Cold Regions Science and Technology 192 (2021) 103394

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Frost susceptibility of Nordic metal mine tailings

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ARTICLE INFO

Keywords:
Frost susceptibility
Frost testing
Tailings
Mine waste
Frost heave

ABSTRACT

The mining industry produces significant amounts of waste materials, with the greatest volumes generated during enrichment. These waste materials or by-products, tailings, may be used as alternative civil engineering materials, reducing the need for natural resources. In cold climates, the frost behaviour of materials is one critical functional requirement in civil engineering applications. The frost behaviour of tailings classified as sand, silty sand, or sandy clayey silt (EN ISO), from four metal mines located in northern Finland and Sweden, was evaluated in this study using basic laboratory characterisation and one-dimensional freezing tests. The laboratory results were compared with existing guidelines on estimating the frost susceptibility of natural soils. Based on grain size distribution, the tailings samples were characterised as non-susceptible or frost-susceptible. Capillary rise values indicated that the frost susceptibility of the samples ranged from negligible to strong. In the one-dimensional frost heave test, measured frost heave after 96 h was 0.1–23.1 mm and calculated segregation potential (SP) was 0–9.7 mm^2/Kh. Based on the frost heave test, the frost susceptibility of the samples ranged from low to strong. The results indicated that the finest samples classified as sandy clayey silt (L1–L3) generated the majority measured amount of frost heave and were classified as frost-susceptible material. The coarser tailings samples (K1-K3 and AK1) classified as sand or silty sand were classified non-susceptible, and measured frost heave amounts were low <1.0 mm (after 96 h). Thus, the tailings samples behaved like natural soils, indicating that classification methods developed for natural soils are valid for evaluation of the frost susceptibility of mine tailings. However, the influence of added reagents should be considered, and standardised frost behaviour methods should be developed.

1. Introduction

The mining industry produces large amounts of waste material, with the largest volumes of raw waste material being generated during the enrichment process (mine tailings). Traditionally, tailings are pumped as slurry to tailings ponds, which are volumetrically the largest man-made structures. Impoundment of tailings causes significant risks for failures and major disasters potential for humans and the environment (Lyu et al., 2019). The consistency of these tailings varies depending on e.g., the mineralogy and the enrichment process used at individual mines (Bhanbhro et al., 2013; Rodriguez and Edeskär, 2013; Hu et al., 2017). Nowadays, each mining business segment, company, and country follows its own strategy to decrease the environmental and climate footprint of mining (Hámor, 2004; Dong et al., 2019). The public opinions and political pressures that colour the debate on environmental issues have increased the pressure to find ways to maximise use of the left-over material from mining (Mahmood and Elektorowicz, 2018a, Dong et al., 2019; Tayebi-Khorami et al., 2019). Utilising tailings to some extent in civil engineering projects and in earthwork structures can reduce the need for exploiting natural soil and at the same time reduce the space needed for tailings disposal. However, material efficiency requirements create a need for a better understanding of the mechanical and chemical behaviour of mine tailings as a source material for earthworks.

Mining takes place all over the world, including in cold regions. A cold climate imposes additional pressures, e.g. soil frost behaviour and its effect on earth structures. Soil frost is a regular occurrence in areas where the winter includes periods with sub-zero temperatures lasting several months. Subsurface below-zero temperatures can cause frost heave and frost penetration, depending on material properties and water balance (Dagli, 2017). Frost also influences the functionality and performance of structures by e.g. increasing the permeability and density of

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https://doi.org/10.1016/j.coldregions.2021.103394
Received 31 January 2021; Received in revised form 9 August 2021; Accepted 25 August 2021
Available online 27 August 2021

the material or increasing the seepage and consolidation rate (Robertson and Clifton, 1987; Peppin and Style, 2013; Dagli, 2017). From an economic point of view, frost heave damages structures and reduces their level of performance, resulting in annual repair costs worth billions of dollars. In the USA alone, for instance, repairing frost-damaged roads costs 2 billion dollars per year (O'Neill and Miller, 1985, DiMillio, 1999, Xu et al., 2019). Soil frost therefore poses challenges to earth- and soil-based structures that need to be accounted for in design, construction and maintenance of these structures. Hence, the material properties of tailings intended for use in earthwork structures in frost-prone conditions must be taken into consideration (Adajar and Zarco, 2013).

Many mines are logistically isolated and therefore the availability of building materials can be limited in terms of transportation cost and time. In the ideal case, tailings should be utilized immediately in the mine area or at least within the near vicinity. For this reason, tailings have been used by Swami et al. (2007) as a road construction material and studied extensively by Mahmood and Elektorowicz, 2017, Mahmood and Elektorowicz, 2018b) for potential use as a road construction material or as an on-site filling material (Fall et al., 2008; Deng et al., 2017).The tailings must meet certain minimum physical and environmental requirements. One of the main parameters with regard to physical behaviour in sub-zero conditions is the frost susceptibility of the material, which is known to be directly correlated with the level of frost-induced damages (Dagli, 2017). Low temperatures and the presence of water are the typical environmental conditions to result in the frost heave. When designing a structure, attention must be paid to these conditions. The importance of understanding the frost behaviour of the material, in this case the tailings, is crucial for the structures' cold climate resiliency. The structures face different climate and weather stress when comparing e.g. a well-drained embankment or road structure and a similar structure near groundwater level or near the surface in the active freezing/thawing zone (Andersland and Ladanyi, 2004, Dagli, 2017). Fig. 1 presents an example of a frost risk in the tailings dams when using the upstream raising method. Typically, tailings dams are raised in phases and normally raisings are made upstream, downstream, or centerline (Vick, 1990; Rico et al., 2008). Regardless of the used raising method, the frost risk must be handled in the design - otherwise, the dam's stability may be compromised (Vick, 1990).

The frost susceptibility of a material can be determined by several methods (Peppin and Style, 2013; Dagli, 2017), but there is no common standardised approach. At present, frost susceptibility classification depends primarily on grain size distribution, according to which a material can be classified into one of several main frost susceptibility categories. The International Society for Soil Mechanics and Geotechnical Engineering (ISSMFE-TC8, 1989) uses the following classification criteria: In level one (1), the grain size distribution of the soil is determined and the curve is compared with pre-defined criteria. Levels two and three is defined in more demanding built object, where level two (2) criteria are based on index properties and/or on the hydraulic properties of materials and in level three (3) materials must perform a frost heave test.

The aims of this study are to a) test the frost properties of metal mine tailings, b) assess the applicability of traditional soil testing methods for

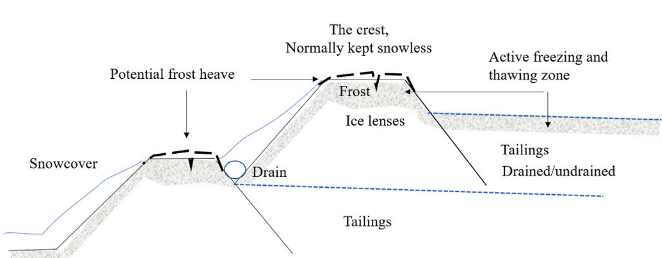

Fig. 1. The principal conceptual model of frost presence in the upstream raised tailings dam.

mine tailings c) and propose a framework for assessing the frost behaviour of metal mine tailings in a cold climate. The focus is on the mechanical properties of tailings. Chemical and environmental aspects are not determined, but their relevance is discussed. Laboratory measurements are performed to determine the frost susceptibility of different mine tailings samples, and the results obtained are compared with the criteria on frost susceptibility of natural soils established by ISSMFE (ISSMFE-TC8, 1989). The validity of natural soil testing methods and approaches for evaluating mine tailings is then assessed. Finally, a framework based on the available frost susceptibility classification for natural soils and on the laboratory data for tailings is developed and future research needs are identified.

2. Materials and methods

2.1. Study areas

The mine tailings samples tested in this study were collected from four mines in the Arctic region: Laiva, Kevitsa, Sotkamo Silver (all in Finland) and Aitik (Sweden). The Laiva mine and Sotkamo Silver mine are located about 200 km and 320 km south of the Arctic Circle, respectively, while the Kevitsa mine and Aitik mine are located about 140 km and 60 km north of the Arctic Circle, respectively (Fig. 2). All four sites are metal mineral mines, producing mainly gold, nickel, copper and silver (Table 1). The mines are situated in a region where winter and snow cover last approximately six months of the year. However, due to the distance of 200–300 km between the individual mines, the conditions differ slightly. In Raahe and Sotkamo, the closest cities to the Laiva and Sotkamo Silver mines, the temperature stays below 0 °C degrees from November to March and mean monthly temperature is +15.9 °C in July and − 9.3 °C in January (Pirinen et al., 2012). In Sodankylä and Gällivare, near where the Kevitsa and Aitik mines are located, the period with temperature below 0 °C lasts seven months, from October to April, and mean monthly temperature is +13.6–14.4 °C in July and − 13.6 to.-14.6 °C in January (Pirinen et al. 2012, SMHI, 2019). The annual snow cover period in Raahe, Sotkamo, Sodankylä and Gälliware is approximately 160, 175, 190 and 225 days, respectively (Pirinen et al., 2012, SMHI, 2019).

Laiva mine opened in 2011 and its main product is gold. The tailings pond (about 0.5 km^2) is situated 6 km from the mine processing plant. The disposal method is thickened tailings or paste, depending on the solids content achieved in the thickener. From the thickener, the tailings are pumped to the tailings pond. The outlet pipe location is moveable, and thus the delivery point can be varied. Tailings deposit thickness varies across the pond, from a few metres to 10 m.

The Kevitsa mine opened in 2012 and it produces mainly nickel and copper concentrate. The tailings are disposed of as slurry, through perimeter spigots. The tailings pond (about 3.0 km^2) is in Kevitsanaapa, next to the processing plant. Tailings are settled hydraulically in the pond and the excess water is pumped back to the process or to a water reservoir from the decant pond.

The Aitik nickel-copper mine is the oldest of the studied sites, established in 1968. Its tailings pond is also the largest (around 13 km^2) and the tailings layer is increasing by approximately 1 m every year. The tailings generated at the mine are disposed of in the conventional way, as slurry to a tailings storage facility.

The Sotkamo Silver mine is the youngest of the mines sampled, opened in 2019. Its main product is silver and the disposal method for tailings is similar to that of Kevitsa mine, i.e. spigotting as slurry to a pond surrounded by dams.

2.2. Characterisation of tailings

Frost susceptibility experiments on the tailings from the Kevitsa and Laiva mines were carried out on samples collected from the pond areas (Fig. 2). The sample of Aitik mine tailings was taken from the outlet

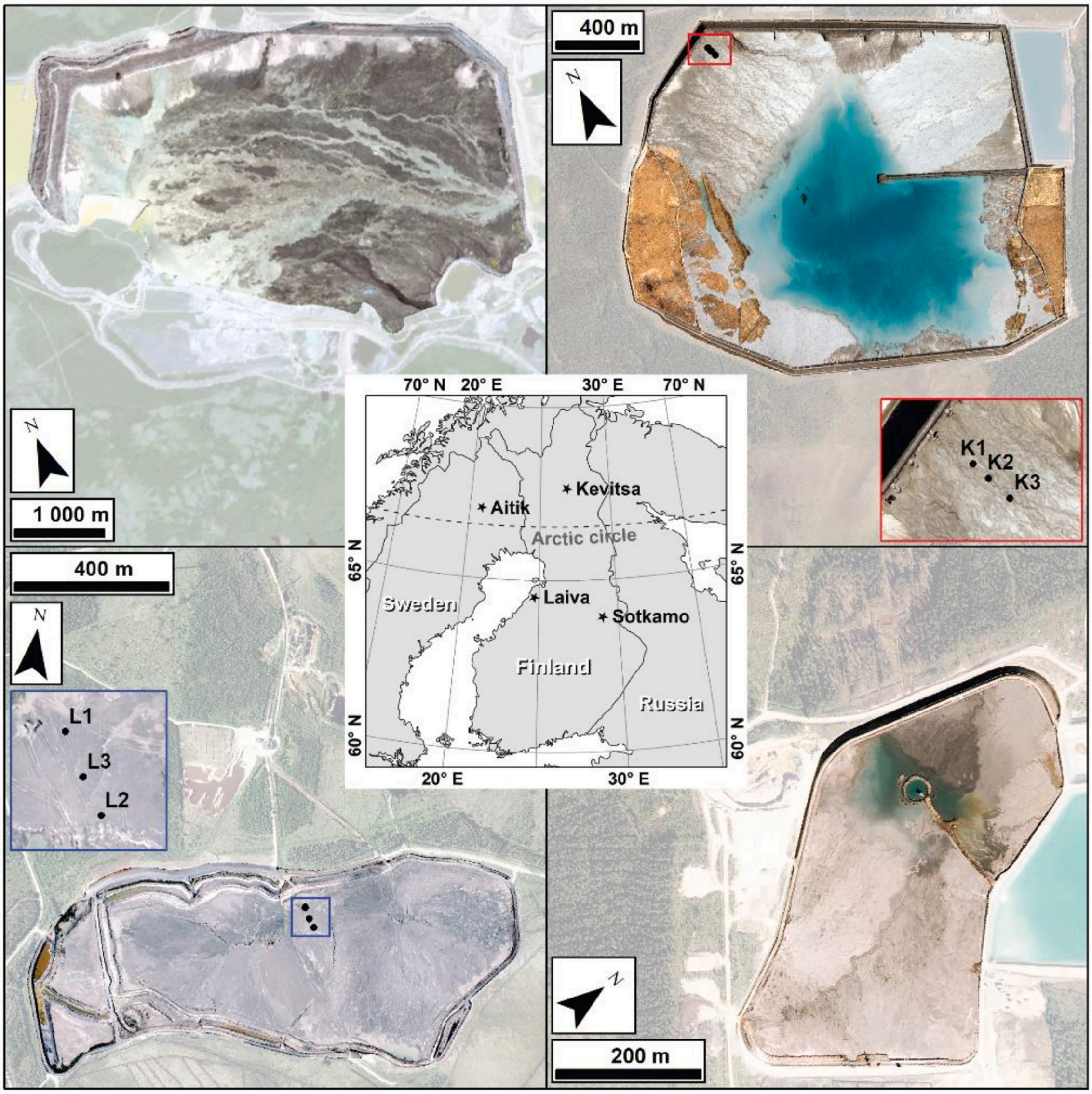

Fig. 2. Satellite/aerial images of the study sites and their locations in Finland and Sweden. *Top left:* Sentinel 2 satellite image of Aitik mine tailings pond in 2020. *Top right:* Aerial image of Kevitsa mine tailings pond in 2015, inset shows tailings sampling locations. *Bottom left*: Aerial image of Laiva mine tailings pond in 2019, inset shows tailings sampling locations. *Bottom right:* Aerial image of Sotkamo Silver mine tailings pond in 2020. (Satellite image courtesy of Copernicus Sentinel data 2020, processed by ESA, aerial imagery courtesy of National Land Survey of Finland.)

Table 1
Details of the mining sites at which tailings samples were collected.

Mine:	Laiva	Kevitsa	Sotkamo Silver	Aitik
Coordinates	64°33′04"N, 24°35′50″E	67°41′40"N, 26°55′24″E	63°56′05"N, 29°02′51″E	67°04′23"N, 20°57′44″E
Opening year	2011	2012	2019	1968
Location (direction from Artic Circle)	200 km South	140 km North	320 km South	60 km North
Main products	Gold	Nickel & Copper	Silver	Nickel & Copper
Temp below 0 °C	Nov.- March	Oct.- April	Nov.-March	Oct.-April
Mean temp in Jul (°C)	+15.9	+14.4	+15.9	+13.6
Mean temp in Jan (°C)	−9.3	−13.6	−9.3	−14.6
Snow cover days	160–175	190–205	160–175	200–225

delivery pipe of the tailings pond. The Sotkamo Silver mine tailings sample differed from others, since full-scale production had not started at the time of experiments and a sample produced in a pilot process was used instead (Table 2). All sampling was carried out during 2014–2017.

Table 2
Sampling depth and year, and sampling method used to obtain mine tailings samples.

Location	ID	Sampling depth [cm]	Disturbed sampling method	Sampling year
Laiva mine	L1	30…50	Spade and vessel	2015
Laiva mine	L2	30…50	Spade and vessel	2015
Laiva mine	L3	170…210	Auger and vessel	2016
Sotkamo silver, pilot	SS1	From pilot	Spade and vessel	2014
Kevitsa mine	K1	30…50	Spade and vessel	2016
Kevitsa mine	K2	30…50	Spade and vessel	2016
Kevitsa mine	K3	30…50	Spade and vessel	2016
Aitik mine	AK1	From pipeline outlet	From stream to vessel	2017

The samples were excavated, stored in separate vessels and transferred to the laboratory refrigerator (+4 °C) for storage prior to the analyses.

Each vessel of sample was measured for initial moisture content (Table 3). The grain size distribution of the tailings samples was measured by sieving according to standard SFS-EN ISO 17892-4:2016 and water content was calculated by Eq. (1):

$$w = m_w / m_s \ 100\% \tag{1}$$

where m_w is mass of water and m_s is dry mass of sample.

Capillary rise was measured with a SAHI capillary meter with tube width 52 mm. Table 3 and Fig. 3 summarise the basic physical properties of the fine tailings used for the laboratory tests. The initial moisture content varied between 5 and 24%. The EN ISO standard classifies tailings as non-natural materials, but here we used the EN ISO classification of natural soil materials to characterise the tailings, to allow comparison with the freezing behaviour of natural soils. In texture classification, the tailings samples from Laiva mine (L1,L2,L3) were classified as sandy clayey silt (saclSi) and the tailings samples from Sotkamo Silver (SS1) and Aitik mine (AK1) were classified as silty sand (siSa). Two of the samples from Kevitsa mine (K1,K3) were also classified as silty sand (siSa) and one (K2) as sand (Sa).

2.3. Segregation potential and one-dimensional freezing test

Segregation potential (SP) calculation is one of the widely used methods for frost susceptibility classification and estimation of frost heave. It assumes that water intake velocity (v) [mm/h] is proportional to the temperature gradient (GradT) [K/mm] in the frozen fringe by a proportionality constant, SP [mm^2/Kh], which can be formulated as (Konrad and Morgenstern, 1981, Slunga and Saarelainen, 2005):

$$\mathrm{v} = \mathrm{SP\ GradT} \tag{2}$$

Segregation potential describes the sensitivity of a material to frost heave, as determined with a frost heave test. The frost susceptibility classifications based on SP values (Konrad and Morgenstern, 1981) and capillary rise (Beskow, 1949) are presented in Table 4.

The frost susceptibility of the mine tailings samples was measured using the frost heave test equipment shown in Fig. 4. There is no standardised method for frost heave testing. The set-up and methodology utilized in this study closely correspond to that used in Dagli et al. (2018). The entire set-up was placed inside a cold room that can maintain a constant surrounding temperature of +3 to +4 °C. All tests were conducted on disturbed tailings samples (Table 2). The samples were compacted to approximate field density (Table 6) and moisture conditions in a cylindrical cell (10 cm height, 10 cm diameter) in five layers, using a hand hammer. The goal was to prepare samples that accurately resembled the composition of tailings within the tailings pond of origin. After compaction, the cylindrical cell was set into the test equipment. Thermocouples were placed within the sample (at 0 mm, 15 mm, 35 mm, 55 mm, 75 mm, 95 mm, and 100 mm) to track the temperature profile during the test. Load was added in order to reflect actual field conditions. Deionised water was made freely available to the porous base plates to allow water to be drawn into the sample already during the settling phase (minimum 20 h). After the settling phase, the sample was thermally insulated in order to minimise heat losses from the sides, and the actual frost heave test was run under partially saturated conditions.

Table 3
Initial water content of the mine tailings samples and classification according to ISO EN standard (SFS-EN ISO 14688-2) as sandy clayey silt (saclSi), silty sand (siSa) or sand (Sa).

ID	Classification (EN ISO)	Initial water content [%]
L1	saclSi	19.92
L2	saclSi	20.46
L3	saclSi	17.59
SS1	siSa	12.50
K1	siSa	6.66
K2	Sa	5.66
K3	siSa	9.70
AK1	siSa	23.37

Each frost heave test typically lasted a minimum of 96 h. The test was started with two cooling units supplying cold (−3.5 °C) and warm (+3.5 °C) temperatures to the top and bottom of the sample, respectively. Freezing then took place one-dimensionally from sample top to bottom. During the test, water was able to be drawn freely from the sample bottom to the frost front. Displacement due to frost heave was recorded using a displacement transducer (LVDT) located at the top of the sample. Temperature data and displacements were recorded by a data logger, which was connected to a computer for further analyses. Segregation potential was calculated based on recorded measurements.

3. Results

3.1. Frost susceptibility based on grain size distribution and capillary rise

The grain size distribution of the tailings samples is shown in Fig. 5, together with the limit curves used for estimating frost heave susceptibility (according to ISSMFE-TC8). A soil is categorised as frost susceptible when the grain size curve lies within region 1 in the grain size distribution diagram and is categorised as having low frost susceptibility when the grain size curve lies in region 1 L (Fig. 5). Soils with grain curves within regions 2, 3, and 4 are classified as non-frost susceptible. If the grain size curve crosses the boundary of the next region on the finer side, the soil is classified as frost susceptible. This rough classification rests on grain size distribution which is based on practical experience and only gives an estimation of the frost susceptibility.

Based on the grain size curves, samples K1, K2, K3 and AK1 were non-susceptible and samples L1, L2, L3 and SS1 were frost susceptible (Table 5). Measured capillary rise for the samples varied between 0.66 and 2.05 m (Table 5). Applying the Beskow (1949) classification to the capillary rise values showed similar results for frost susceptibility as found with grain size curves. Samples K1-K3 and SS1 were classified as having low susceptibility, samples L1-L3 as strongly frost susceptible and sample AK1 as having negligible frost susceptibility (Table 5).

3.2. One-dimensional freezing test

The overburden pressure was set to 3 kPa by default (empty load frame) for all samples except SS1, for which it was set to 15 kPa because that material was intended for use under a thin (0.5 m) protective soil layer. Based on previous frost heave tests on soils (Kujala, 1991), this load difference may have had a significant impact on the frost susceptibility of the materials. This means that the frost susceptibility result for sample SS1 may have been higher if 3 kPa overburden pressure had been used for that sample too. Fig. 6a, b, and c show the frost depth that developed during the tests, the measured temperature at 55 mm depth in the samples, and the amount of frost heave generated, respectively. According to the displacement transducer, the measured frost heave after 96 h varied between 0.1 and 23.1 mm (Fig. 6c, Table 6). Based on the measured values, the segregation potential (SP) was calculated to vary between 0 and 9.7 mm2/Kh (Table 6). It is noteworthy that it took more than 24 h before the samples seemed to stabilise and reach an equilibrium state. After that point, the frost depth and temperature changes in the sample did not increase significantly (Fig. 6).

Table 6 shows the frost susceptibility classification for the tailings samples based on the frost heave test results. Samples K1, K2, K3, and AK1 showed negligible frost heave and were classified as non-susceptible, whereas samples L1, L2, and L3 showed evident frost heave and were classified as strongly frost susceptible. Sample SS1 showed low frost heave and was classified as having low frost susceptibility. Thus the frost susceptible classification was generally in line

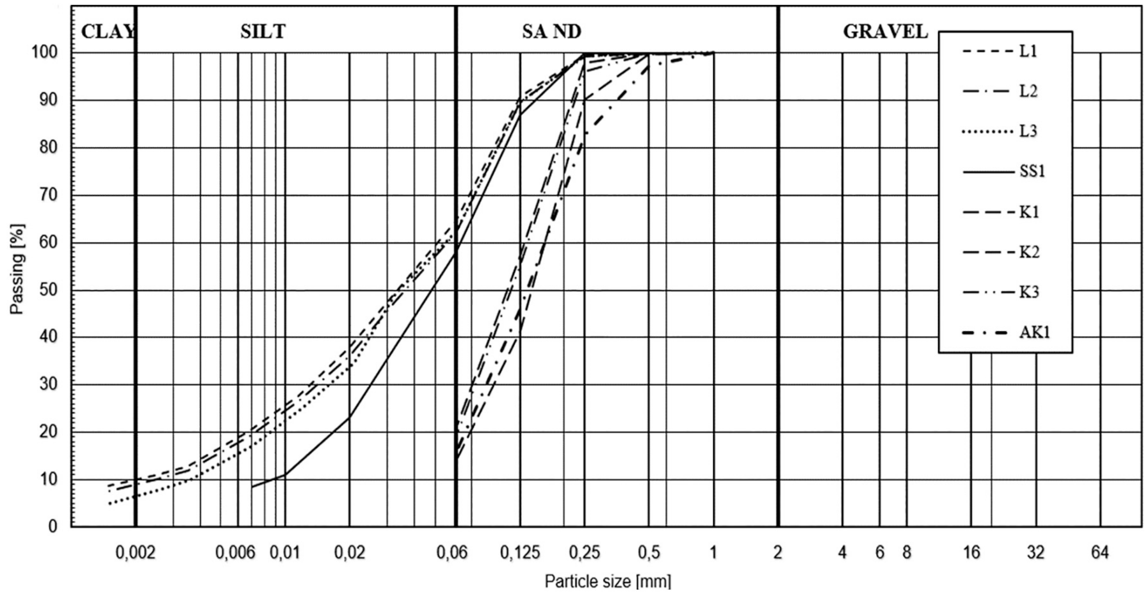

Fig. 3. Grain size distribution of the mine tailings samples.

Table 4
Determination of frost susceptibility of a soil type based on segregation potential (SP) value and capillary rise (ISSMFE-TC8).

Frost susceptibility class	Segregation potential SP (Konrad and Morgenstern, 1981) [mm^2/Kh]	Capillary rise (Beskow, 1949) [m]
Negligible	<0.5	<1.0
Low	0.5–1.5	1.0–1.5
Medium	1.5–3.0	1.5–2.0
Strong	>3.0	>2.0

with that based on grain size distribution and on capillary rise (Table 6).

4. Discussion

4.1. Frost susceptibility estimation

In terms of grain size distribution and frost susceptibility classification, the mine tailings samples behaved similarly to natural soils. However, on combining results from Table 6 and Fig. 5, sample L1 was found to produce more frost heave than samples L2 and L3. The grain size distribution in sample L1 consisted of slightly more fines than that in samples L2 and L3, which might have affected the amount of frost heave generated. Note also that different samples were used in the analyses, which could have resulted in differences in the composition of the experimental samples due the heterogeneous nature of the tailings material. A comparison of the frost heave results for samples K1 and K3, which were both classified as silty sand (siSa), showed that sample K3 produced more frost heave than sample K1, despite the similar grain size distribution. The amount of frost heave was small in all samples, but it is obvious that even a small change in grain size distribution, e.g. through compaction causing grinding and deformation, can increase frost heave. However, all samples K1-K3 were classified as non-susceptible. Unwanted deformation due to e.g. grinding or ageing during compaction work or due to dynamic loading can be harmful in real constructions and can increase the amount of frost heave (Nurmikolu, 2005; Bilodeau et al., 2019).

In mining, the enrichment process generating tailings and the tailings disposal method creates unique conditions which must be understood and taken into account. Difficulties in characterisation of grain size distribution for mine tailings have been reported previously (Kerry et al., 2009; Hu et al., 2017). In the enrichment process, reagents such as flocculants and coagulants are used, which can affect the content of fine grains determined using hydrometer analysis, which relies on the settling velocity of grains (Stokes' law). The reagents used in a typical extraction process speed up the settling process, which can cause systematic error in determining the finest fraction of the grain size distribution. As a result, the material may seem coarser than it really is. In general, the coarser the material, the lower the frost susceptibility (except for material containing fines, like the clay and grain size curve lie in area 1 L, see Fig. 5). If grain size distribution analysis involves this systematic error, the frost susceptibility of the sample will normally be underestimated. Therefore it is important to analyse particle size distribution by several methods, e.g. sieving and laser particle size analysis, in order to get reliable results. However, if a mine makes modifications to its process or the reagents it uses, this may affect the consistency of tailings and possibly their physical behaviours. In such circumstances, the frost susceptibility of tailings must be determined all over again.

The tailings disposal method used also affects the settling of tailings to the pond or disposal area. If the hydraulic deposition method is used, the segregation of tailings in ponds can form zones with different physical properties (Fourie, 2009; Bhanbhro, 2014). Zones near the pond inlet, i.e. the unloading point, will have the most coarse-grained material and, depending on the topography of the pond, the finest particles will be carried farther into the pond with the flow. Use of thickening or paste will keep the consistency of the tailings more homogeneous, and segregation will not be as significant during disposal (Robinsky, 1978; Fourie, 2009). In characterisation of tailings, analysts must take account of the fact that tailings consistency may vary locally and that, due to possible segregation, the frost susceptibility of materials from different areas of the tailings pond may differ.

Use of mine tailings in earthworks etc. must always be environmentally sustainable. In disposal of tailings, mine water and its storage play a significant role (Gunson et al., 2012). Tailings include metals that are harmful to the environment and which occur in soluble form in acid conditions (Feng et al., 2000; Heikkinen et al., 2009). To avoid environmental impacts, new technology for treating metal-containing mine tailings has been developed (Ahmari and Zhang, 2012; Rao and Liu, 2015; Luukkonen et al., 2018). In the geopolymerisation approach, different binders are mixed with the tailings. When the tailings are mixed with reactive materials, their mechanical behaviour can change, e.g. binders often harden the material and prevent harmful metals from entering liquid solution. However, testing hardened material in the

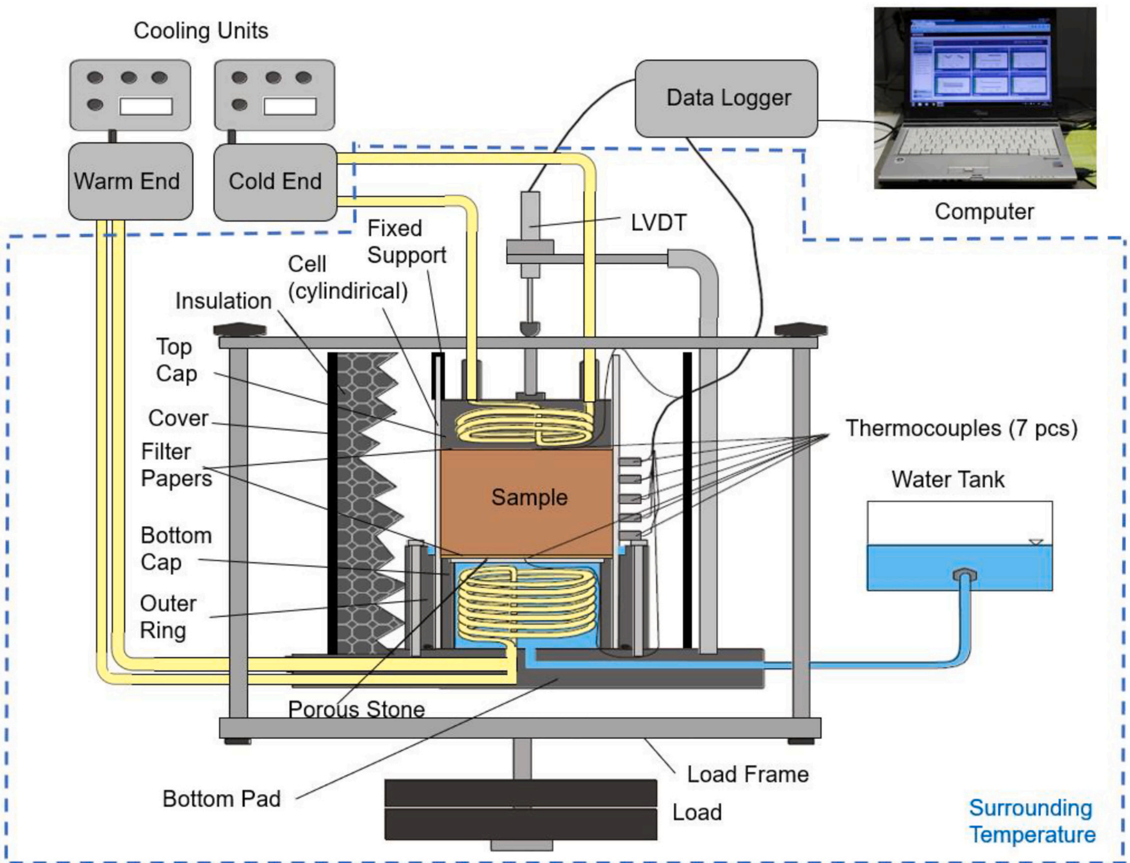

Fig. 4. Schematic representation of the equipment used in frost heave tests (modified from Dagli et al., 2018).

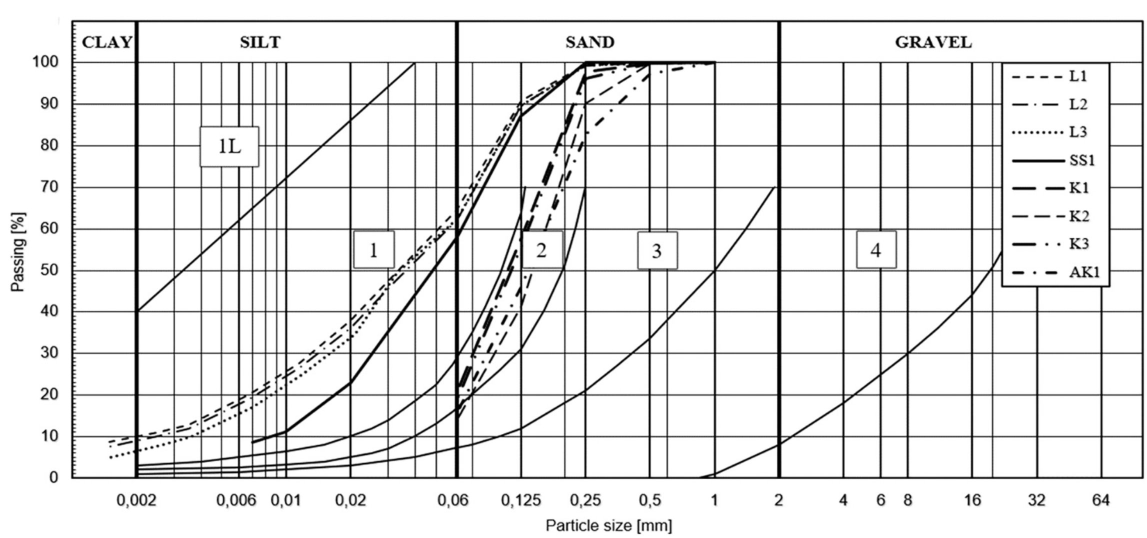

Fig. 5. Determination of frost susceptibility of mine tailings on the basis of grain size curves according to ISSMFE-TC 8. Samples in regions 1 L and 1 are classified as having low and high frost suceptibility, respectively. Samples in regions 2, 3, and 4 are classified as non-frost susceptible.

laboratory is challenging, creating a need for alternative monitoring tests (e.g. pilot-scale testing, step 3 in Fig. 7).

When examining the steps in the frost heave test procedure, it was not possible to use undisturbed tailings samples from the preceding stages, so the effect of sample disturbance on the sensitivity to frost heave could not be assessed in this study. The moisture in the samples corresponded to the conditions at sampling. Uncertainty deriving from the use of additives is not known, e.g. effects on the freezing point of the tailings and whether the tailings freeze like natural materials. The chemicals used may be changed, causing changes in the stability of the tailings. The same applies to granularity, so if the process is modified, the quality of the tailings may change. Further, the composition of the additional water taken up is an unexplored variable that differs between mine tailings and natural materials during frost heave in the real environment. Under natural conditions, the additional water taken up by natural materials during frost heave is absorbed groundwater. In mining

Table 5
Comparison of the frost susceptibility categorisation of mine tailing samples based on the grain size distribution and on the capillary rise.

ID	Texture classification (EN ISO)	Frost susceptibility based on grain size (ISSMFE-TC8)	Measured capillary rise [m]	Frost susceptibility based on capillary rise (Beskow, 1949)
L1	saclSi	Frost susceptible	2.05	Strong
L2	saclSi	Frost susceptible	2.05	Strong
L3	saclSi	Frost susceptible	2.02	Strong
SS1	siSa	Frost susceptible	1.35	Low
K1	siSa	Non-susceptible	1.09	Low
K2	Sa	Non-susceptible	1.07	Low
K3	siSa	Non-susceptible	1.35	Low
AK1	siSa	Non-susceptible	0.66	Negligible

tailings basins, the additional water taken up is mixed water from the mining process and rainwater. The effect of this difference in water source is worth exploring in future work.

One characteristic feature of the frost heave test equipment used at the University of Oulu is its structure, which allows both the sample and the cylindrical cell to rise without friction between their contact surfaces during frost heave. Movement of the upper part of the sample in the cell is prevented by the top cap on the sample. The sample with the cell is placed on the bottom cap, along the edges of which they can jointly slide upwards during the formation of frost heave.

In order to better understand the behaviour of tailings as a building material in a real environment, e.g. in a tailings dam, assessment of their behaviour during freezing must be complemented with other analyses. In addition to the freezing phase, tailings undergo one or more thawing phases during the different seasons of the year. Some previous studies have examined the ice melting cycle in tailings (e.g. Beier and Sego, 2009). A method for testing during the thawing cycle has been identified as the major development target for the existing frost heave test equipment at the University of Oulu. The thawing cycle will be included in future testing of mine tailings once the functionality of the thawing cycle test equipment has been confirmed.

There is currently a lack of standardisation in frost heave testing. Throughout the history of frost heave research, a variety of test devices and procedures have been used (Chamberlain, 1981; Nurmikolu, 2005; Dagli, 2017). Efforts have been made to standardise frost heave testing, e.g. by the International Society for Soil Mechanics and Geotechnical

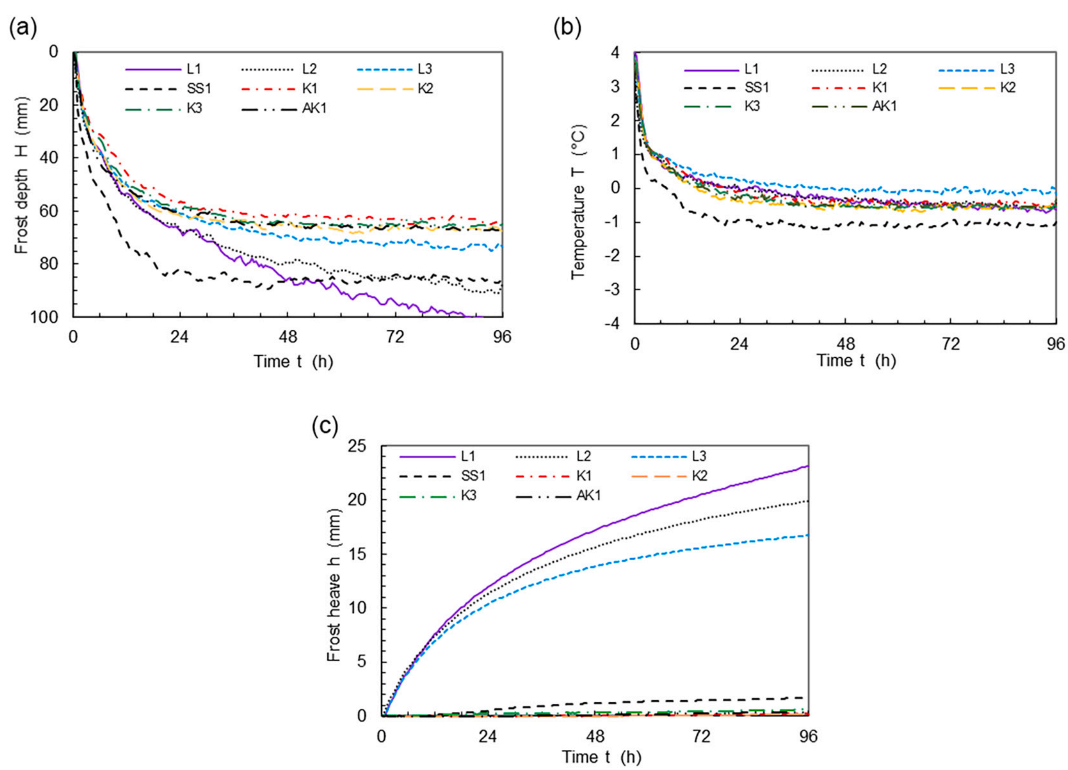

Fig. 6. Progress of a) frost depth, b) temperature at 55 mm depth in the samples and c) cumulative frost heave during the frost heave tests.

Table 6
Frost susceptibility of tailing samples based on the different categorisation systems.

ID	Texture classification (EN ISO)	Measured capillary rise [m]	Dry density [kg/m^3]	Overburden pressure [kPa]	Frost heave (96 h) [mm]	Segregation potential (SP) [mm^2/Kh]	Frost susceptibility based on SP (Konrad, 1980)	Frost susceptibility based on grain size (ISSMFE-TC8)	Frost susceptibility based on capillary rise (Beskow, 1949)
L1	saclSi	2.05	2145.4	3	23.1	9.7	Strong	Frost susceptible	Strong
L2	saclSi	2.05	2130.1	3	19.9	6.2	Strong	Frost susceptible	Strong
L3	saclSi	2.02	2138.4	3	16.7	3.5	Strong	Frost susceptible	Strong
SS1	siSa	1.35	1666.8	15	1.7	1.1	Low	Frost susceptible	Low
K1	siSa	1.09	1823.3	3	0.2	0	Negligible	Non-susceptible	Low
K2	Sa	1.07	1813.6	3	0.2	0	Negligible	Non-susceptible	Low
K3	siSa	1.35	1921.0	3	0.6	0.1	Negligible	Non-susceptible	Low
AK1	siSa	0.66	1653.6	3	0.4	0.1	Negligible	Non-susceptible	Negligible

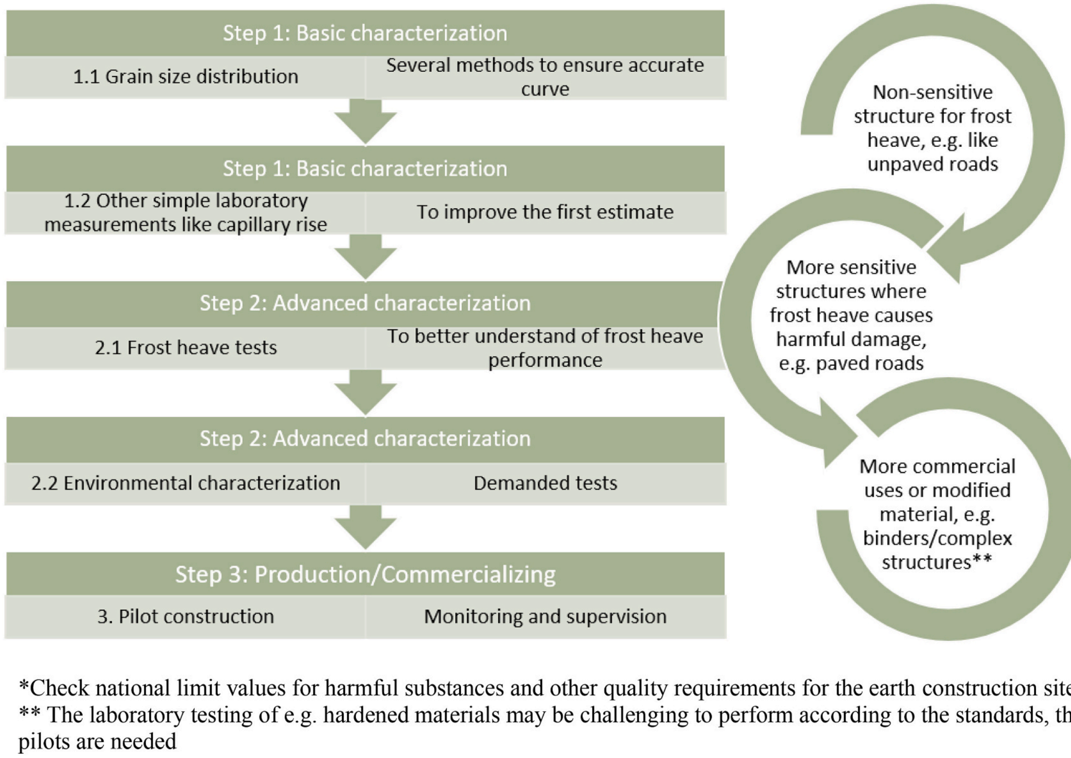

Fig. 7. Proposed framework for estimating the frost susceptibilility of mine tailings before use in earthworks and other structures.
*Check national limit values for harmful substances and other quality requirements for the earth construction sites.
**The laboratory testing of e.g. hardened materials may be challenging to perform according to the standards, therefore pilots are needed.

Engineering (ISSMGE) Frost Technical Committee TC216 (ISSMGE, 2020).

4.2. Framework for estimating the frost susceptibility of mine tailings

Abundance of mineral resources are located in cold regions. It is therefore relevant to make most use of the tailings materials in civil engineering applications to minimise the use of natural resources, and frost resiliency is one key requirement for alternative materials. We developed a framework for estimating the frost susceptibility of mine tailings (Fig. 7), based on existing knowledge of standardised soil classification methods and on the most important aspects identified in the measurements and tests presented in this paper. In straightforward cases, such as use of tailings as building materials for unpaved mining roads, testing the grain size distribution (Step 1 in the framework) is the typical requirement. Step 2 needs to be incorporated in the case of more sensitive and complex structures, like paved road and surface structures, where frost heave can cause significant damage and economic losses. Swami et al. (2007), for instance, has studied tailings as road construction material used to replace natural materials in a subbase, base or wearing courses. Frost heave testing is one important measure to avoid structural damages of the road pavement and underlying courses. Therefore in Step 2, the frost heave test should be used. The environmental acceptability of tailings must be determined and the requirements vary globally. The national demanded quality assurance system shall be ensured and the acceptability of tailings must be studied. Step 3, involving pilot construction, prototyping and performance evaluation, is necessary when the material is intended for use e.g. in commercial settings or for replacing conventional materials in more demanding civil engineering structures, such as environmental protection layers. Therefore, all steps from 1 to 3 should be followed if the material is planned for broader commercial applications and acceptance is required by regulating bodies. Without standardised methodology, it would be difficult for any regulator to set requirements on the use of tailings materials.

5. Conclusions

Freezing poses serious challenges in Arctic conditions, including for mining operations. Material properties and water balance leading to possible frost heave may cause damage to earthwork structures and economic losses. Therefore, utilisation of mine waste tailings in such structures in regions with sub-zero winter temperatures requires a good understanding of the frost behaviour of the tailings. One of the key parameters for estimating material behaviour under freezing is frost susceptibility, which is correlated with frost-induced damage.

Laboratory measurements conducted in this study indicated that metal mine tailings behaved similarly to natural soils in terms of frost properties. Mine tailings that included fine particles were categorised as frost susceptible based on the grain size distribution, while results from one-dimensional frost heave tests confirmed this categorisation. Correspondingly, mine tailings that contained mainly coarse particles were classified as non-frost susceptible based on the grain size distribution and the results of the one-dimensional frost heave tests.

However, particular attention must be paid to determination of grain size distribution, since e.g. reagents added during the enrichment process can render the hydrometer test ineligible for analysing fine particle distribution in mine tailings. Reagents speed up the settling rate of particles and cause error by decreasing the theoretical proportion of fines. The effects of reagents were not addressed in this study.

In future research, the focus should be on standardisation of freezing test methods, harmonising testing procedures and interpretation of the results. Comparison of test results from different sources is currently difficult or even impossible. Standardised data are needed by e.g. the regulatory bodies mandated to set standards for building codes and materials and by public sector procurers, who play a key role in decisions on civil engineering structures, i.e. infratructures such as roads, rail lines, embankments, dams and protection walls.

Mine tailings can be a significant source of raw material for the construction and building industry. Having standardised testing methods for determining the applicability of mine tailings for different earthworks and structures would reduce the need to exploit natural resources. Tailings can thus be considered an important prospective candidate in the circular economy and in resource-efficient use of materials.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was funded and supported by Maa- ja Vesitekniikan tuki r.y, K. H. Renlunds foundation and Tauno Tönning foundation. The authors would like to acknowledge the support received from the personnel at the Water, Energy and Environmental Engineering and Structures and Construction Technology research units at the University of Oulu, especially MSc Jenna Colpaert, MSc Toni Sievola and Laboratory Engineer Tuomo Pitkänen.

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