU) as part of a Msc in Civil and Environmental Engineering. It was carried out during spring 2020 within the master specialisation Highway Engineering at the institute of Bygg og Miljø (IBM). The thesis is related to the ongoing Frost protection of roads and railways (FROST) project at NTNU in collaboration with Norwegian Public Roads Administration (NPRA).

There are still remaining tests needed to be done, as Covid-19 prohibited further laboratory work after the 12^{th} of March. These are both preliminary tests, such as Methylene blue, XRD and Thermal Conductivity in addition to frost heave tests. Remaining frost heave tests are of samples from Lørenskog and Vassfjell treated with Terrasil and Zycobond.

This paper was authored by Siri Sisselsdotter Stolpestad with Professor Inge Hoff, PhD Elena Scibilia and PhD student Benoit Loranger as advisors. Potential future submissions of this paper will be with Siri Sisselsdotter Stolpestad, Professor Inge Hoff, PhD Elena Scibilia and PhD student Benoit Loranger as authors.

Gløshaugen, Trondheim, 2020-06-10

Siri S. Stolpestad

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Lastly, I would like to express my gratitude towards the NPRA for their financial support.

S.S.S

Contents

1 Introduction

Background

Frost heave is uplift of ground surface caused by formation of ice. A soil will freeze heterogeneously if surface temperatures are suddenly lowered below freezing point of water and an accumulation of ice bodies of almost pure ice will form, called ice lenses. These lenses are separated by soil and their sizes may become several centimetres thick and grow parallel to the surface [Palmer, 1967].

Conditions necessary for formation of ice lenses are; water supply, frost-susceptible soils and subfreezing temperatures [Konrad, 1999]. A frost-susceptible soil will swell during freezing because it is porous enough for capillary action to occur, but not too porous to break the capillary continuity. A soil element undergoing the freezing process can be divided into three zones, frozen zone, unfrozen and frozen fringe [Zubeck and Doré, 2009].

As temperatures fall and penetrates the ground interstitial water in soil matrix will freeze and expand. This volume expansion is proportional to 9% of pore volume and called in-situ freezing. If the rate of freezing in a saturated, fine-grained soil is slow, suction will occur at the frozen fringe. Water migrates from adjacent unfrozen zone toward the ice lens - created by in-situ freezing - by capillary action, facilitating further growth. Following the capillary theory, formation of ice lenses are related to the hydraulic conductivity of the unfrozen part, pore sizes and the temperature gradient [Zubeck and Doré, 2009, Lay, 2005, Zhang et al., 2019b].

The ice lens will grow in direction of least resistance parallel to heat flow [Kaplar, 1970]. Such growth of ice lenses is unlimited as long as the thermal gradient remains constant and sufficient water supply is maintained [Lay, 2005]. However, the water supply diminishes and eventually ceases due to exhaustion of unfrozen water in the region below the frozen fringe. When water supply becomes limited, latent heat of crystallisation becomes larger than the heat removed by the soil. This will cause the frost front to move downwards, until conditions needed to form ice lenses again are fulfilled [Konrad and Morgenstern, 1980].

Problems with frost actions in soils

Two detrimental effects from frost-action in soils are frost-heave and thaw-weakening. Although frozen soil has a higher mechanical strength than an unfrozen soil, thaw period result in reduced bearing capacity.

Thus differential frost heaving caused by variability of soil characteristics is a major factor affecting winter roughness of roads [Zubeck and Doré, 2009].

Illustrating, one may observe the following effects;

- **Movement in structures and cracking of road surface.**

  Dissimilar ice accumulation and variable gradation in the soil results in an irregular freezing plane and uneven near-surface topography. This causes movement of objects on or in the ground due to uneven strength and force distribution [Saetersdal, 1981, Rowley et al., 2015].

  Cracking of road surface causes poor and dangerous driving conditions in addition to substantial maintenance associated with resurfacing.

- **The loss of strength upon thawing.**

  The unbound layers, such as base layer, subbase and subgrade soil provide the road with sufficient bearing capacity, most effectively at fully saturated conditions [Elshaer et al., 2017]. Bearing capacity is a function of the apparent angle of internal friction and cohesion, and melting during thaw-cycle will affect both these factors.

  Soils with presence of segregational ice lenses will become over-saturated during the thaw-cycle. Increase of water molecules will displace soil particles because of water's lower specific weight. This, in turn, reduces contact forces between individual soil grains, called internal soil cohesion, and subsequently weakens the internal bearing strength [Geotechnical, 2019].

  Because of this, frost protection layers are constructed on top of frost-susceptible soils to prevent segregational ice lenses to form in unbound layers.

Early studies

Until 1914, it was believed all frost heaving was caused by in-situ freezing. In 1930, Taber published a paper concerning the mechanism of frost heaving, which further investigated how different systems, closed or open, affected frost heaving [Taber, 1930].

- Freezing in an open system may be classified as "freezing of water in-situ and of additional water migrating to the freezing front "[Stahl and Sego, 1995]. The mechanism behind this theory was further described by Konrad and Morganstern in 1980 [Konrad and Morgenstern, 1980].
- Freezing in a closed system is "freezing of in-situ water without the presence of additional water". Such absence may be due to impermeable boundary conditions or reduced permeability [Stahl and Sego, 1995].

Observations made by Taber showed that observed heaving was too great only to be explained by in-situ freezing. Excessive heaving results when water is pulled through the soil to build up horizontal layers of segregated ice [Taber, 1930]. The observed heave was mulltiple times larger than heave caused by volume change of in-situ freezing [Konrad and Morgenstern, 1980].

Penner observed that real-life fields operated as an open system with a high water table and as a closed system with a low water table [Penner et al., 1972]. Further, Morgenstern and Morgeau performed frost heave tests in 1979 on both open and closed system on completely frozen Devon silt sample [Mageau and Morgenstern, 1980]. The objective was to observe change in moisture content of soils subjected to different thermal gradients. Results showed that in an open system, frozen soil draws substantial amounts of water up from the unfrozen zone increasing water content on the cold side of the ice lens. These results confirmed that temperature-induced migration of water occurs.

In 1980, Gilpin developed a model for frost heave prediction based on soil properties such as thermal conductivity and exogenous boundary conditions such as overburden pressure and surface temperatures [Gilpin, 1980]. However, the disadvantage with this model - the assumption of phase-change happening just at the freezing front - was highlighted by Nixon for further development [Nixon, 1991].

Further studies and the Segregation Potential Model

Konrad and Morgenstern performed the research on prediction of frost heave in the laboratory during transient freezing [Konrad and Morgenstern, 1982]. Their theory predicts that total frost heave is made of two components, the first one is in-situ heave, caused by freezing of pore water in-situ and the second component is segregational heave caused by water arriving at the freezing front [Nixon, 1982]. This theory introduces the concept of segregation potential (SP-model) and is the key method used to predict frost heave reliable enough to comply engineering needs [Stahl and Sego, 1995].

The first component, in-situ heave accounts for volume expansion of water present in the soil matrix of 9%. Knowledge regarding porosity and void volume of the soil is important for calculation of this component.

The second component: water arriving at the freezing front may be found by equation (1):

$$V_o = SP_o \nabla T \tag{1}$$

Where V_o is the water intake flux (mm/d), ∇T is the temperature gradient $^oC/hs$ and the segregation potential, SP_o is the constant of the linear relationship between V_o and ∇T, $(mm^2/^oC)$. From laboratory experiments, SP_o can be found and represents the ratio of the water intake rate and the temperature gradient across the frozen fringe and unfrozen soil.

According to Konrad and Morgenstern, the water intake at the formation of the final ice lens will be proportional to the temperature gradient across the frozen fringe during permanent thermal regime [Konrad and Morgenstern, 1981, 1982]. The frozen fringe is the zone between the growing ice lens and the frost front [Miller, 1972]. In other words, the segregation potential is the rate of water flowing to the freezing front proportional to the temperature gradient at the level of ice segregation [Konrad and Morgenstern, 1982]. Of the two components presented in the theory by Konrad and Morgenstern, segregational heave is the major source of heaving as long as the steady-state is achieved [Lay, 2005]

After several years of applying the engineering model proposed by Konrad and Morgenstern, certain limitations became clear due to incomplete recognition of water movement in a freezing soil [Nixon, 1991].

Some limitations were:

1. The SP-model does not account for expulsion of in-situ water during freezing.
2. The real-field rate of heaving does not appear to be as sensitive to suction at the advancing frost front, as in the laboratory.
3. The SP-model assumed that suction at the frost front and overburden pressures affected the heave rate independently. [Nixon, 1991]

Alternative models

Nixon adapted the discrete ice lens theory as a frost heaving model by continuing the analytical technique of Gilpin which was described before in 1980. His more comprehensive model predicts the location of ice lenses within the freezing fringe using inputs such as hydraulic conductivity and temperatures, contradicting Gilpin's model which assumed that ice lenses occurred only at the frost front [Nixon, 1991]. In comparison to the SP-model, the discrete ice lens theory also predicts the effect in heave rate with a change in overburden pressure [Nixon, 1991].

Since the discrete ice lens theory described by Nixon, further models have been developed. The Clayperyron equation and creep foundation was used by Razaqpur and Wang to form a new model predicting water migration, equation (2) [Razaqpur and Wang, 1996]:

$$I_w = -\frac{1}{gd_f}\left(\frac{P_{is}}{\rho_i} + L_h ln\frac{T_s}{T_f}\right) \tag{2}$$

Where I_w is the hydraulic gradient in the frozen fringe $J = kgm^2/s^2$, ρ_i is the density of ice, (kg/m^3), P_{is} is the ice pressure (Pa) at the coldest side of the frozen fringe. d_f is the thickness of the ice fringe (m) and g is the gravitational acceleration. T_s is the segregation freezing temperature (K), T_f is the freezing temperature (K) at atmospheric pressure and L_h is the latent heat of fusion (J/Kg) [Razaqpur and Wang, 1996].

In 2006, a paper was published to calculate frost heave ratio as a function of overburden pressure and freezing rate using Takashi's equation [Kanie et al., 2006]. This equation is known to give an estimation of satisfactory accuracy for engineering purposes and shown below, (3):

$$\zeta = \zeta_o + \frac{\sigma_o}{\sigma}\left(1 + \sqrt{\frac{U_o}{U}}\right) \tag{3}$$

In this equation ζ is frost heave ratio, the increase in volume to the initial volume, σ is constraining stress in the freezing direction $(Pa)$and U is freezing rate (m/s). ζ_o,σ_o and U_o are constants for the specific soil material [Zheng et al., 2015].

The porosity rate model published by Michalowski in 2006 develops a material function which determines the average increase in volume of the soil due to growth of ice lenses [Michalowski and Zhu, 2006]. The model seeks to visualise that porosity changes as ice formation develops, i.e porosity increases as ice lenses form and is shown in equation (4):

$$\dot{\eta} = \dot{\eta}_m\left(\frac{T - T_o}{T_m}\right)^2 e^{1-\left(\frac{T-T_o}{T_m}\right)^2} (1 - e^{\alpha\frac{\delta T}{\delta x_l}} e^{-\frac{\bar{\sigma}_{kk}}{(1-\eta)\zeta}} \tag{4}$$

Where $\dot{\eta}$ and $\dot{\eta}_m$ are the porosity rate and maximum porosity rate and T_m is the temperature at which the maximum porosity rate occurs (^oC). α and ζ take account of the temperature gradient and the stress state, and $\bar{\sigma}_{kk}$ is the first invariant of the average Cauchy stress tensor (Pa). This function applies only to soil freezing. The porosity increase is then related to the expansion of the soil due to heave through a function analogous to a strain rate tensor [Henry et al., 2005].

The models shown above are derived experimentally. Thus, the coefficients are specifically determined, such as correlations between heave and specific soil parameters and other conditional factors. When these models are applied to various soils and different conditions, large variations in accuracy may occur. Saareleinen suggested in 1992 a more detailed model to compensate for the weaknesses of previous models, named the SSR model [Saarelainen, 1992].

This model is based on heat balance at the freezing front used for estimation of frost heave and frost penetration, shown below in equation (5):

$$q = q_+ + q_f + q_s \tag{5}$$

This equation states that heat flow through the frozen layer q is equal to the sum of heat flow to the freezing front from unfrozen ground, q_+, heat flow generated by the freezing in-situ pore water, q_f and heat flow generated by ice segregation, q_s. All components are in W/mm^2 [Saarelainen, 1992].

Saarelainen then substitutes each of the heat flow components into equation (5) and solving for increase in frost penetration, Δz_o, the equation can be written as follows (6):

$$\Delta z_o = \left(T_f - T_p\right) dt \frac{\left(1 - SP\frac{L_w}{\lambda_{fz}}\right)}{L_{fz}R_{fz}} - \frac{S\nabla T_+ \Lambda_t dt}{L_{fz}} \tag{6}$$

where:

- R_{fz} is the thermal resistance of the frozen layers ($\frac{m^2K}{W}$).
- z_i is the thickness of the frozen layer (m).
- λ_{fi} is the thermal conductivity of the frozen layer ($\frac{W}{Km}$), i and λ_{tz} is the thermal conductivity of the freezing front ($\frac{W}{Km}$).
- SP is the segregational potential ($\frac{m^2}{Kh}$).
- L_w is the latent heat of fusion of water while L_{fz} is the latent heat of fusion of the freezing front ($\frac{Wh}{m^3}$).
- S is a coefficient describing the intensity of the ground heat,
- ∇T is the temperature gradient ($\frac{K}{m}$).

Increase in frost penetration, Δz_o, is then calculated by the computer program "SSR", hence the name of the model.

This detailed freezing soil model however, requires a considerable number of soil parameters to be identified, some of which are difficult to determine in laboratory experiments. Thus, the SP-model, equation (1), appears to be an appropriate simplification for ice segregation and a useful link between laboratory tests and real-life frost heaving.

Present day challenges and adaptations

In Norway, tradition is to use natural aggregates like sand and gravel for construction purposes. Due to shortage of natural aggregates, construction of frost-resistant pavement with natural aggregates is becoming increasingly expensive. With resource scarcity, Norway is now using crushed rock aggregates in the granular layers [Kuznetsova et al., 2016]. A crushed product will contain different particle size distribution and different mineral composition compared to natural aggregates. The difficulty with using crushed rock aggregates lies with controlling percentage of fines content [Kuznetsova et al., 2016]. It has proven difficult for producers to crush stones without producing a large amount of the finest materials. Therefore, many quarries have large amounts of fine-grained materials, 0-4 mm, which cannot be used due to restrictions given in the Handbook N200 [Bordal, 2018].

In Finland, the same problem of scarcity of natural rock aggregates has encouraged studies of alternative use of quarry fines. The possibility of exploiting quarry fines as an additive rather than as a major construction material has been studied [Zhang et al., 2019b]. Studies indicate these may be utilised to improve physical, mechanical and swelling properties of soil subgrade [Gautam et al., 2018]. Zhang et. al performed a further study in 2019 to determine if the material could be qualified as a pavement base or subbase. Durability was evaluated in terms of frost-susceptibility to verify whether the material was suitable for application in cold regions.

A series of frost heave tests were performed on compacted, saturated samples with different surface load conditions [Zhang et al., 2019b]. The frost-susceptibility indicators derived from these experiments were frost heave, frost penetration depth and frost heave coefficient titulated the segregation potential. The segregation potential values obtained indicated a class of low frost-susceptibility. However, even though the values indicated low frost-susceptibility for the material, it is still susceptible to frost actions and not ideal to use as pavement construction material in cold regions. The study recommended to use stabilisation techniques, such as waterproofers, before utilising quarry fines in pavement constructions [Saarelainen, 1992].

Frost-susceptibility of soils

Several criteria exist for classification of frost-susceptibility [Saetersdal, 1981]. Chamberlain revealed in 1981 that there is no commonly accepted criterion for a qualitative assessment of frost-susceptibility [Chamberlain, 1981]. Konrad and Chamberlain identified three levels of sophistication in estimating frost-susceptibility [Konrad, 1999, Chamberlain, 1981].

1. The first level is based on the percentage of soil fines ≤ 0.075 mm. This level does not provide a clear separation between the frost and the non-frost-susceptible soils.

2. The second level is based on grain-size distribution and tests regarding soil-water interaction, such as hydraulic conductivity and capillary rise.

3. The third level is empirical, based on previous studies and observations in the field or laboratory. In the laboratory tests, freezing of samples are either performed with fixed temperature boundary conditions or with varying temperatures to maintain a constant frost penetration curve.

In Norway a sub-grade-frost-susceptibility criterion is used when constructing roads resistant to frost heave. Soils are divided into four groups, from T1 to T4. For soils which classify as T1 and T2 no further frost protection is needed, while soils classified as T3 and T4 require a frost protection layer. The base and subbase layer should be non-frost-susceptible. Whereas the frost protection layer may be slightly frost-susceptible [Loranger et al., 2017]. This classification is given in handbook N200 and is shown in Table 5:

Table 1: Frost-susceptibility criterion classification, [Bordal, 2018]

Frost-susceptibility classification of soils			
Frost-susceptibility group	Material < 22,4m		
	Mass %		
	$< 2\mu m$	$< 20\mu m$	$< 200\mu m$
Non frost-susceptible	T1	< 3	-
Sparsely frost-susceptible	T2	3-12	-
Moderately frost-susceptible	T3 (1)	> 12	>50
Highly frost-susceptible	T4 < 40	>12	>50

(1) Also soil with more than 40% of $< 2\mu m$ are considered as moderately frost susceptible (T3).

Modification of frost-susceptible soils

A frost-susceptible soil can be made non-frost-susceptible by washing out fines. However, this is a time consuming, cumbersome and costly operation if the soil contains more than a small percentage of fines [Lambe, 1956]. Therefore, the use of additives is a more promising alternative.

Lambe (1956), Brandt (1972) and Webster (1989) all studied the possibility of utilising additives to treat one or more of the three conditions necessary to produce frost heave . As Konrad stated in his paper in 1999, "eliminating one of these conditions generally suffices to significantly reduce the intensity of frost action."[Konrad, 1999]

In 1956, the Massachusetts Institute of Technology performed a freezing test by the Arctic Construction and Frost Effects Laboratory (ACFEL) [Lambe, 1956]. The experiment lasted for three years, where fifteen soils and forty additives were tested to see how frost heave and bearing capacity was affected during thaw-cycle. Four different groups of additives were tested and their effects further described by Brandt [Brandt, 1972].

1. Cement agents adhere soil grains to larger ones to decrease frost-susceptibility.
2. The freezing-point depressants decrease the freezing point of the matrix water.
3. Dispersants are surface active agents which destroy soil structure separating the particles.
4. Waterproofing chemicals diminish water absorption and consequently interfere with water supply to the frozen fringe.

Lambe (1956) tested numerous additives and rated dispersants and inorganic cationic aggregates as the most promising. This because of easy applications, low cost and effectiveness at moderately low concentrations. The waterproofing agents were somewhat less promising even though they were excellent for frost heave modifications, because off need for extensive drying once soils had been treated [Lambe, 1956]. These disadvantages are no longer obstructive as recently discovered waterproofing chemicals limit water absorption without need to cure beforehand. [Brandt, 1972, Padmavathi et al., 2019].

In 1989 a report on the effect of additives on frost heave of a subbase gravel was published [Webster and West, 1989]. Research was carried out to see whether the addition of cement, lime and bentonite would affect frost heave and strength of the material and presented in the report. Frost heave tests were carried out following the British procedure developed by the Transport and Road Research Laboratory (TRRL) testing different percentages of materials [Sutherland and Gaskin, 1973].

Proportions of each additive chosen varied from 2% to 10% in addition to three specimens of gravel without any additive tested in parallel. The bentonite specimens were subjected to the normal TRRL frost heave test immediately after preparation. For the specimens with lime and cement, the chemical reaction between the additive and material were expected to influence the frost heave. Because of this, samples were cured for 24 hours before testing, to let effects of chemical reactions develop before initiating the TRRL test.

The results were promising for each type of additive; 2 % of cement or bentonite reduced frost heave to almost zero, and the same proportion of hydrated lime reduced frost heave by half [Webster and West, 1989].

Present days

The frost heave test performed as part of this study at the Norwegian University of Science and Technology (NTNU) with the Multi-Ring Frost cell studied two different additives; Lignosulfanate and a combination of two polymers, Terrasil and Zycobond [Barbieri et al., 2020]. The objective was to investigate whether the use of these additives would diminish frost-susceptibility of the crushed rock aggregates.

Earlier, requirements given in Handbook N200 for frost-susceptibility were based only on particle size gradation [Kuznetsova et al., 2016]. However, there are no restrictions regarding mineralogy and use of soils with a wide range of particle distribution is accepted as a frost protection layer.

As we are headed into an era with focus on recycling and circular economy, a reduction in frost-susceptibility of the 0-4 mm fraction may lead to use of most, if not all, fractions of crushed rock aggregates. For the road construction industry it would be of great benefit if a surplus problem in this manner could be turned into a valuable product. Such use would make the industry more sustainable by reduction of the mass transport and increased use of local materials [Kuznetsova et al., 2016].

Use of additives reduce water intake and frost heaving. If more tests can be performed to investigate the effect of additives on mechanical properties, we are one step closer to render the 0-4 mm fraction into a usable product. But there are still remaining tasks to be done before drawing final conclusions.

1.1 Objectives

The main goal of this study is to investigate how to alter the usage of the 0-4 mm fraction to improve frost-susceptibility properties and thus its suitability in a frost protection layer.

1. Increase the understanding of behaviour of 0-4 mm mineral fraction in a frost protection layer.

2. Investigate frost-susceptibility of selected quarry materials using The Multi-Ring Frost cell.

3. Test whether use of additives can improve frost-susceptibility of 0-4 mm mineral fraction of crushed rock aggregates.

2 Materials and Methods

2.1 Crushed rock aggregates

To gain knowledge about use of 0-4mm fraction in a frost protection layer, it is necessary to have information related to rock types produced at different quarries to understand the material and its characteristics correctly, such as particle size distribution.

As rock type varies geographically it would be ideal to test aggregates from the whole country. This to achieve a result which may be applied wherever and with whichever type of local quarry material used in future road construction. However, it was unfeasible to include all quarries. Therefore, the quarries were selected based on the most common type of rock in Norway. When studying different quarries, it was observed that the three most common rock types produced were gneiss aggregate, granitic gneiss and gabbro in descending order of abundance. Therefore, to achieve a representative overview the quarries selected delivered the above-mentioned rock types. In addition to these, a quarry producing high quality aggregate - dacite - at high volume was also included for reference purposes.

The quarries chosen are shown below in the Table 2:

Table 2: Quarries supplying crushed rock aggregates.

Quarry	**Region**	**County**	**Rock type**	**Grain Density** $\frac{gr}{cm^3}$
Lørenskog	Viken	Lørenskog	Gneiss	2.88
Vassfjell	Trøndelag	Trondheim	Gabbro	3.02
Sarpsborg	Viken	Sarpsborg	Granite	2.75
Tau	Rogaland	Strand	Dacite	2.65

2.2 Additives

As previously mentioned, additives like cement, lime and bitumen have been tested and proven useful as stabilisation agents. Two non-traditional additives have also shown promising laboratory results by increasing the resilient modulus [Barbieri et al., 2020]. These are Dustex (lignosulfonate) and a mixture of Terrasil and Zycobond. Further description of these are found below.

Both additives coat and bond material particles closer together enabling their use in the pavement unbound layers. These layers (base and subbase) provide the construction with sufficient bearing capacity and have strict restrictions regarding particle size distribution and water content. Because of previously promising results regarding mechanical strength, these two agents have been included to investigate their effect on frost-susceptibility of crushed rock aggregates.

Dustex

This agent is a lignin-based, non-toxic, water-soluble and non-corrosive natural polymer, consisting of both hydrophilic and hydrophobic groups. It is a byproduct from the production of wood pulp and thus determined as "renewable" [Barbieri et al., 2020]. The lignin is mixed 50% with water, the mixture is called Dustex.

This lignin-based chemical leads to increased strength and durability of soils. In addition to this, it does not harm the environment. Previous studies performed by Noorzad and Ta'negonbadi (2017) showed that use of Dustex reduced the coefficient of soil erosion and significantly increased the critical shear stress [Ta'negonbadi and Noorzad, 2017].

Research suggested that a better improvement in percentage swelling in clay soils increased with increasing curing time.

Terrasil and Zycobond

Terrasil and Zycobond are both manufactured by Zydex Industries. The combination of the two inherits great bonding properties, rendering treated soils nearly 98% water resistant and with near permanent erosion control [Padmavathi et al., 2019].

Terrasil is an organosilane, man-made inorganic, water-soluble and a heat resistant product used as a reactive soil modifier. When the agent is mixed with rock particles, a chemical reaction between the agent and the rock surface forms a siloxane linkage between the two components. This linkage converts the soil particles from hydrophilic polar to hydrophilic non-polar particles, which create a strong water repellent nano layer. This modification is near permanent [Barbieri et al., 2020, Padmavathi et al., 2019].

The agent modifies the rock surfaces and improves mechanical properties. A challenge with the 0-4 mm soil aggregates is water susceptibility, where the use of Terrasil will halt capillary rise and ensuing problems linked to this mechanism. Further, Terrasil allows the treated material to "breathe" as flow of air through its structure is permitted, preventing thermal insulation [Padmavathi et al., 2019].

Zycobond is an acrylloc co-polymer which dissolves in the soil binding particles together, providing water resistance in the unpaved areas [Mulla and Guptha, 2019]. Mixed with Terrasil, it further stabilises and strengthens the soil, imparting resistance to fatigue and erosion [Padmavathi et al., 2019].

2.3 The Multi Ring Frost Cell

The study was performed with The Multi-Ring Frost Cell at NTNU, which was designed and built at University of Laval, Quebec, Canada. An illustration of the apparatus is shown in Figure 1 below:

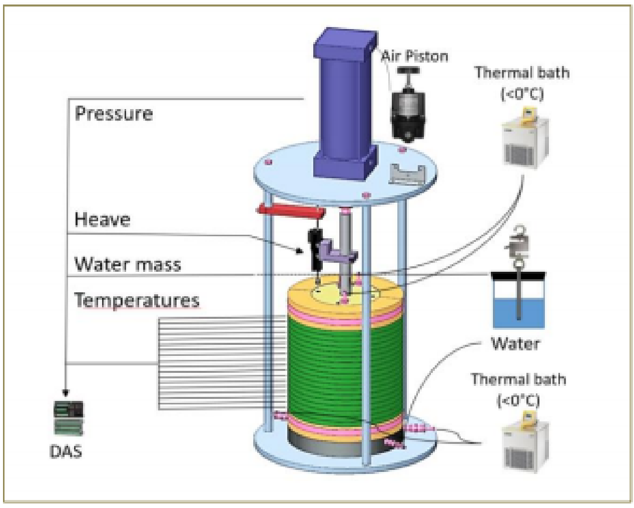


Figure 1: NTNU Multi-ring frost heave cell, (Loranger et al, 2019)

The apparatus consists of 18 rings made of polyethylene placed on top of each other with rubber spacers between each ring. The height including spacers is 225 mm with a 150 mm diameter. Located inside each ring are 18 thermistors measuring temperatures with an accuracy of 0.1^oC. Each thermistor is secured with epoxy glue.

Each sample is prepared using a steel split-mold and compacted to reach an estimated 95-95 % of the maximum strength to simulate in-field conditions. A rubber membrane is placed around the unmolded sample, which is placed on a bottom plate. A thermostat is located inside both top - and base - plate to regulate temperature exposure. Finally, the rings are stacked vertically one by one before securing the sample by inserting a split ring on top and bottom to seal the membrane.

The cell was first placed in a fridge at 2^oC to limit the temperature variation before initiating the freezing process. This was the conditioning phase. During this phase, an open water tank was placed beside and connected to the apparatus to allow free flow of water into the sample. The purpose of this water access was to saturate the sample as far as possible and later identify water intake by cryosuction during the freezing phase. Further, the termostats at base and top plate were set to 2^oC with low hydraulic gradients to limit the temperature variation and prevent fines migration in the sample as advised by Zubeck and Doré [Zubeck and Doré, 2009].

After 24 hours - the conditioning phase completed - the temperature at the top plate lowered to -4^oC and the water bottle was closed. This to ensure that hydraulic pressure does not push water inside the sample. The only way water may enter is by cryosuction, the pressure difference caused by thermal gradient. Water flux is then measured as volume change in the Mariotte burette (the water tank). To measure frost heave a potentiometer is placed on top of the sample, measuring heave with ±0.01 mm precision.

The samples were submitted to freezing for 96 hours with data recorded every 5 minutes. The data recorded were;

1. The 18 different temperatures for each of the rings (^oC)

2. The displacement at the potentiometer at the top plate (mm)
3. The water mass entering the sample from the Mariotte Burette (gr)

From this set of data the frost penetration depth, frost heave and segregation potential for each of the aggregates and additives were studied.

3 Results and discussion

To evaluate frost-susceptibility of soils certain ground properties has to be known in order to obtain reliable modelling results. Prior to the laboratory freezing test, geotechnical properties such as mineralogy, density and water content were determined.

3.1 Preliminary preparations and tests

Sieving

The particles were hand sieved using sieve sizes from <0,065 mm to 8 mm. The sieving was thoroughly performed with multidirectional rotation, to assure all particles which could would pass through the sieve. The percentage of each fraction was calculated by dividing the fraction of particles restrained by the sieve by total weight of initial sample. Cumulative curves were constructed based on the weight percent and number percent for each sample [Fernlund, 1998].

Hydrometer Test

Frost-susceptibility of granular materials are influenced by particle size distribution of the fines fraction. To find this distribution, a hydrometer test was performed. This method, a hydrometer test, is based on the phenomenon that particles of varying size settle in a liquid at different rates [Zhang et al., 2019b]. This is elucidated by Strokes' law which establishes the terminal velocities of small spherical particles in a fluid medium. The test was undertaken in accordance with the R210 Norwegian Laboratory Handbook [NPRA, 2014].

Pycnometer

A pycnometer is used to determine the density of soil particles. The principle behind a pycnometer is the difference in mass of the instrument with and without the soil particles, utilised to calculate the density. In detail, density is found by dividing the mass of soil by volume [Vlierberghe et al., 2014]. The specific gravity found is in turn used to calculate degree of saturation and void ratio. The degree of saturation is further important when performing a frost heave test, since water present in the voids will attribute to frost heave.

Falling cone

The falling cones test measures the liquid limit, Atterberg limit and the plastic limit of a soil specimen [Tanaka et al., 2012]. A cone is allowed to pierce into a soil specimen under its own weight. The cone moves at steady speed while registering the required force, the penetration depth and - additionally - estimate the undrained shear strength of the material. Undrained shear strength is a parameter to the bearing capacity of subsoil which in turn is important for pavement design purposes.

3.2 Planned Tests

Methylene blue

Methylene blue is commonly used to detect clay content and ion adsorption capacity of a material (surface area per unit of mass) [Hegyesi et al., 2017]. Methylene blue has the chemical formula $C_{16}H_{18}N_3SCI$ and behaves like a cationic dye when mixed with water. When mixed with a soil solution, chloride ions change place with cations in clay minerals of the material. Methylene blue is a useful indicator of a soils swell potential, as this is highly related to the amount of clay particles [Yukselen and Kaya, 2008].

Half of these tests were not performed but should be in the future for further knowledge of material properties.

Thermal Conductivity

Knowledge of frost penetration depth is important in road design to avoid freezing of frost-susceptible soils. Thermal conductivity is the most important soil characteristic that define heat transfer in road structures.

The thermal conductivites will be measured at NTNU following the Laval University Procedure. Due to resource scarcity of natural rock aggregates, Norway is using an increasing amount of crushed rock aggregates. These aggregates show varying thermal properties compared to natural materials, thus there is a need for evaluation of thermal conductivity [Rieksts et al., 2017].

These tests were not performed but should be in the future for further knowledge of material properties.

X-Ray Diffraction

Different aggregates have different chemical compositions and microstructures, which will give different X-ray diffractions (XRD). XRD Diffraction - is a non-destructive test method used to analyze the structure of crystalline materials. Such diffraction is an effective method to analyse the crystal structure and microstructure of rock-based minerals. By testing each of the aggregates from the different quarries, it is possible deduct the composition of each of these [Sanjurjo Sánchez et al., 2008]. This is useful because it may influence frost-susceptibility. The analysis is used to identify crystalline phases present in a material and thereby reveal information of chemical composition.

These tests were not performed but should be in the future for further knowledge of material properties.

Table of preliminary results

Table 3: Results of routine tests performed at the Norwegian University of Science and Technology.

Quarry	Sieve	Hydrometer	Pycnometer	Falling cone	Methylene Blue
	PSD-coarse, %	PSD-fine, %	$\rho_s(\frac{kg}{m^3})$	$w_L(\%)$	SSA $\frac{m^2}{g}$
Lørenskog	80,9	**19,1**	2881	31,0	6,40
Vassfjell	87,3	12,7	3020	27,3	6,60
Sarpsborg	92,4	7,6	2755	28,7	-
Tau	79,4	**20,6**	2651	32,2	

By studying the preliminary results, materials from Tau and Lørenskog are expected to be more frost-susceptible than alternatives due to their high percentage of fines both in the vicinity of 20%.

Gradation curve

In the gradation curve, Figure 2 a separation between the coarse and fine particles were made at 0,075 mm. This because percentage of fines indicates frost-susceptibility of the material. The fine fraction being ≤ 0,075 mm and coarse being > 0,075 mm.

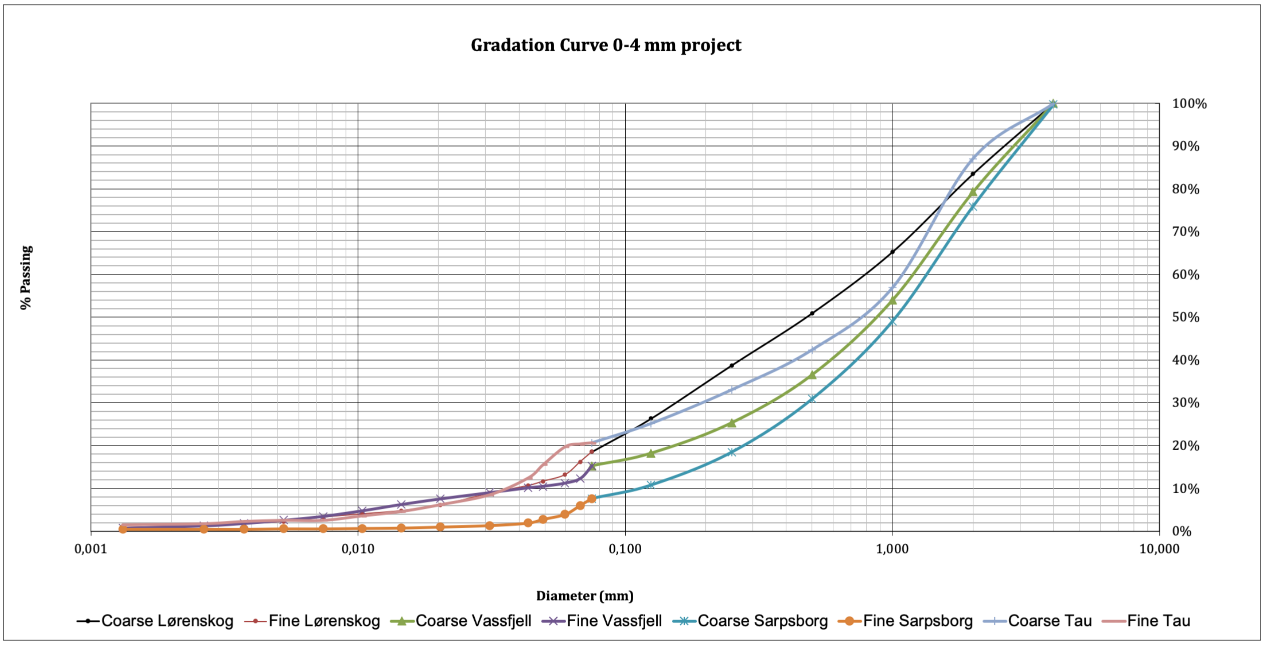


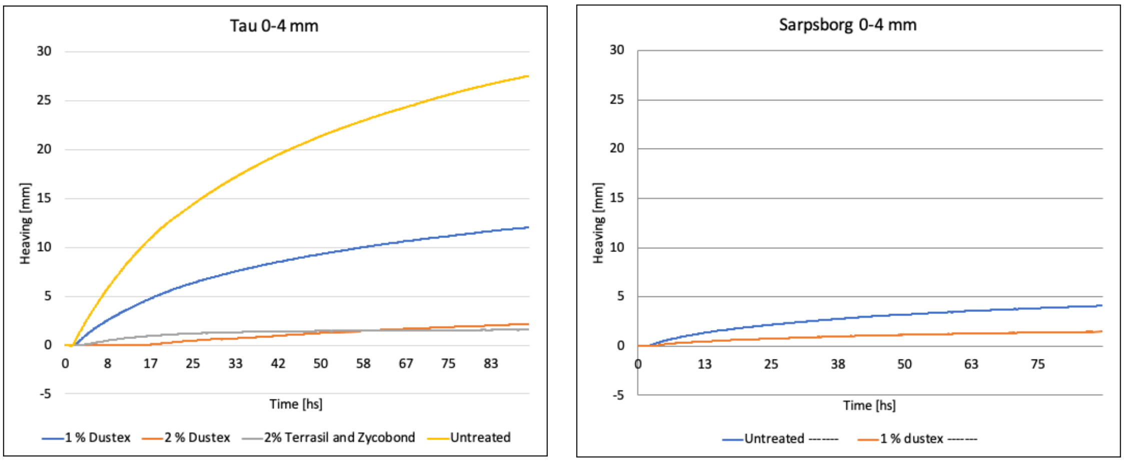
Figure 2: Gradation Curve of all crushed rock material

3.3 Results from Multi-Ring Frost cell

Frost heaving

Several tests were performed to investigate the frost-susceptibility of the crushed rock aggregates, both with and without additive.

Untreated samples were tested first, to establish a base understanding of frost-susceptibility of the material without use of stabilisation techniques. An illustration of frost heave registered for Tau and Sarpsborg are shown in Figure 3:



(a) Tau

(b) Sarpsborg

Figure 3: Frost heave vs. time

The complete frost heave results are shown further on under discussion.

Sarpsborg quarry displayed the least initial heave, due to its low percentage of fines (7,6%), compared to Tau (20,6%), significantly so. Because of low initial heave and subsequent low figures for 1% Dustex, no further tests were performed on this material.

The gradation curve, Figure 2 above, showed that materials from Tau and Lørenskog have a large amount of fines. Therefore, more frost heave tests with additives were performed on these.

Frost heave was registered with the Multi-Ring Frost Cell for different aggregates and additives. The results followed the expected hypothesis, that the heaving was significantly reduced for samples containing additives. This can be seen in Figure 3 above and summarised in the Table 4 below:

Table 4: Frost heave results (mm)

Quarries	Untreated	Dustex		Terrasil and Zycobond	
		1%	2%	1%	2%
Lørenskog	19.52	6.23	3.04	-	-
Vassfjell	24.83		2.58	-	-
Sarpsborg	3.97	2.46	*	*	*
Tau	28.32	12.68	5.67	*	1.58

(*) Not tested because previous results were sufficient enough.

(-) Remaining tests because of Covid-19.

Calculation of Segregational Potential to find frost-susceptibility

Whether use of additives can improve frost-susceptibility of crushed rock aggregates is a key objective to this study. In order to define such frost-susceptibility we have chosen to use the segregation potential method (SP-method) as an intermediate step.

The SP-model developed by Konrad and Morganstern uses heave rate at steady state to investigate the build up of ice lenses [Konrad and Morgenstern, 1981]. This method measures only the capability of a soil to form such ice lenses. A high SP_o value indicates high capability, hence high frost-susceptibility and a low value indicates a low frost-susceptible soil.

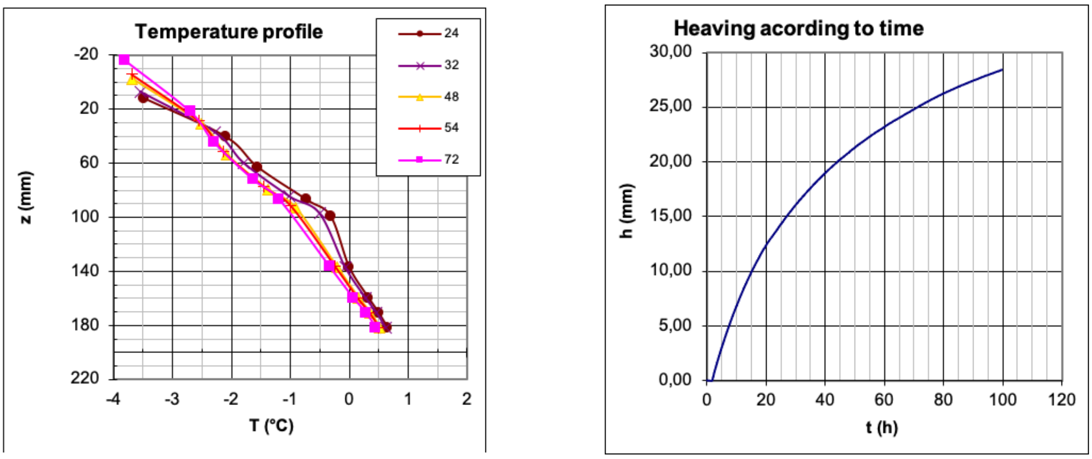
For this investigation, we have used the following equation (7) to obtain an SP_o value:

$$SP_o = \frac{dh/dt}{\nabla T_{eff}} \tag{7}$$

The specific components of the formula need to be determined from graphical illustration of the freezing process and are interpreted below.

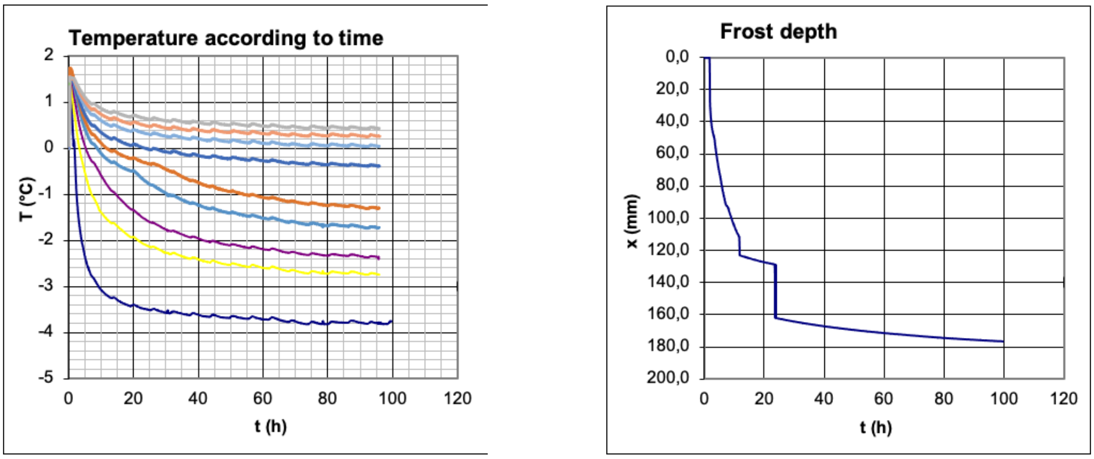
Data from all samples have been recorded and SP_o values may be calculated accordingly. As an example of this calculation, Figure 4 and subsequent calculations below show how these components may be obtained. The graphs illustrated are from the "Tau untreated" sample.

It can be observed that frost penetration stabilises after approximately 50 hours. Following this, temperature gradient and heave ratio are found once the permanent thermal regime is reached, at 50 hours and used to calculate the segregational potential, given in equation (7).



(a) Temperature profile at depth, different times

(b) Heave vs.time



(c) Temperature of thermistors vs.time

(d) Frost penetration depth vs. time

Figure 4: Graphs for calculation of Segregation Potential value

First, from Figure 4a we approximate the following components:

$$dz = -140mm$$

$$dT = -1,0^{o}C$$

$$\nabla T_{eff} = 0,025\frac{^{o}C}{mm}$$

Secondly, heave ratio is determined from Figure 4b with the tangent slope at 50 hours:

$$dh = -8mm$$

$$dt = -36h$$

$$\frac{dh}{dt} = 0,222\frac{mm}{h}$$

Subsequently, the obtained values are inserted into equation (7) and we achieve SP_o value at approximately 250 $mm^2/^oCd$

$$SP = \frac{dh/dt}{\nabla T_{eff}}$$

$$= 195,7\frac{mm^2}{^oCd}$$

This value is neither absolute nor precise, but comparing various samples with different percentages of additives, a clear trend in reduction of SP_o can be observed. This matches a similar decline in the previous heave observations, shown in Table 4.

Classification of the frost-susceptibility by use of SP_o value is shown below in Table 5.

Frost-susceptibility	SP $mm^2/^oCd$
Negligeable	< 12
Low	12 to 35
Moderate	35 to 75
High	75 to 200
Very high	> 200

Table 5: Frost-susceptibility Segregation Potential, [Doré et al., 2006]

Figure 5 below indicate how use of additives significantly affected and reduced the value of SP_o.

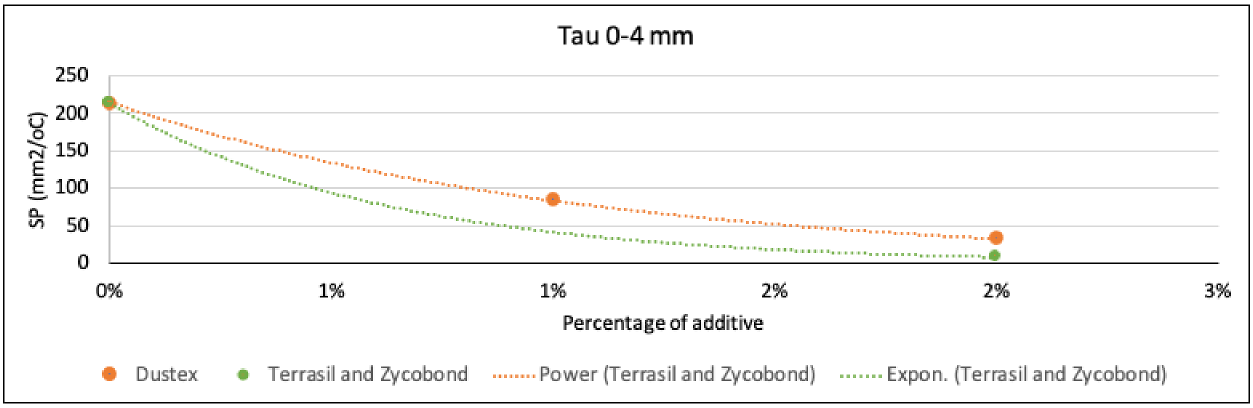


Figure 5: Segregation Potential value for Tau

We may also add that the effect of additives appears to be marginally decreasing, i.e, initial effect is larger than consecutive increases.

It may be noted that in addition to identify frost-susceptibility, the SP_o value may also be used to calculate segregational heave. This, in turn gives us the ability to estimate pore space heave (in-situ), as total heave is the sum of segregational and in-situ heave.

Segregation heave can be calculated once the SP_o value has been found.

$$h_{sp} = 1.09 * \Sigma(V_o t) \tag{8}$$

Where V_o is the water intake flux, $\frac{mm}{d}$ and t is the time of the permanent thermal regime, given in days [Konrad, 1999]. For Tau untreated this was reached after 50 hours, or 1,88 days. The 1,09 takes into account the volume increase of frozen water.

$$h_{sp} = 1.09 * (195,7 * 0,025) * 1,88 = 10mm \tag{9}$$

Thus the in-situ heave is obtained by:

$$h_{in-situ} = h_{total} - h_{sp} = 28,32 - 10 = 18,3mm \tag{10}$$

The results of the results were calculated using the same scheme and are presented in Table 6 and in the Appendix.

Further investigation on the effect of additives on in-situ heave is outside the scope of this work and will not be delved on further but looks promising for further investigations.

To summarise, Table 6 below shows the values of SP_o found and estimated heave and share of h_{sp}.

Table 6: Segregation Potential results

Quarries	**Additives**	SP_o $mm^2/^oCd$	h_{sp} mm	$h_{in-situ}$ mm	Frost-susceptibility
Lørenskog	Untreated	163,3	8,4	11,2	High
	1 % Dustex	36,1	2,4	3,9	Moderate
	2 % Dustex	12,5	0,6	2,4	Low
Vassfjell	Untreated	195,7	9	10,5	High
	1 % Dustex	11,4	0,9	1,7	Negligeable
Sarpsborg	Untreated	34,7	1,5	2,5	Low
	1 % Dustex	15	0,6	1,8	Low
Tau	Untreated	195,7	10	18,3	High
	1 % Dustex	77,7	4,7	8,0	Moderate
	2 % Dustex	20,5	1,4	4,3	Low
	2 % Terrasil and Zycobond	7,4	0,3	1,3	Negligeable

SP_o are segregation potential values.

h_{sp} is segregational heave.

$h_{in-situ}$ is in-situ heave.

3.4 Discussion

From the literature study the field of frost-heave investigation have gone from the assumption that all heave was caused by in-situ freezing to the belief that frost heave is made up two components, in-situ heave and segregational heave.

Segregational heave is what caused the most damage during thaw cycle, because the melting of these ice lenses leaves the soil over-saturated and reduces its bearing capacity. Since SP_o values indicates frost-susceptibility, the SP-model seemed to be the most viable way to evaluate and predict frost-susceptibility and thus, frost heave.

The gradation curve provided by both the hydrometer and sieving methods confirmed the necessity of performing frost-susceptibility tests. This because a substantial fraction of fines - in this case 19,1% for Lørenskog, 12,7% for Vassjfell 7,6% for Sarpsborg and 20,6% for Tau - renders the material inappropriate to apply in base or subbase layers.

The materials provided by the selected quarries were classified as frost-susceptible and therefore not suitable for use in a frost protection layers untreated. This is shown in Table 6 where untreated samples from Lørenskog, Vassfjell and Tau were all classified as high frost-susceptible materials, with SP_o values > 150 $mm^2/^oCd$

From preliminary results two quarries, Lørenskog and Tau, were identified and expected to be more frost-susceptible than the rest, with a percentage of fines around 20 %.

Difference of density varied from 2651 kg/m^3 for Tau to 3020 kg/m^3 for Vassfjell. Bulk density is an indicator of soil porosity, indicating a high porosity for samples from Tau and a low porosity for samples from

Vassfjell.

This initial assumption was partially affirmed by the Multi-Ring frost test results, reinforcing the theory of a strong relation between frost-susceptibility and percentage of fines. The SP_o value of untreated samples from Lørenskog and Tau were close to 200 $mm^2/^oCd$ and heave registered for untreated samples were respectively $19,52mm$ and $28,32mm$.

However, untreated samples from Vassfjell contradicted the assumption from preliminary tests. Untreated samples proved to be highly frost-susceptible, with an SP_o of 195,7 $mm^2/^oCd$ and initial heave of $24,83mm$ even though percentage of fines was 13%, remarkably lower than samples from aforementioned quarries .

Results from the Multi-Ring tests indicated that use of additives significantly affected and reduced segregational heave attributed by cryosuction process.

Calculated SP_o values for samples from Tau was reduced from 195,7 $mm^2/^oCd$ to 20,5 $mm^2/^oCd$ by use of 2% Dustex and to 7,4 $mm^2/^oCd$ by use of 2% Terrasil and Zycobond. This is a reduction in frost-susceptibility of respectively 85% and 96%, favouring use of additives.

Observations showed that the effect of additives decreased with increased percentage. As for Lørenskog, frost-susceptibility went from **Moderate** with use of 1% Dustex and a SP_o value of 36,5 $mm^2/^oCd$ to a **Low** classification and a SP_o value of 12,5 $mm^2/^oCd$. Table 5 implies that a low frost-susceptibility classification are SP_o values between 12 and 35 $mm^2/^oCd$. This may influence the cost benefit part of this study and effects the practical use of stabilisation techniques.

One may ponder on the observation that in-situ heave as fraction of total heave in all samples increased, although these results are by no means accurate or conclusive. If this is indeed a phenomenon it would further strengthen the case that additives are mostly effective at reducing segregational heave, both in actual heave and fraction of total heave but have effect on in-situ as well. The fraction of segregational heave (as part of total heave) varied from 40 %, untreated, to 20% with use of additives.

Lay stated that segregational heave was the major source of heaving [Lay, 2005]. This was contradicted by our results as in-situ heave seems to be larger. However, it is true that segregational heave is the major component damaging infrastructures and bearing capacity, as the amount of supplementary water drawn into the frozen fringe in the SP-process exceeds the available void volume in the soil matrix.

Finally, it should be noted that additives definitely seem to have a positive effect on in-situ heave as well as segregational heave. Either way, both effects are desirable and strengthen the case of additive usage.

3.5 Limitations and uncertainties

Calculation of penetration depth is shown and calculated as a discrete value when, in fact the temperature change is analogue. This provides at uncertainty for every point where the temperature changes. For simplification purposes, frost penetration depth was calculated to be the point at which the thermostat changed to a temperature below zero degrees Celsius. The output would be the depth of the thermostat. Nevertheless, this is not a correct representation of how frost penetrates continuously through the sample.

However, this implicit mistake in the first calculation may be minimised if all calculations are done consistent with the same approximation.

Other uncertainties are "data outliers". These may be due to human errors or instability in the equipment. When observing the graphs, the objective is to understand the accentuated underlying trend, not the point-details.

Determination of components necessary for SP_o calculation is highly uncertain. Temperature gradient is approximated as gradient of the tangent line in the intersection of the frozen and unfrozen part of the graph. A steeper tangent line will result in a higher SP_o value and subsequently a higher safety factor by overestimation of segregational heave.

3.6 Restrictions

A problem noticed whilst calculating the segregation heave was the difficulty to ensure beforehand whether the samples had been fully saturated or not. If the sample is not fully saturated at the start of the freeze cycle, then water intake at the beginning dominated by tendency to saturate the unfrozen part of the soil.

To differentiate between water intake for saturation and for segregation heave, data from the conditioning phase were studied. The data showed maximum water content sucked into the sample with the water table above sample to allow free flow of water. At the end of this phase, some water might have been drained out.

If the sample turned out not to be fully saturated when starting the freezing, the initial water would attribute to completely saturate the sample before contributing to segregational heave.

For saturation purposes it was believed that the porosity of the sample remained constant throughout the whole freezing process. However, the porosity theory model developed by Michalowski showed that this was not the case. This made saturation calculation more challenging, since the porosity after initiating the freezing increased as ice lenses developed.

A restriction in the use of Dustex as an additive is its water solubility. It is difficult to guarantee how much lignin is dissolved from the sample after a test. The lignin further needs to cure to reach maximum strength. This curing process is ideally completed without access to water, which makes use of this additive in real life problematic. Few roads are constructed in Norway without exposure to water.

Due to climate changes, the annual freeze-thaw cycle is increasing in frequency, making a freeze-thawing test necessary to see how stabilised quarry fines are capable to sustain such environmental conditions [Zhang et al., 2019a]. The resistance to the cyclic action of freezing and thawing is critical when considering quarry fines as construction material.

4 Conclusion and recommendations

Resource scarcity has encouraged use of crushed rock aggregates in road construction. However, there is a large fraction of this material which remains unused due to high percentage of fines. This material-fraction is referred to as the 0-4 mm fraction and causes high economic losses for quarries and society by not being utilised and therefore considered as waste.

The percentage of fines is critical because it facilitates capillary suction and allows segregational heave in unbound layers. Such heave in these layers causes cracking of road surfaces during wintertime and a reduction in bearing capacity during thaw season.

This study was carried out with the objective of observing whether stabilisation techniques reduced frost-susceptibility of materials, allowing its use in a frost protection layer.

Selected crushed rock aggregates were provided by four quarries across the country - Lørenskog, Vassfjell, Sarpsborg and Tau - and tested in a Multi-Ring Frost cell at NTNU. Both untreated and treated samples were tested using various additives. The additives were Dustex, a lignin-based organic polymer and a mixture of Terrasil and Zycobond, both inorganic man-made polymers.

Frost heave test results were promising, establishing a clear trend in reduction of segregational heave with the use of additives.

The SP-model correctly identified frost-susceptibility of the materials indicating that this model would be relevant for predictions of frost heave.

From our tests, it appears that the inorganic polymers Terrasil and Zycobond performed better than Dustex. Further challenges with water solubility and need for curing hampers the attractiveness for Dustex as an additive. Nonetheless, this conclusion is by no means final, as number of tests treated with Dustex exceeds the number of tests treated with Terrasil and Zycobond.

However, questions regarding change in mechanical properties by the use of these additives, cost - and environmental - implications still remain unanswered. Because of this, remaining tests needs to be done before drawing any final conclusions.

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Appendices

A Frost heave

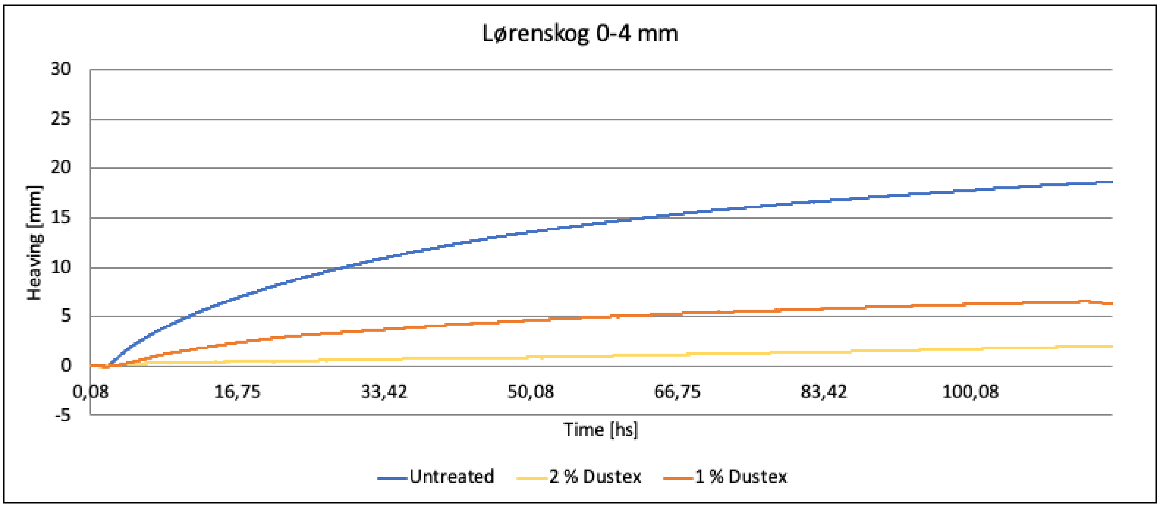


Figure 6: Frost heave versus time for untreated and treated by additives samples of Lørenskog

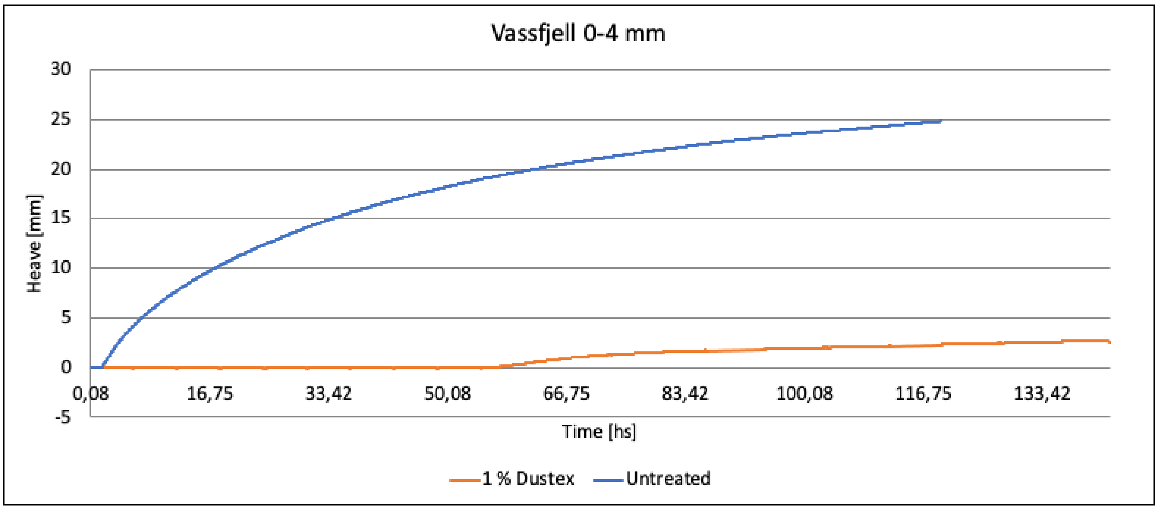


Figure 7: Frost heave versus time for untreated and treated by additives samples of Vassfjell

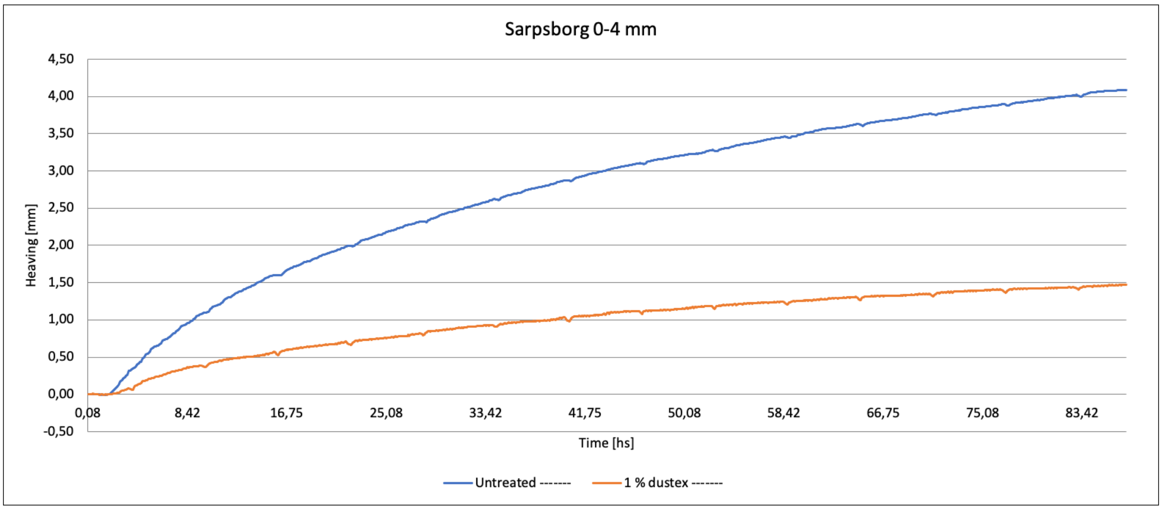


Figure 8: Frost heave versus time for untreated and treated by additives samples of Sarpsborg

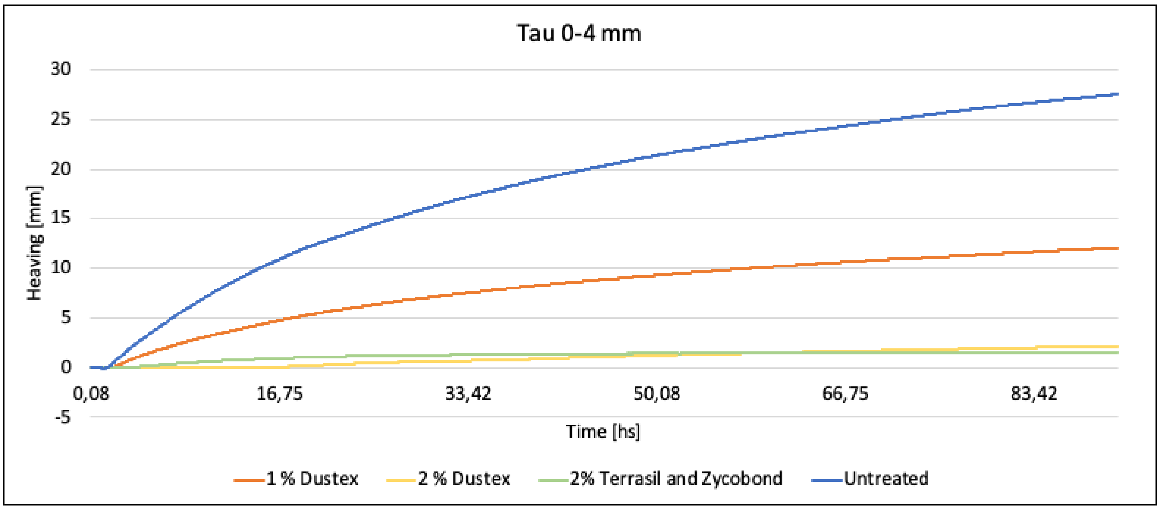


Figure 9: Frost heave versus time for untreated and treated by additives samples of Tau

B Segregation potential graphs

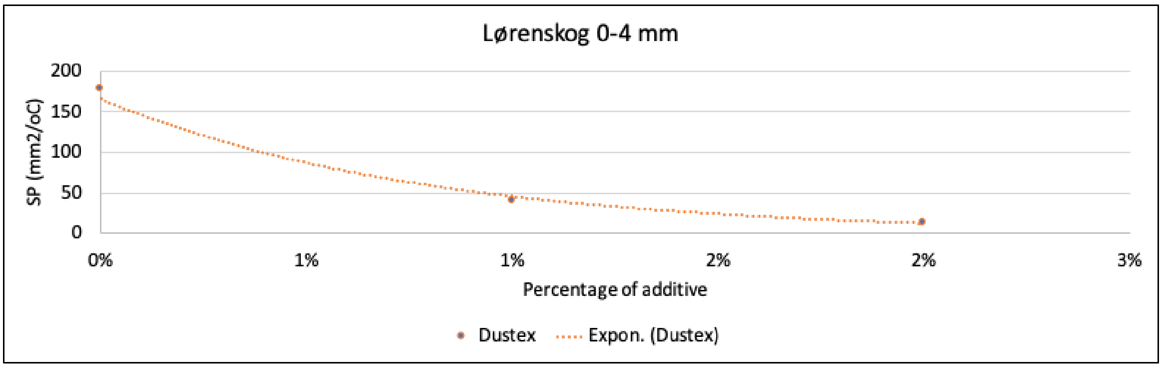


Figure 10: Segregation Potential of crushed rock material from Lørenskog with different percentage of Dustex

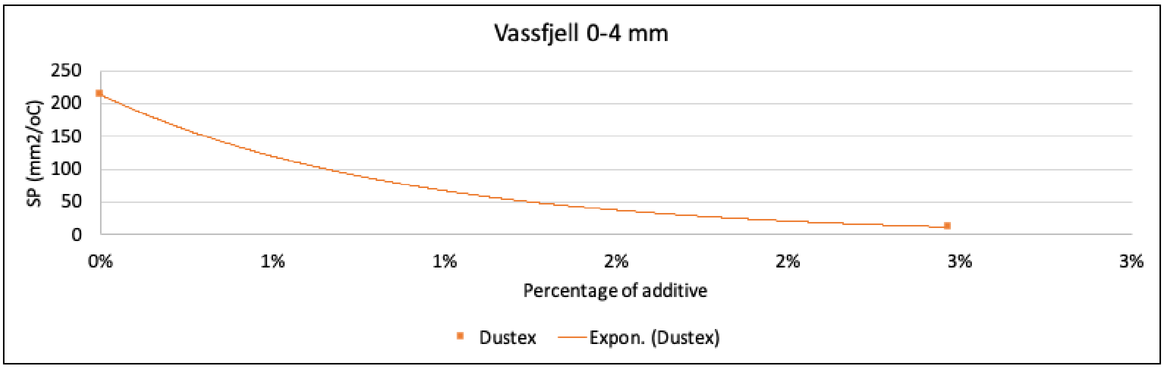


Figure 11: Segregation Potential of crushed rock material from Vassfjell with different percentage of Dustex

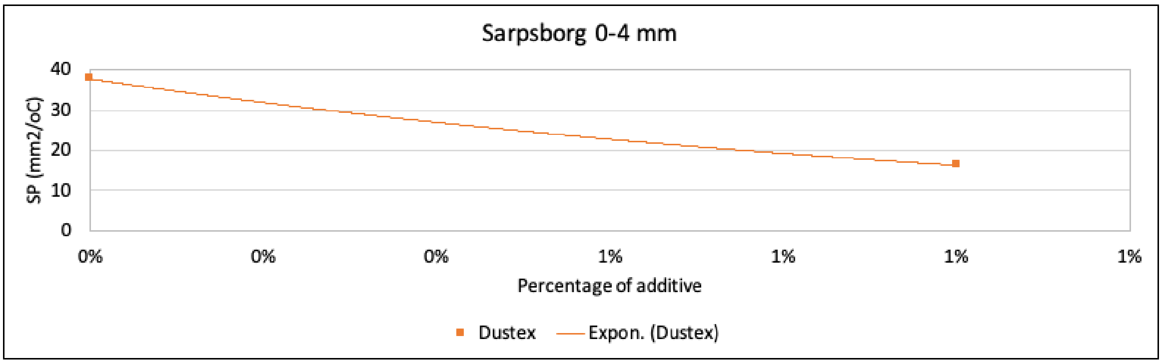


Figure 12: Segregation Potential of crushed rock material from Sarpsborg with different percentage of Dustex

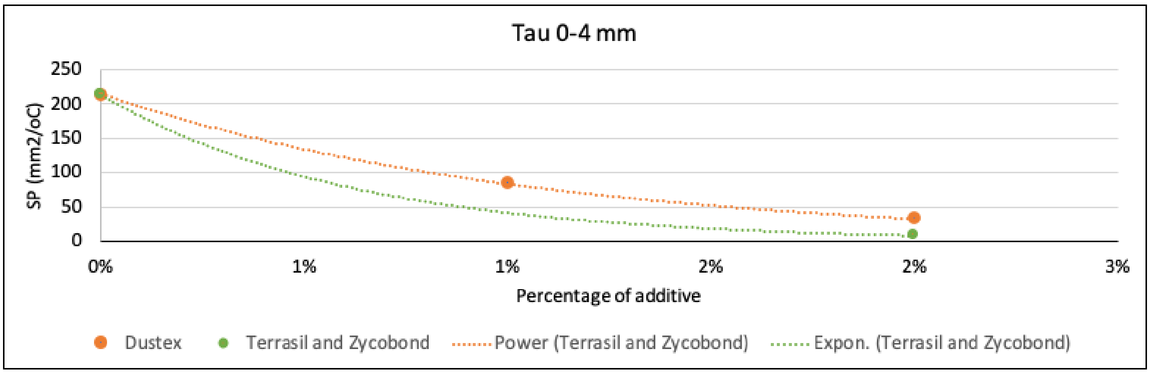


Figure 13: Segregation Potential of crushed rock material from Tau with different percentage of additives

C Laboratory Photos

(a) Compaction of sample

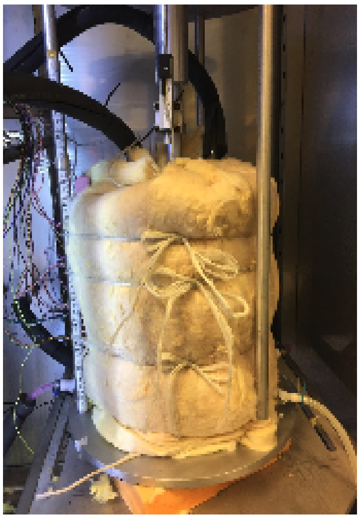
(b) Weighing the sample

(c) Unmoulding and measurements on the frost cell

(d) Installing top head, porous stone and filter paper

(e) Sample with the membrane and the rings.

(f) Sample in frost cell, water and thermistors are plugged in.



(g) Sample with insulation

(h) Measurements of frozen sample

(i) Formation of ice lenses

D Covid 19

NTNU
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Department of Civil and Environmental Engineering

1 of 1

Date	Our reference
3 June 2020	
Your date	Your ref

To Whom it Might Concern

Master thesis spring 2020 - consequences of the Covid 19 pandemic

The pandemic situation in spring 2020 made it necessary to change or adjust the topic for master theses at NTNU. The university closed including laboratories and did not allow any type of field work, thus made it impossible to continue planned work for many students.

Sincerely yours

Inge Hoff

Inge Hoff
Professor

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NO-7491 Trondheim

This letter was sent to all students with specialisation in Transport, Road or Railways in the Civil and Environmental study program to be included as an attachment in their thesis.

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