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A laboratory investigation of the frost heave susceptibility of fine-grained soil generated from the abrasion of a diorite aggregate

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ABSTRACT

One-dimensional frost heave testing of soil samples of differing composition (Devon silt and the fines generated from the abrasion of an aggregate) demonstrates a contradictory assessment of their frost heave susceptibility based on the rate of segregation heave and the segregation potential (*SP*). Specifically, the rate of segregation heave is representative of the frost heave susceptibility during transient conditions, whereas the *SP* is an indicator of the frost heave susceptibility under steady state conditions. The contradiction between these two measures is due to the transient conditions that result from the differing thermal conductivity of the soils. Limitations of frost susceptibility criteria are discussed in light of these results.

1. Introduction

The silt-sized fines and rock flour generated due to the abrasion and degradation of railway ballast may be highly susceptible to frost heave (Nurmikolu, 2005; Nurmikolu and Kolisoja, 2008). Nurmikolu (2005) conducted laboratory testing to determine the frost susceptibility of comparable materials. These materials were found to generate high rates of segregation heave, but have low frost heave susceptibility when evaluated using the segregation potential (*SP*) concept (Konrad, 1980; Konrad and Morgenstern, 1981). Though the mechanism of frost heave has been well described (Andersland and Ladanyi, 2004; Konrad, 1980; Loch, 1979a,b; Miller, 1972; Mitchell, 1993; Taber, 1929, 1930), these differing measures result in an uncertain assessment of the frost susceptibility of these types of materials. This uncertainty is also reflected in the modified ASTM D5918-13 test standard (ASTM, 2013), which presents only a *tentative* frost susceptibility criteria based on the heave rate of the material after eight hours of freezing.

The focus of this study was to compare results from the one-dimensional frost heave testing of fine grained material generated from the abrasion of a diorite aggregate (railway ballast) to the well quantified and published Devon silt. The contributions of this work include: (1) new laboratory testing results for a unique material that may be used for the calibration and generation of future models; (2) an examination of existing methods and their limitations for the quantification of the frost susceptibility of these two materials; (3) identification of the key mechanism that results in the disparity between assessments; and (4) conclusions with respect to how these results should impact the development of a transient frost susceptibility characterization criterion.

2. Materials and methods

One-dimensional frost heave testing methodology was adopted from Konrad (1999), with modifications including the addition of a fluorescent tracer to monitor the freezing front and its advance (Xia, 2006) and a reduction of the stress applied to consolidate the specimens (σ_{vo}) to a range more indicative of the estimated range of *in situ* preconsolidation stresses of ballast fines. Seventeen specimens (12 comprised of ballast fines, 5 of Devon silt) were subjected to one-dimensional frost heave tests.

2.1. Source of soil samples

Devon silt is a well-known frost susceptible soil. The material was chosen because it is locally available (53°21′28.25″N, 113°42′31.80″W) and has been the subject of extensive testing (Azmatch et al., 2012; Konrad, 1980, 1999; Xia, 2006). The crushed rock ballast used to generate the fines was obtained from McAbee pit, a railway quarry located at Mile 41.0 Ashcroft Subdivision, west of Kamloops, British Columbia (50°47′13.75″N, 121°18′43.74″W). The ballast material is a hard, grey, and medium-grained rock, likely diorite, based on visual inspection (Jubien and Mekechuk, 1990). The specimens used for the frost heave tests consisted of fine-grained material (<75 μm) generated

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from Los Angeles Abrasion (LAA) testing of ballast specimens. The fines generated from the LAA tests were washed through a 75 μm sieve with the passing grains collected and stored in a moisture room to allow the soil particles to settle. The settlement of the fines was assumed complete when the suspension liquid appeared clear and the density of the suspension was below 1.05 g/cm^3. The settled particles were then oven dried.

2.2. Characterization of soil properties

The grain size distribution (GSD; Fig. 1) and relevant index properties, such as liquid limit (W_L), density of solid particles (ρ_s), average particle dimension of the fines fraction ($d_{50}(ff)$), and specific surface area (S_s) (Table 1), were measured for each of the soils. The grain size distribution was determined using hydrometer analysis following ASTM Standard D422-63 (ASTM, 2007). The particle diameter at which 50% of the particles are smaller (d_{50}) was determined from the grain size distribution.

Applying the United States Army Corps of Engineers (USACE) frost design classification system, the soils were classified on a scale susceptibility that ranges from non-frost susceptible (NFS) to F4 (highly susceptible). The high silt content of both soils tested here resulted in USACE classifications of F4 (USACE, 1984).

The W_L of the ballast fines could not be determined using ASTM D4318-10 (ASTM, 2010), which is based on the Casagrande method; the number of blows required to close the groove remained below 25 regardless of the water content and, as such, the ballast fines were classified a non-plastic soil. The W_L was instead determined using the Swedish fall cone method as specified in CAN/BNQ 2501-092-M-86 (Sridharan and Prakash, 2000). In this method, the liquid limit of a soil is determined when a 60°–60 g cone produces a 10-mm penetration. The W_L of the Devon silt was determined using both methods. The difference in characterizability with respect to W_L is important as it illustrates that the ballast fines do not exhibit clay-like behaviors despite the large quantity of clay-sized particles; this implies that these particles are not clay.

The S_S for both materials was determined using the methylene blue absorption method (Santamarina et al., 2002). This value is used to quantify the water adsorption property of the soil and the degree of colloidal surfaces. The S_S was 8.3 m^2/g for the ballast fines and 89.9 m^2/g for the Devon silt; this result also emphasizes the different nature of the clay-sized particles in these soils.

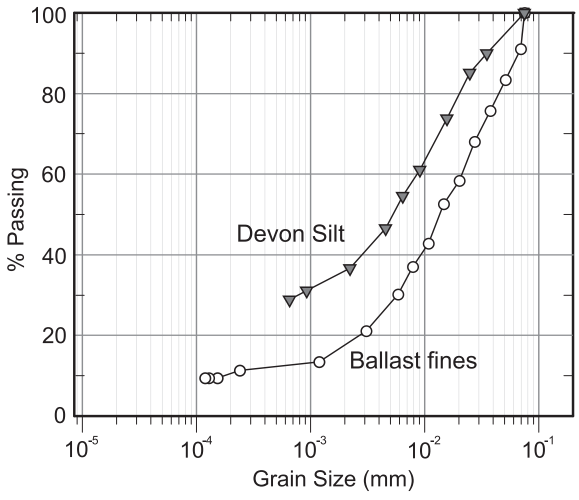

Fig. 1. Grain size distribution of materials used in this study.

2.3. One-dimensional frost heave testing

2.3.1. Laboratory testing apparatus and data recording

The experimental apparatus (Fig. 2) is the same as that used by Xia (2006) and Azmatch et al. (2012). The freezing tests were performed in cells each consisting of a rigid, transparent, acrylic tube, with an internal diameter of 101.4 mm and platens at both ends. These cells are long enough to accommodate specimens with heights of 250 mm. A transparent cell wall was used to monitor the location of advancing frost front. The cell wall was lubricated using petroleum jelly to reduce the friction developed between the soil and the cell wall.

Temperature measurements were taken using five resistance temperature detectors (RTDs) embedded in the sample (Fig. 2). These RTDs were spaced at 25 ± 1 mm intervals, with the lowest RTD located 5 mm above the base of the specimen. The RTDs had a reported accuracy of ±0.05 °C.

The temperatures of the top and bottom platens of the cell were maintained with ethylene glycol mixed with an equal measure of water circulated between temperature-controlled reservoirs and channels machined within the platens. The circulated glycol mixture was used to maintain the temperature of the upper platen below freezing, and the lower platen above freezing. Freezing progressed downward from the top of the specimen to the bottom. The tests were carried out in a cold room maintained at a constant 2 ± 1 °C. The above freezing temperature of the cold room limited the need for defrost cycles within the cold room, which did not coincide with testing. The cell was surrounded with mineral wool to insulate it and to allow the specimen to develop a one-dimensional temperature gradient.

A vertical stress of 2 kPa, from the weight of the freezing cap, was applied to the specimen during freezing. The vertical displacement of the top of the specimen was measured using a linear voltage displacement transducer (LVDT) with an accuracy of ±0.01 mm. All installed sensors were set to take measurements at 15-minute intervals.

The specimens were allowed ready access to water during freezing. Water was supplied via a horizontal burette tube at a height of 25 mm above the base of each specimen. Water intake from the burettes was recorded using a video camera and manually transcribed at 15-min intervals. A solution of fluorescent tracer ($C_{20}H_{12}O_6$; 5 g/L in water) was used to determine the location of the boundary between the frozen and unfrozen portions of the specimen. Based on results presented in Xia (2006), the presence of the fluorescent tracer was not anticipated to affect the frost susceptibility or behavior during testing.

The entire freezing process was carried out as per ASTM D5918-13 (ASTM, 2013). Minor modifications included a reduced temperature gradient across the specimen of 0.08 to 0.073 °C/mm in stage 3, and lengthening of the duration of stages 2 and 3. The modifications permitted the frost heave susceptibility to be assessed from the segregation potential theory and heave rate of the materials under laboratory test conditions. The total freezing time for all specimens tested was between 96 and 120 h.

2.3.2. Laboratory specimen preparation

The specimens used to measure frost susceptibility were made using a slurry of each soil type prepared with water content between 1.2 and 1.3 times the W_L. This slurry was poured into the freezing cell and subjected to one-dimensional consolidation under σ_{vo} values of 2, 10, 20, or 30 kPa. This range of σ_{vo} was selected as it is inclusive of the overburden stress of the ballast layer (ideally 600 mm) and the variation of this depth due to the history of a site. Specimen heights before consolidation were 120 ± 5 mm. Specimens were consolidated until primary consolidation was complete, as determined by a plot of displacement vs. $\sqrt{\text{time}}$ (Das, 2008). Axial strain of the specimens after consolidation ranged between 7 and 12% and increased with σ_{vo}. After consolidation, the platens were placed on the specimens. The properties of the