Geo-Resilience 2023 Conference, Cardiff, Wales
D.G. Toll & M.G. Winter (Eds)
British Geotechnical Association, London. 2024
https://doi.org/10.53243/Geo-Resilience-2023-3-3

Effects of Wet-dry and Intermittent Freeze-thaw Cycles on the Volume Change Behaviour of Some Geomaterials

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Abstract

Climate change has led to more extreme weather events during the last decades. Seasonally hot weather regions have experienced harsh winters. Similarly, global warming has contributed to raising the mean summer temperature in cold regions. Geomaterials in various civil engineering applications are expected to experience changes in environmental loading conditions and may undergo freezing, thawing, wetting and drying processes accompanied by volume change which may cause severe distress to many civil engineering structures. In this paper the effects of wet-dry cycles accompanied by intermittent freeze-thaw cycles on the volume change behaviour of some materials (soils and industrial waste) were studied. Compacted samples of the materials were prepared, subjected to several wet-dry cycles and then exposed to one cycle of freeze-thaw. The patterns of wet-dry and freeze-thaw cycles were repeated. The intermittent freeze-thaw cycles destabilised the equilibrium strain that was achieved by the materials during the previous wet-dry cycles; however, a new equilibrium in terms of vertical strain was attained by the materials with an increasing number of wet-dry cycles, but with a reduced equilibrium strain. Wet-dry cycles caused an increase in the frost heave and thaw settlement for the materials studied indicating that the hydraulic conductivity increased due to exposure of the materials to increasing number of wet-dry cycles.

Keywords: Climate change, wet-dry cycles, freeze-thaw cycles, volume change

1. Introduction

Soils and industrial wastes are compacted and used in many civil engineering structures (pavements, railway formations, liners and backfills). These materials undergo freezing and thawing processes in cold climates and wetting and drying processes in temperate climates. The volume change behaviour of compacted geomaterials as a result of seasonal fluctuation in water content, suction and temperature changes is of significant interest to geotechnical and geoenvironmental engineers and practitioners (Konrad 1989; Tripathy et al. 2002). Studies in the past have shown that the volume change, permeability, water retention and mechanical behaviour of soils and industrial wastes are affected by wet-dry and freeze-thaw cycles (Tripathy and Subba Rao 2009). It has been have shown that heave and shrinkage/settlement, permeability and shear strength attain a consistency after several freeze-thaw and wet-dry cycles (Chamberlain et al. 1990; Tripathy et al. 2002; Konard 2010; Cui et al. 2014).

Extreme and unusual weather events have become more common in the hot-seasonal regions of the world as a result of climate change (Zhou et al. 2011; Herring et al. 2015). The temperate regions of the world have been experiencing unusually low (below 0°C) temperatures, whereas the global average temperature has increased above pre-industrial levels. It is not very well understood how geomaterials respond to such weather pattern changes. The main objective of the present study is to investigate the effect of intermittent freeze-thaw cycles on the volume change behaviour of some geomaterials that were exposed to several wet-dry cycles.

2. Materials and methods

2.1 Laboratory test setup for wet-dry and freeze-thaw tests

A laboratory test setup was used to perform the cyclic wet-dry and freeze-thaw tests (Figure 1) (Al-Hussaini 2017; Tripathy et al. 2020). Using the test set up, it is not required to dismantle a specimen at any stage of the test while the specimen is taken through wet-dry as well as freeze-thaw cycles. The test set up enabled measuring vertical deformation and changes in the temperature at various predetermined heights of the specimen (diameter = 103.3 mm and height = 65 mm).

The test setup consists of a cylindrical polyvinyl chloride (PVC) mould assembly, a vortex tube that can supply hot or cold air of desired temperatures to a top cooling/heating chamber, linear variable displacement transformers (LVDTs) to measure vertical deformation, six thermocouples (two within the heating/cooling chamber to monitor temperature at the top of the specimen and four for establishing temperature profiles of the specimen), a porous stone, a water reservoir, a thermal insulation sheath, an air supply system, and a data acquisition system. The PVC mould assembly comprises a single-flanged exterior mould and a step-flanged interior mould. The exterior mould is attached to a PVC base plate. An acrylic hollow cylinder-stand with a perforated acrylic disc at the top is placed within the exterior mould in order to create a water reservoir. A porous stone is placed on the perforated acrylic disc. The interior mould, with the thermocouples attached to the inner face, is made to rest on the perforated acrylic disc. The annular space between the interior and exterior moulds accommodates the ultrathin wires of the thermocouples. The specimen is placed on the porous stone, whereas the cooling/heating chamber is placed above the specimens during the tests. The LVDT holders are attached to a horizontal frame (not shown) which in turn is positioned directly on top of the device. The LVDTs on the heating/cooling chamber and on the flange of the interior mould measure the vertical deformation of the specimen and the interior mould.

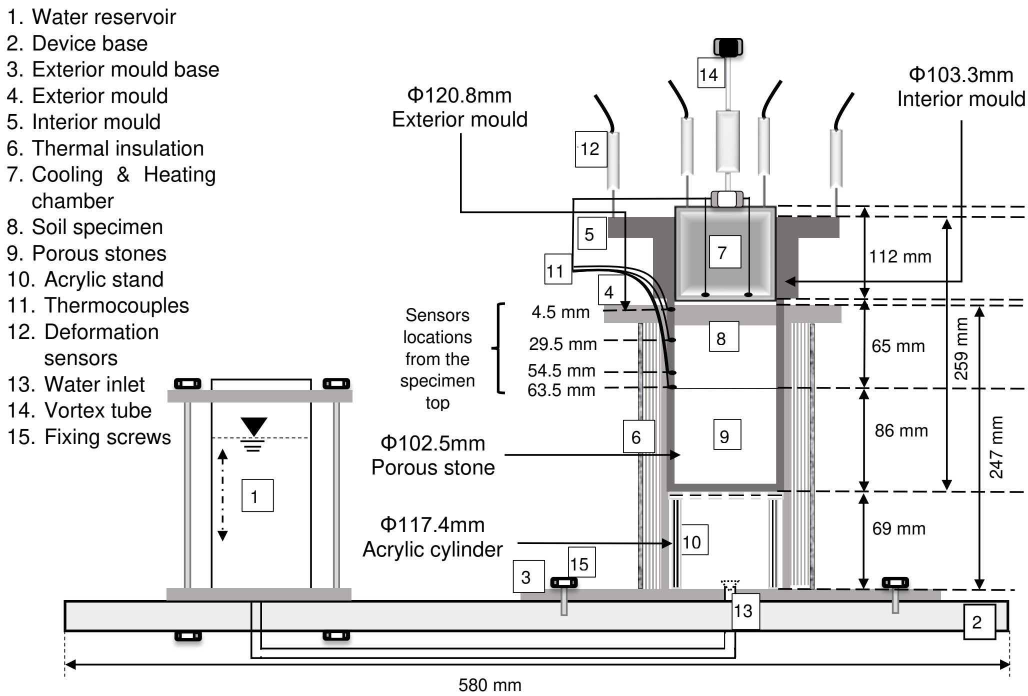

Figure 1: Experimental setup used for cyclic wet-dry and freeze-thaw tests.

The vortex tube is connected to the top cooling/heating chamber, which is a composite cylinder with a stainless-steel side and a 1.8 mm thick copper base. A 12.5 mm-thick PTFE disc with six air vents, each 10 mm in diameter, is attached firmly to the top open end of the stainless cylinder. Compressed air (7-bar) is fed transversely into the generation chamber of the vortex tube that is made to spin by a generator. The air moves down the long tube in which hot air separates outwards and towards the wall of the tube due to the inertia of motion, whereas the cold air is pushed to the centre of the tube. A percentage of the hot air is made to exit (hot end), whereas the remaining air flows towards opposite end (cold end). The cold air supplied by the vortex tube can be used to apply freezing temperature at the top of the specimen, whereas the hot air can be used during the drying cycle. The pressurised air (cold or hot) is made to exit the top chamber via the air vents.

2.2 Materials used and experimental methods

Speswhite kaolin, Pegwell Bay soil and a cement kiln dust were tested. The properties of the selected materials and initial conditions the compacted specimens tested are shown in Table 1. Compacted specimens were prepared by static compaction method.

Table 1: Properties and initial compaction conditions of the materials tested.

Properties	Speswhite kaolin	Pegwell Bay soil	Cement kiln dust
Specific gravity	2.61	2.69	2.72
Liquid limit, plastic limit and shrinkage limit (%)	69, 42 and 33	30, 19 and 16	42, 27 and 21
Sand, silt- and clay-size (%)	0, 6 and 94	7, 84 and 9	0, 71 and 29
Mineralogy	Kaolinite (95%), Illite (4%)	Calcite (16%), Dolomite (6%), Quartz (78%)	Calcite (85%), Silicon oxide (14%)
Optimum water content (%) and maximum dry unit weight (kN/m^3)	28.0 and 14.56	16.0 and 17.27	28.0 and 14.86
Initial water content (%) and dry unit weight (kN/m^3) of compacted specimens	30.0 and 14.16	19.0 and 16.91	24.2 and 12.50

The duration of the seasons can have a significant impact on the volume change behaviour of various geomaterials. The experimental program adopted in this study does not replicate the length of the seasons and are only laboratory-scale testing of materials with assumed temperature and hydraulic boundary conditions for predetermined periods of testing.

The specimens were wetted at room temperature. The supplied water to the specimens was at ambient laboratory temperature of 21 ± 2 °C. The wetting cycles were considered completed after the deformation of the specimens was found to be stabilised (usually less than three days). The temperature at the top of the specimen was maintained at 52 ± 1.5 °C during the drying process. The drying stage was completed when the vertical deformation of the specimen attained a constant value which occurred after more than ten days for the materials studied. During the initial phase of the investigation, the water contents of the materials at the end of drying cycles were determined. The results showed that the materials underwent partial drying process. After termination of the drying stage and before starting the next wetting stage, a duration of 24 hours was allowed for the temperature in the specimen to attain the room temperature. The vertical deformation at that stage was recorded prior to the commencement of the next wetting stage. During the freezing process, the temperature at the top of the specimens was lowered to -19 ± 0.5 °C and maintained for 24 hours, whereas the thawing process occurred at the ambient laboratory temperature. No water was supplied to the specimens during the drying process. During the wetting process, the water level was kept at the top the specimens, whereas during freezing and thawing stages the water table was kept at the bottom of the specimens.

The sequence of the climatic processes adopted in this study was by subjecting compacted specimens of the materials to cycles of wetting and drying until an equilibrium was attained in terms of the vertical deformation. Then, one cycle of an intermittent freeze-thaw process was introduced. Once the freeze-thaw cycles were completed, the specimen was further subjected several wet-dry cycles followed by another cycle of freeze-thaw and so on. The cyclic tests were carried out at an applied vertical pressure of 2.0 kPa (the self-weight of the heating/cooling chamber and the attached accessories). The vertical deformation of the specimens during wetting, drying, freezing, and thawing processes were measured at the top of the cooling/ heating chamber. The temperature at the top and at the predetermined levels along the depth of the specimens was monitored during the tests.

The frictional resistance between the specimens and the inner surface of the PVC mould was minimised by using silicon grease. During a freezing cycle, the adfreezing effect (the top of the specimen was frozen and adhered to the wall of the interior mould) at the top of specimen did not allow the increase in the volume of specimens towards the top. The volume change specimens in this occurred towards the bottom and all the four the LVDTs measured the vertical deformation of the specimens during freezing cycles (Al-Hussaini 2017).

3. Results and discussion

3.1 Cyclic wet-dry and intermittent freeze-thaw test on Speswhite kaolin

The compacted specimen of Speswhite kaolin was first subjected to several wet-dry (WD) cycles followed by an intermittent freeze-thaw (FT) cycle and further the climate sequence was repeated. A FT cycle was introduced at the end of a wetting cycle. At the end of a FT cycle, the specimens were subjected to a drying cycle prior to implementing the subsequent wetting cycle. Typical results of the cyclic wet-dry test with intermittent freeze-thaw cycles for the compacted specimen of Speswhite kaolin are presented in Figure 2. The vertical deformations of the specimen with increasing number of climate cycles are shown in Fig. 2a. The measured temperatures at top of the specimen (TC0) and at various depths (TC1, TC2, TC3 and TC4) during the test are shown in Fig. 2b.

It can be seen in Fig. 2b that the temperature at top of the specimen during wetting (W), drying (D), freezing (F), and drying (D) cycles were about 25, 55, -18, and 25 °C, respectively. The temperature at various depths of the specimens were smaller than at the top.

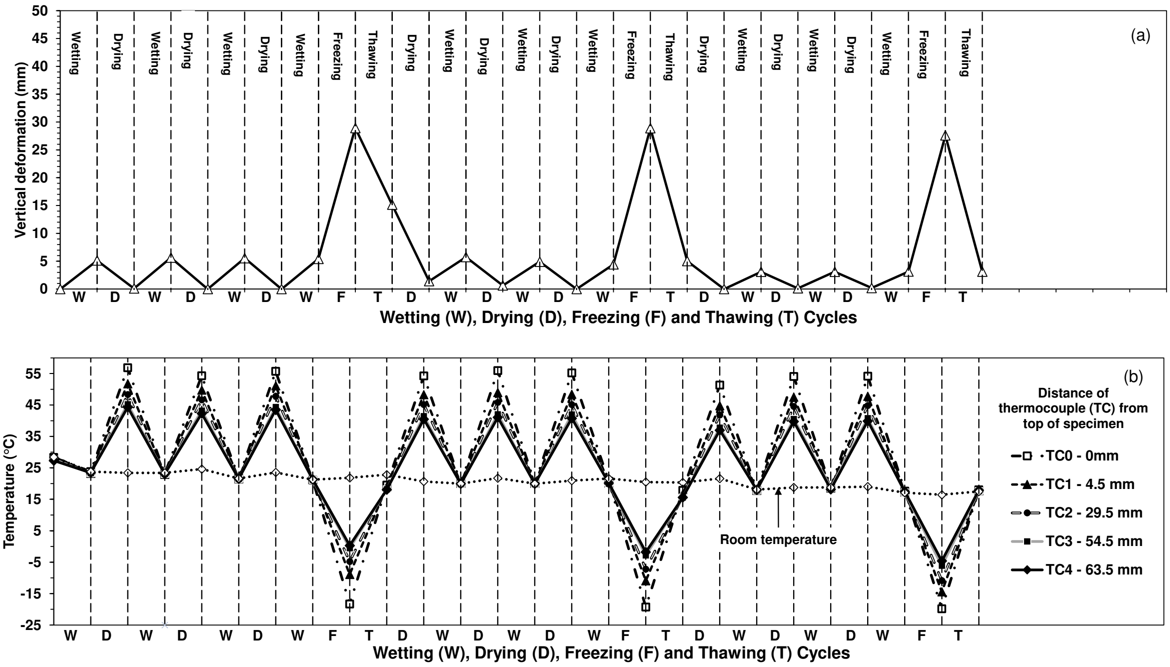

Figure 2: (a) Vertical deformation and (b) temperature changes of Speswhite kaolin specimen with an increasing wet-dry with intermittent freeze-thaw cycle.

The specimen of Speswhite kaolin exhibited swelling deformation (5.1 mm) during the first wetting cycle and shrinkage deformation (5.0 mm) during the first drying cycle. In the second WD cycle, the swelling and shrinkage deformations increased slightly and then remained similar during the third WD cycle (about 5.5 mm). Upon subjected to a sub-zero temperature of -18 °C at the top of the specimen during the first intermittent freezing cycle after the fourth wetting cycle, the specimen exhibited a frost heave of 23.5 mm and the settlement during the thawing cycle was 13.8 mm. The deformation of the specimen during the drying cycle following the first thawing cycle was 13.7 mm. In the subsequent WD cycles following the first intermittent FT cycle, the swelling and shrinkage deformations were found to decrease and then stabilised at about 4.5mm. The frost heave and thaw settlement in the second intermittent FT cycle were 24.5 and 23.9 mm, respectively; that is, an increase in the vertical deformation as compared to that occurred in the first intermittent FT cycle. The deformation during the shrinkage cycle following the second intermittent FT cycle was 5.3 mm which was significantly lesser than that occurred during the shrinkage cycle following the first intermittent FT cycle. The deformations during the WD cycles following the second intermittent cycle were found to be lesser (about 3 mm) as compared to that occurred in the earlier WD cycles. The deformations due to frost heave and thaw settlement were found to be similar (24. 5 mm) during the third FT cycles, at which the test was terminated.

Soil specimen showing an equilibrium in terms of the vertical deformation after several wet-dry cycles agrees well with the findings reported in the literature (Tripathy et al. 2022). The test results showed that the intermittent freeze-thaw cycles destabilised the equilibrium deformation that was achieved by the materials during the previous wet-dry cycles; however, a new equilibrium in terms of vertical deformation was attained with an increasing number of wet-dry cycles, but with a reduced equilibrium deformation.

3.2 Impact of wet-dry and intermittent freeze-thaw cycles on vertical strain of the materials

Compacted specimens of Pegwell Bay soil and cement kiln dust were first taken through several WD cycles and then an intermittent FT cycle as in the case of Speswhite kaolin. The climate sequence was then repeated. Figure 3(a), (b) and (c) present the vertical strains of the specimens of Speswhite kaolin, Pegwell Bay soil and cement kiln dust, respectively. The vertical strain (%) in each cycle was calculated based on the height change of the specimens with reference to the initial height of the compacted specimens (i.e., 65 mm).

The material type influenced the vertical strains during the WD cycles. The swelling and shrinkage strains were far greater in case of Speswhite kaolin, whereas both Pegwell Bay soil and cement kiln dust exhibited strains of less than 0.5% during any WD cycles. The clay-size fractions in case of Speswhite kaolin, Pegwell Bay soil and cement kiln dust were 94, 9 and 29 %, respectively. The type of mineral present in the material is known to influence both swelling and shrinkage magnitudes. The inability of Pegwell Bay soil to exhibit swelling and shrinkage strains may be attributed to the presence of rock minerals in the soil. The cementitious property (i.e., the cement phase reaction causing bonding between particles) and the presence of rock minerals may be held responsible for the very low swelling and shrinkage strains in case of cement kiln dust. Kaolinite is a non-expanding mineral which only exhibits expansion upon hydration from dry state and when compacted to very high dry densities. The presence of illite in Speswhite kaolin may be attributed to the cause for swelling and shrinkage strains of the clay.

The strains associated with frost heave and thaw settlement for Speswhite kaolin, Pegwell Bay soil and cement kiln dust in the first, second and third intermittent FT cycles are shown in Fig. 3. It can be seen that WD cycles enhanced the frost susceptibility and thaw settlement of the materials. Viklander (1998) reported that the void ratio of compacted soils increases due to freeze-thaw processes and as a result of changes in particle rearrangements. With an increase in the frost heave and thaw settlement, and a lesser shrinkage strain during the partial drying cycles, Pegwell Bay soil and cement kiln dust specimens exhibited uprising movement and accumulation of plastic strain.

4. Conclusions

In this study, the volume change behaviour of some selected geomaterials were studied by subjecting compacted specimens to several wet-dry cycles with intermittent freeze-thaw cycles. A test set up was used that enabled performing the wet-dry and freeze-thaw tests. The following conclusions can be drawn from the study.

(1) The vertical deformation of the materials attained an equilibrium state after several wet-dry cycles at which the magnitudes of strains during wetting and drying processes were found to be similar. These tests results agree well with the findings reported in the literature.

(2) The intermittent freeze-thaw cycles destabilised the equilibrium strain that was achieved by the materials during the previous wet-dry cycles; however, a new equilibrium in terms of vertical strain was attained by the materials with an increasing number of wet-dry cycles, but with a reduced equilibrium strain.

(3) Wet-dry cycles caused an increase in the frost heave and thaw settlement for the materials studied indicating that the hydraulic conductivity increased due to exposure of the materials to increasing number of wet-dry cycles.

Acknowledgements

This study has been funded by the Engineering and Physical Sciences Research Council (EPSRC) as part of the Climate Adaptation Control Technologies for Urban Spaces (CACTUS) project.

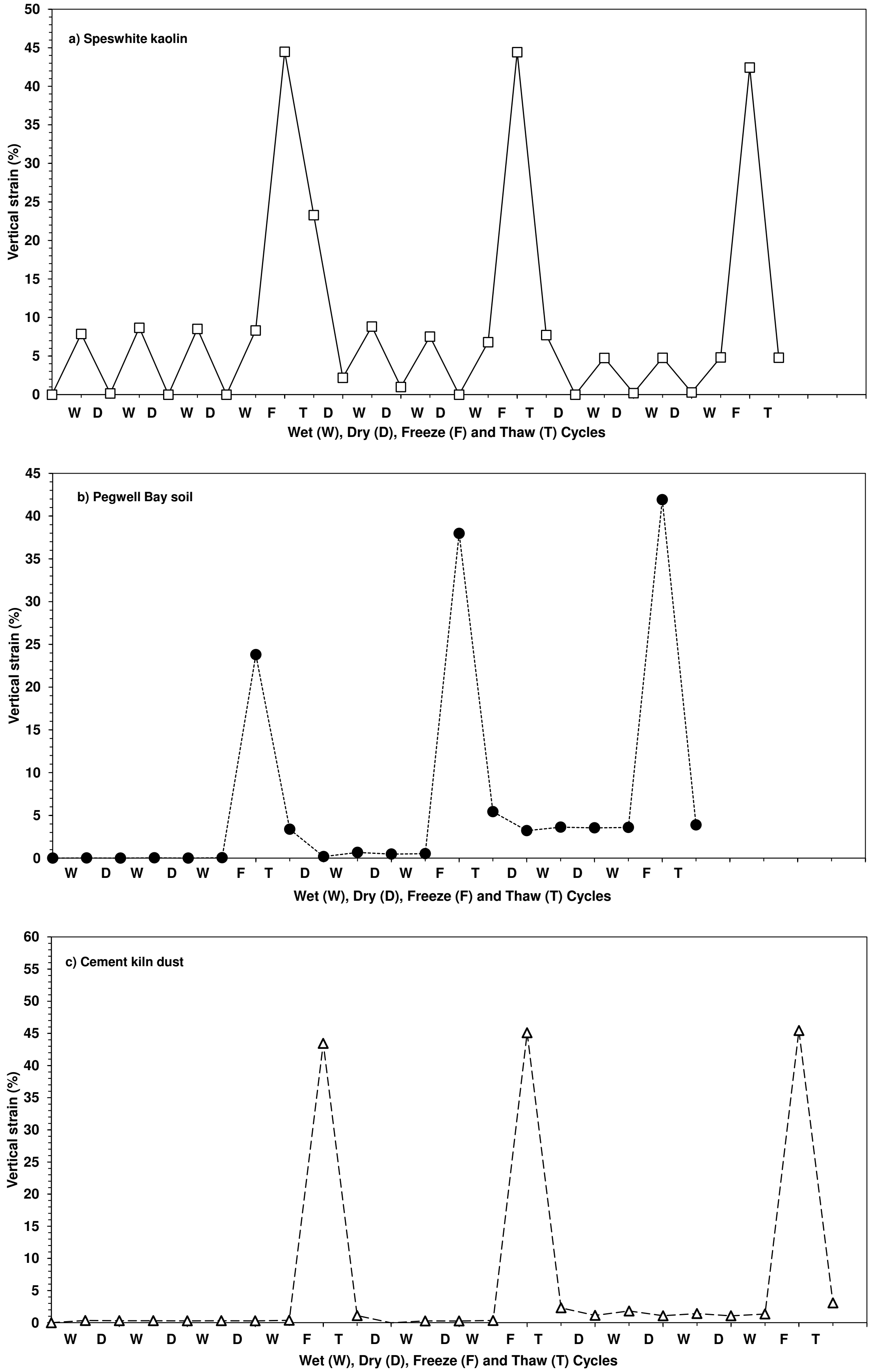

Figure 3: (a) Vertical strains during cyclic wet-dry and intermittent freeze-thaw cycles for (a) Speswhite kaolin, (b) Pegwell Bay soil and (c) cement kiln dust.

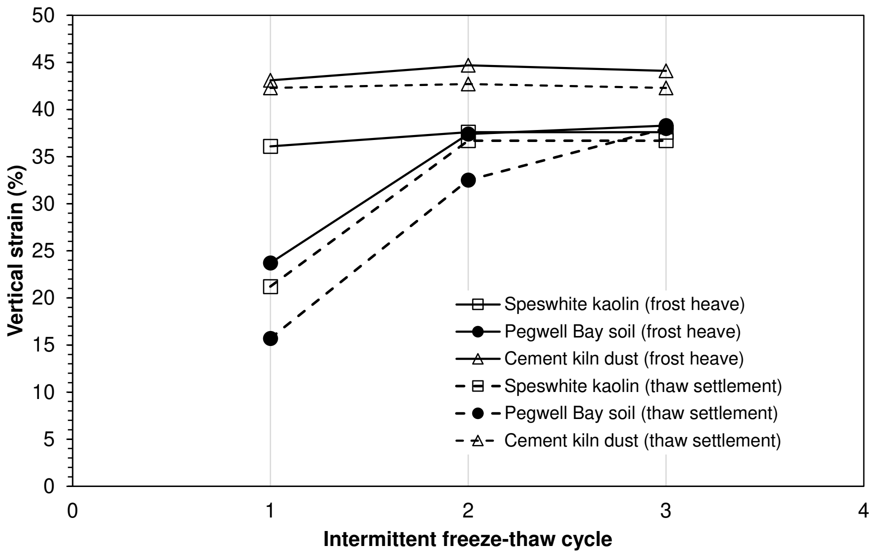

Figure 4: (a) Vertical strains of the materials due to frost heave and thaw settlement during the intermittent freeze-thaw cycles.

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