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Evaluation of frost heave and moisture/chemical migration mechanisms in highway subsoil using a laboratory simulation method

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ABSTRACT

Seasonal processes in cold countries significantly affect the engineering characteristics of highway subsoil over time. Cyclical freeze-thaw leads to changes in thermal and moisture conditions. As a result, road bearing capacity can progressively change from the initial design. In this work, a modified laboratory method was developed, with cyclical freeze-thaw of soil samples and simultaneous supply of deionised water and a de-icing agent (sodium chloride) to the base. The benefits of the test procedure included slow freezing, simulating the conditions that can be experienced by highway soils in cold environments, extended soil column heights and a larger number of identical soil samples, which allowed experimental variability to be assessed. The method included the monitoring of moisture and chemical mass transfer in the soils. Samples supplied with deionised water experienced ice segregation in their upper parts, and significant heave. While soils supplied with NaCl solution behaved in a similar fashion during their first freeze-thaw cycle, the second cycle saw a reduction in the rate of migration of the freezing front within the soils and also less ice segregation and less heave due to increased salinity. Salt was preferentially transferred upwards in the soil columns as a result of the thermal gradient, including negative pressure associated with cryosuction, and osmotic pressure. The new method provides a more realistic laboratory approach to assessing potential freeze-thaw impacts, and the effects of de-icing agents on soils beneath roads, and in different settings.

1. Introduction

Highway subsoils are subject to significant variability in terms of their moisture-temperature regime, especially in countries with a severe cold climate. As highway pavements have higher densities and thermal conductivities, the near surface layers freeze before, and at a faster rate than roadside soils (Vasilenko, 2011; Vasilenko, 2011; Chunpeng et al., 2010; Simonsen et al., 1997). The temperature gradient in the highway sub layers may also induce a significant upwards and lateral migration of moisture supplied from the ground water table (Konrad and Samson, 2000).

In a highways context, this groundwater may be modified by deicing agents, with a resultant depression of the freezing point easily down to −25 and with more difficulty up to −41 °C, depends on the chemical content (Wan et al., 2015). Wan et al. present a modified methodology to examine this depression and the degree to which it enhances migration of soil moisture towards the freezing front under the pavement structure. It also explores whether the de-icing chemical migration responds to the thermal gradient in the highway subsoils. When the temperature of a soil falls sufficiently, the interstitial water starts to segregate into ice crystals. The remaining, unfrozen, water becomes progressively enriched with dissolved salts and has a depressed eutectic temperature (Bing and He, 2011; Torrance and Schellekens, 2006).

Previous studies have provided contradictory evidence for the movement of de-icing agents within soil: Vidyapin and Cheverev (2008) report de-icing chemicals moving towards the freezing surface, while Brouchkov (2000) detected no obvious salt migration during the freezing period. As a result, little certainty can be derived from the published literature about the potential nature of frost heave in highway subsoils.

The nature of change in mechanical characteristics during the spring thaw is also unclear. Thawing occurs both from the pavement and base of the frozen soils. However, some parts of the saturated sub soils can remain frozen for some time and block the drainage of moisture downwards. Localised ice lenses and associated deformation of subsoils may lead the significant strains in the pavement structures due to the rapid oversaturation and the weakening of sub base soils (Miller, 1972). A thorough review based on the frost heave thermodynamics has been prepared by Henry (2000).

Numerous studies have attempted to explain the soil properties during the freeze and thaw period since early 1900s (Miller, 1972; Hoekstra, 1969; Hoekstra, 1966; Taber, 1930). Most of the studies have taken place under laboratory conditions to provide experimental control and improved accuracy in the results (Nagare et al., 2012; Bronfenbrener and Bronfenbrener, 2010).

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Progressive approaches have been performed in a triaxial cell within a negative temperature (Cui and Zhang, 2015; Zhang et al., 2013; Hazirbaba et al., 2011; Sinitsyn and Løset, 2011; Ishikawa et al., 2010; Qi et al., 2006; Brouchkov, 2002). Triaxial cell tests enable contemporaneous mechanical loading but only one sample can normally be tested at a time. The size of the tested sample is also restricted by the size of the test cell.

There are several standard methods which are used for freeze-thaw cycles of soils in different countries: BS 812-124:2009, ASTM D 5918-06, GOST 28622-2012 and BS EN 1997-2:2007, Section 5, 5.5.10. These typically involve testing 15 cm high soil samples over a limited and controlled temperature range, usually +3 and −3 °C. The number of simultaneously tested samples is normally limited to four. The standard methods provide uniformity and predictability of the obtained results and are suitable for classification tests. However, the sample height and limited range of variables do not allow for a detailed examination of the role of thermal gradient, including a descending freezing front, migration of pore water, or the effects of changing soil water chemistry to be examined. Therefore, in order to better understand the complex processes in the highway sub soils, a laboratory method for freeze-thaw cycles with simultaneous supply of water at the base of the sample was developed.

2. Materials and methods

A new laboratory method with freeze-thaw cycles has been developed from the ASTM D 5918–06 Standard. This allows a more realistic simulation of freeze-thaw with depth.

The height of the soil column was increased up to 1.00 m, including 5 cm of saturated soil at the base. Water was supplied to the base through a 5 cm fine sand filter (Fig. 1). The samples were made from non-saline soil. This enabled the observation of salt mass transfer from a solution supplied at the base of each soil column. Application of the non-saline soils and feeding the base 5 cm layer with sodium chloride solution in the new method facilitates the observation of the chemical mass transfer and its possible secondary salinization in consequence of the freeze-thaw of the soil mass.

2.1. Experimental soil characteristics

The soils used in this experiment were remolded on geotechnical data from Astana, Kazakhstan (Karaganda GIIZ, personal communication), where the winter air temperature can drop to below −35 °C. Kazakh Steppe soils typically consist of ancient sedimentary rocks that have been transformed by chemical and physical weathering to residual layers, together with alluvial soils of irregular thickness according to KazGIIZ geological report. To ensure comparability in laboratory tests a remolded sandy clay, reflecting frequently occurring soils 1 m below the surface, was manufactured from 50% sand with angular shape of the grains (cross-sectional dimension less than 2 mm) and 50% kaolinite clay. A particle size distribution of the sand part in the soil sample is presented in Fig. 2. Average plastic and liquid limits were 23.77% and 37.05%, respectively. Initial classification properties of the remolded soils are presented in the Table 1.

The variability in dry bulk density with moisture content of the remolded soil is shown in Fig. 3. The 95% value of maximum dry density is 1.8 Mg/m^3, which corresponds to the w = 17.2% moisture content, with the compacted soil being almost completely saturated.

California bearing ratio was derived according to BS 1377-4:1990. The percentage of standard forces for penetrations of 2.5 and 5 mm were calculated. A sequence of CBR tests was conducted for a range of moisture content values (Fig. 4). The corresponding dry density and CBR values at different moisture contents are given in Table 2.

2.2. Sample preparation

The dry soil mass was mixed with 17.2% of deionised water by mass and stored for 24 h to let the moisture distribute uniformly. Previous studies have used salinized soil from the start (e.g. Nguyen et al., 2010; Arenson et al., 2005). The moistened manufactured soil was then compacted within heavy duty plastic 10 cm × 10 cm cylinders using a 2.5 kg hammer to produce a dry bulk density of 1.8 Mg/m^3. This was done by alternately adding 5 cm of soil and then compacting using 31–32 hammer blows, to provide the same compactive effort as in BS1377-4:1990. After filling and compaction, each stack weighed 16.784 ± 0.1 kg. The cylinder at the bottom included a basal, 5 cm thick layer of fine sand to act as a filter layer. Water was supplied to the base via a pipe to produce saturated conditions in the bottom

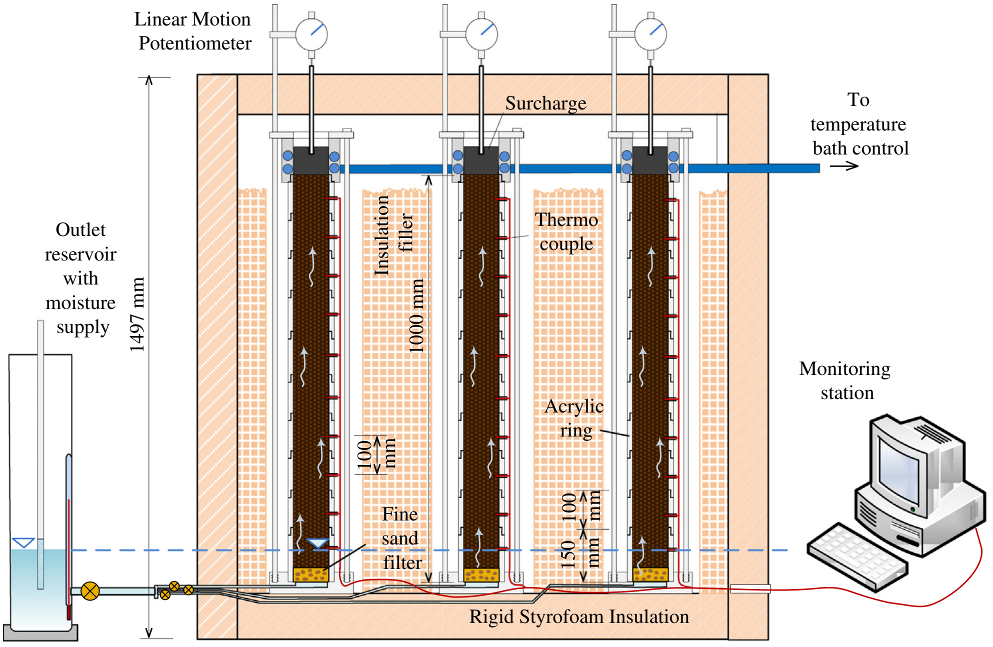

Fig. 1. Environmental chamber for freeze-thaw cycles with 9 soil samples capacity.