geotechnics

Review

Review of the Effects of Freezing/Thawing Cycles on the Engineering Properties of Soilcrete

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Abstract: Soil mixing, which blends the natural soils with cementitious materials (or binders), has been used to enhance the soft ground and improve problematic soils for several decades. With developments in technique and machinery, the embedded depth of soil mixing has increased from the shallow ground to as deep as tens of meters, especially when deep soil mixing and grouting emerged in the 1970s. Extensive studies have been undertaken on the physical and mechanical properties of the mixing products (soilcrete) with regard to water content, soil type, binder type, binder content, curing age, and curing condition. However, most studies initially focused on soil mixing in temperate weather. In recent decades, soil mixing in cold regions has become common. Thus, plenty of research has been conducted on the engineering properties of soilcrete exposed to weathering conditions in cold regions, namely freezing/thawing (F/T) cycles. However, while summaries of studies on soilcrete used in temperate conditions have been undertaken by researchers, reviews of studies on soil mixing in cold regions are still rare. In order to link potential research on soil mixing with previous studies and point out the possible research directions, a review of works on soilcrete subjected to F/T cycles was composed. The present paper summarizes the testing methods adopted by various studies and the change in engineering properties of soilcrete caused by F/T cycles.

Keywords: soil mixing; soilcrete; F/T cycles; engineering properties

Citation: Liu, C.; Berard, C.; Deng, L. Review of the Effects of Freezing/Thawing Cycles on the Engineering Properties of Soilcrete. *Geotechnics* **2022**, 2, 1003–1026. https://doi.org/10.3390/geotechnics2040047

Academic Editor: Abbas Taheri

Received: 5 October 2022
Accepted: 11 November 2022
Published: 15 November 2022

1. Introduction

The soft soil has been an obstacle for engineers and developers worldwide. Many ground improvement methods have been established since the 1920s [1–4] to deal with soft problematic soils, including shallow soil mixing, vertical drains, stone columns, and deep soil mixing (DSM). Among them, soil mixing has been used in a wide range of applications, including road pavement, subgrade, dams, shallow and deep foundations, slope, and contaminant treatment. As one of the most commonly used methods, soil mixing stands out because of the following advantages: readily available cementitious materials (or binders), relatively fast construction speed, significant improvement in strength and compressibility, and cost-effectiveness.

Soil mixing is an in situ method that blends binders with naturally incompetent soils. Generally, the binders used are lime, cement, slag, etc. Cement is the most commonly used material as it is easily made and has relatively constant components. In practice, the treated soil is abbreviated as soilcrete to represent the property changes due to the binders. Many researchers have studied the physical, chemical, and mechanical behavior of soilcrete [5–7]. In principle, the treatment effect is site-specific, depending on the mineralogy, deposition process, and particle size distribution of natural soils. However, most studies initially targeted the factors that influence the behavior of the soilcrete in temperate conditions, mainly in subtropical areas, because the soil mixing technique was mainly undertaken in temperate areas.

Since soil mixing has been extensively adopted in cold regions in recent decades, for example, in the applications of contaminant containment [8] and foundations for oil storage tanks [7,9], the effect of the freezing process on the soilcrete has attracted researchers' attention, particularly when the soilcrete is anticipated to provide compressive or tensile resistance to geotechnical or structural systems. Studies have investigated the changes in the mechanical and physical behavior of soilcrete after freezing/thawing (which is often denoted as F/T) cycles in road construction, contaminant containment, foundations of superstructures and canals, and so on. So far, researchers have thoroughly documented the behavior of soilcrete in temperate conditions and have agreed on the physical and mechanical performance of soilcrete in terms of different factors, including binder content, water content, curing age, etc. However, the understanding of the engineering behavior of soilcrete subjected to F/T cycles varied according to different researchers. Thus, it becomes necessary to review the studies on soilcrete subjected to F/T cycles critically.

A thorough review of the engineering properties of soilcrete subjected to F/T cycles is conducted in the present paper. The specific objectives are as follows: (1) summarize the effects of F/T cycles on the mechanical and physical properties of soilcrete; (2) review current F/T methods and equipment; (3) present the existing understanding of the microstructure of soilcrete with and without F/T cycles; (4) propose potential future studies on soilcrete in cold regions; and (5) introduce a recent study on the effect of F/T cycles on cement-treated stiff clay used as foundation support.

2. Engineering Properties of Soilcrete in Temperate Conditions

Ordinary Portland cement is the dominant binder material in most soil mixing projects, which consists of oxides, including the main components CaO (calcium oxide) and SiO (silicon dioxide). The calcium silicate hydrate is the major product of cement hydration. Because of various chemical compositions and morphology, calcium silicate hydrate is often denoted as CSH. The soil particles or particle clusters are bonded by the CSH agglomeration or gels. As the soilcrete matrix becomes alkaline owing to the formation of calcium hydroxides ($Ca(OH)_2$), the pozzolanic reaction occurs and generates additional CSH and calcium aluminate hydrates (CAH) [10], generating more bonds in the soilcrete. Noticeably, the CSH gels are responsible for improving the strength and stiffness of natural soils.

The binder hydration in the soil mixing usually occurs under temperate conditions, which means warm environments with an ambient temperature above 0 °C in the laboratory, on sites with a subtropical climate, or in the summer seasons of cold regions.

Many studies have been carried out on the properties of soilcrete and the performance of soil mixing projects under temperate conditions. Table 1 summarizes a few representative publications, showing the most commonly used testing methods in studies on soilcrete, such as the uniaxial compression strength (UCS) test, triaxial test, and oedometer test. Among all testing methods, the field testing has been used to identify the damage to soilcrete caused by the surroundings, and the lab testing has been used to obtain data for soil mixing design. In the beginning, core specimens obtained from the field, representing the soilcrete with in situ curing, were adopted for the lab testing [11,12]. However, the core drilling is costly, and mechanical properties of the soilcrete are necessary at the design stage. Thus, designing a proper mixing and casting procedure for the lab testing has been widely adopted.

2.1. Mechanical Properties of Soilcrete in Temperate Conditions

Products of the binder hydration enhance the mechanical properties of soilcrete under compression. Generally, the strength of soilcrete increases with curing time. Curing conditions, such as curing stress and curing temperature, also affect the strength of the soilcrete. At the early curing stage, the initial loading has been shown to remove the entrapped air in the soilcrete and greatly enhance the UCS strength of specimens [13–15]. Low temperature has decelerated the binder hydration, slowing down strength development [16].

Table 1 lists several representative studies that investigated the mechanical properties of soilcrete with various testing methods. The strength and stiffness are influenced by bonds formulated by the binder hydration. The UCS test is a primary method for determining the mechanical properties of soilcrete due to its reliability and speed. Based on the results of UCS testing, models considering the water/cement ratio were developed to predict the strength of soilcrete at long curing ages to facilitate the design process [17–23]. By comparison, Ref. [24] introduced the clay–water/cement ratio (natural clay water mass to cement mass) to determine the strength of soilcrete for fine-grained soils, which was incorporated into a prediction model and expanded the application to coarse-grained soils [25]. Additionally, Ref. [17] proposed an empirical equation for predicting the strength of soilcrete with consideration of the post-peak behavior.

Triaxial testing has also been conducted to investigate the mechanical properties of soilcrete [14,23,26–30]. It was concluded that the strength of soilcrete increased with confining pressure, and the performance of soilcrete resembled an overconsolidated clay, showing a strain-softening behavior. The cohesion and the friction angle have been observed to increase with cement content [27]. Many studies have implied that the preconsolidation pressure also increased with cement content [14,24,31].

The tensile strength (σ_t) is of great importance for soilcrete columns used for earth-retaining structures, such as slopes, dams, hydraulic barriers, runway subgrades, riverbanks, road and highway embankments, etc. Disregarding tensile forces could result in failures of soilcrete columns, as reported by [32]. Even though cement addition increases the σ_t of soilcrete, it does not prevent the tensile cracks from happening when subjected to external factors, such as differential settlement, wetting/drying cycles, F/T cycles, and large loads. The σ_t can be determined from a direct shear test, also known as the uniaxial tension test, and other testing methods. The authors of Ref. [33] determined the σ_t of soilcrete with the split tensile and three-point loading tests and introduced a relationship between UCS and σ_t.

Table 1. Key references on the performance of soilcrete under temperate conditions.

Reference	Soil Type	Application	Binders	Binder Dosage	Test Methods
[34]	Sandy clay	S/S for landfill grout	Cement	NA	UCS, permeability
[26]	Sandy silt	NA	Cement and fly ash	Cement 2% and fly ash 4%	UCS, CU, CD
[35]	Soft clay	Columns	Cement	5 to 25%	UCS
[27]	Silty clay	Columns	Cement	6 to 18%	CU
[10]	Marine clay	Stabilization	Cement	10%, 30%, 50%	XRD, SEM, MIP, PSD by laser diffractometric
[17]	Soft clay	Stabilization	Cement	5 to 20%	UCS, oedometer
[36]	Soft clay	Columns	Cement	8 to 33%	UCS, CU, CD
[14]	Marine clay	Stabilization	Cement, lime, slag, fly ash	50 to 200 kg/m^3	CU, CD, oedometer
[31]	Marine clay	Stabilization	Cement	5 to 60%	CU, CD
[37]	Soft clayey soil	Highway embankment	Cement	22.5%	UCS, in situ plate loading
[38]	CL (created clay and natural clay)	Stabilization	Cement	10 and 20%	UCS, CIUC, CIUE, CIU Cyclic loading, oedometer
[39]	Macadam	High-speed railway subgrade	Cement	1%, 3%, 5%	Compaction, permeability, UCS
[22]	CH	Land reclamation	Cement and blast-furnace cement	14% (or s/c = 7)	UCS

Note: S/S—solidification/stabilization; NA—not applicable; CU—consolidated undrained; CIUC—isotropically consolidated undrained compression; CIUE—isotropically consolidated undrained extension; CIU—isotropically consolidated undrained; PSD—particle size distribution; CL—clay of low plasticity or lean clay; CH—clay of high plasticity or fat clay.

2.2. Physical Properties of Soilcrete in Temperate Conditions

A non-destructive method using elastic waves has been adopted to detect defects in soilcrete columns and obtain the elastic modulus. P and S waves propagated through the material, and the modulus of the specimen was estimated from the relationship between the travel speed of waves and the stiffness of soilcrete [40]. Moreover, the ultrasonic wave has been adopted by researchers to investigate the properties of soilcrete [41,42].

Due to the addition of cement, soilcrete has different physical properties from natural soils. It has been reported that the density of soilcrete increased with cement content [5,43]. Since compaction is often adopted to cast soilcrete specimens in many studies, dry density and optimum water content were important factors when the properties of soilcrete were analyzed. The authors of Ref. [5] observed that the maximum dry density and Atterberg limits of soilcrete increased with cement content for Iranian lean clay, but the specific gravity decreased.

The hydraulic conductivity (or permeability) of soilcrete is critical for landfill liners and deep excavation retaining structures, so determining the permeability is necessary for these studies. It has been observed that since the pores of soilcrete were filled with the binder hydration products, the permeability of soilcrete was reduced significantly [9,44,45]. The authors of Refs. [46,47] proposed a modified Moulton's empirical equation for predicting the permeability of soilcrete by considering the effects of cement hydration and freezing. In Ref. [45], the authors showed that strength was related to permeability to a certain extent.

3. Engineering Properties of Soilcrete Subjected to F/T Cycles

Seasonal weather is typical in cold regions and detrimental to infrastructure and buildings. In light of research on the effect of seasonal weather on the behavior of concrete and natural soils, extensive studies on soilcrete subjected to F/T cycles have been undertaken. Table 2 summarizes the studies on soil mixing used in cold regions, in which the seasonal weather was simplified as F/T cycles in the lab. UCS, triaxial tests, monitoring changes in physical properties (size, water content, and mass of specimens), and permeability tests have been used to investigate the behavior of soilcrete subjected to F/T cycles. Several standards for implementing the F/T cycles have been formulated. But these standards are not suitable for soilcrete because they mainly focus on multiple cycles in a short period. Instead, a 3D F/T method with a long period in a freezer has been adopted in many studies. UCS decrease, mass loss, and size change are commonly used to indicate the detrimental effect caused by F/T cycles.

Table 2. Key references on the performance of soilcrete subject to F/T cycles.

Reference	Application	Soil Type	Binders	Binder Dosage	Test Methods	F/T Method	F/T Cycles	Comments
[48]	Subgrade	Crushed concrete and natural soil	Cement	3.5%	dynamic cone penetrometer, Clegg hammer	Field condition	N/A	50% of compressive strength loss after F/T cycles
[34]	Pavement	Granular soils	Cement	5, 7, 9%	UCS, brushing test	Freezer, 3D, 22 h + 22 h	12	Proposed relationship between mass loss and decrease in UCS
[49]	Road construction, earthquake application	Sand–gravel mixture	Silica fume, fly ash, lime, red mud, cement	2.5 to 20%	UCS, CBR, ultrasonic wave, dynamic tests	Freezer, 3D, ASTM C 666, 2.3 h + 2.3 h	60	Addition of waste materials reduced the compressive strength loss significantly
[50]	Pavement	ML	Cement, fly ash	2 to 30%	UCS	Freezing cabinet, 3D 24 h + 23 h, ASTM D560	7	Addition of 10% fly ash and 2% cement has the best performance against F/T cycles

Table 2. *Cont.*

Reference	Application	Soil Type	Binders	Binder Dosage	Test Methods	F/T Method	F/T Cycles	Comments
[51]	Base layers of high-speed railway	Northeast China clay soil	Cement and calcium lime	3 to 12%	Cyclic loading	Freezer, 3D, 12 h + 12 h	15	Cement improved the durability more than lime with the same content
[52]	Highway embankment	CH	Bassanite, furnace cement	5 to 30%	UCS, volume, WC	Freezer, 3D, 24 h + 24 h	5	Early F/T cycles caused more damage than later ones
[53]	Earthworks	CH	Bassanite, furnace cement, coal ash	5 to 20%	UCS, volume, WC	Freezer, 3D, 24 h + 24 h	5	Coal ash only does not result in improvement
[54]	Stabilization	CH and CL	Cement	5 and 10%	UCS, ultrasonic wave	Freezer, 3D, ASTM C 666, 2.3 h + 2.3 h	5	UCS prediction equation using clay water to cement ratio; the relationship between UCS and ultrasonic wave velocity
[55]	Stabilization	Artificial soils: well-graded sand and silty sand	Cement	10%	Permeability, UCS, brushing test	Freezer, 3D, 24 h + 24 h	12	Permeability increased significantly; compressive strength decreased by over 50%
[56]	Subgrade	Lishi loess	Cement, lime, and fly ash	3 to 10%	Frost heave and thaw shrinkage, SEM	Freezer, 3D, 12 h + 12 h	8	The contents resulting in the best improvement are 5% cement, 6% lime, and 10% fly ash
[57]	Earthwork	CH	Coal fly ash, carbide lime	3 to 9%	UCS, mass loss, XRD	Freezing cabinet, 3D 24 h + 23 h, ASTM D560	12	Mass loss and porosity/lime index to indicate the UCS
[39]	High-speed railway subgrade	Macadam	Cement	1, 3, and 5%	Compaction, permeability, UCS	A special device, 1D, 48 h + 48 h	25	UCS becomes stable after 10 F/T cycles; grain-size composition affects permeability, UCS, and frost sensitivity
[58]	SNWTP	expansive clay	Cement	3, 5, 7%	UCS, volume change, mass loss	Freezer, 3D, 12 h + 12 h	12	Cement reduces the volume change of expansive clay
[16]	Stabilization	Silty sand	Cement and cement kiln dust	6 and 8%	UCS	Freezer, 3D, 12 h + 36 h	12	4 °C curing; healing effect

Note: CBR—California bearing ratio; SNWTP—south to north water transfer project; ML—silt.

3.1. Applications of Soil Mixing in Cold Regions

As the population is increasing fast in urban areas worldwide, insufficient competent land has become an obstacle, especially in cold regions such as Japan, North America, Russia, and northern Europe. Thus, soil mixing has gradually attracted the attention of practitioners and researchers in these areas.

Figure 1 shows the typical applications of soil mixing adopted in cold regions. Soil mixing played a critical role in resisting uneven and large settlements when working as the foundations for superstructures, for example, oil storage tanks (Figure 1a) [59]. In addition, due to its increasing tensile strength stemming from the binder hydration product, soil mixing can mitigate the damage caused by the seismic load and lateral load, such as embankment (Figure 1d) [39,49,52] and retaining walls (Figure 1b). Since the permeability of soilcrete has become significantly lower than that of natural soils, soilcrete, which is often adopted in S/S, has been used to deal with contaminants (Figure 1f) [16,54,55] and reduce seepage as the dam core (Figure 1e). Soil mixing has also been used to enhance the shallow ground layer to support linear structures, such as highways [34,50], railways [39,51], and SNWTP [58].

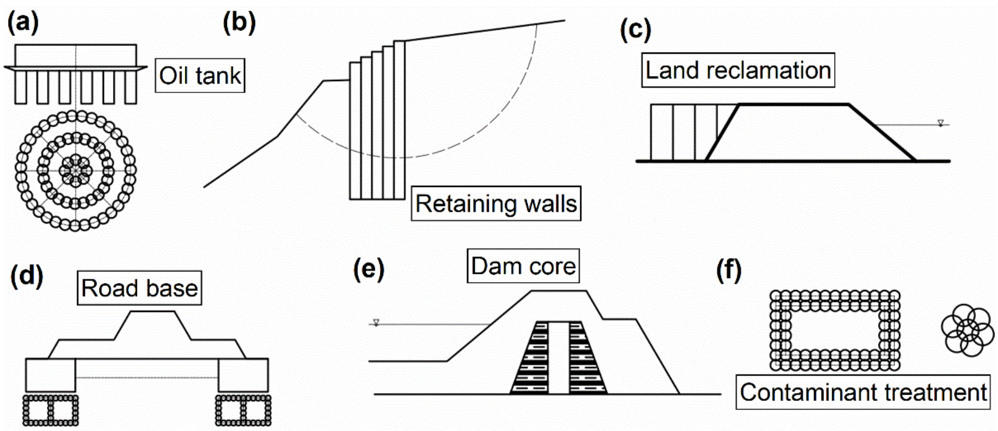

Figure 1. Applications of soil mixing in cold regions: (**a**) oil tanks using DSM as the foundation, (**b**) retaining walls, (**c**) support for land reclamation, (**d**) soil mixing base to mitigate the potential seismic activity, (**e**) dam core to eliminate seepage, and (**f**) contaminant containment with the S/S method (drawings not to scale).

3.2. Damage Mechanism in Soilcrete by F/T Cycles

It is generally accepted that the volume of geomaterials expands under subzero temperatures because of the phase change of water to ice. The volume increase in soils is about 9% [60]. Since soilcrete resembles natural soils, its volume change under freezing is compatible with that of soils. The freezing in soilcrete is usually unidirectional (from the ground surface to underground). As the freezing front moves downward, the ice crystals absorb the water [61], creating ice lenses in the connected pores of the soilcrete. Thus, the small pores in soilcrete are enlarged and new cracks occur. Moreover, the volume of soilcrete contracts during the subsequent thawing process. Soilcrete structures deteriorate when such an F/T reaction is repeated. For example, the permeability of soilcrete increases with the enlargement of the pores that are left after the thaw of ice crystals, as micro-fissures are enlarged and melted ice in the soilcrete matrix leaves large internal pore spaces; finer particles might move out of large pore spaces during F/T cycles [54].

Several theories for the mechanism of damages caused by F/T cycles have been summarized by [8], including the hydraulic pressure theory and the micro-ice-lens model derived from concrete studies. The hydraulic theory states that the expansion of frozen water can generate excess pore water pressure in the capillary pores. The cracks occur when the pore pressure exceeds the material's tensile strength. In the micro-ice-lens model, on the other hand, the first F/T cycle does not damage the material significantly. Because the melting progresses from the surface to the core, the ice in the large pores remains frozen for a certain period. Thus, the ice in large pores absorbs the water from the surroundings, causing the saturation of the materials to increase notably. Hence, the damage becomes more severe with more F/T cycles.

Noticeably, the intensity of the F/T cycles plays an important role in the durability of soilcrete in cold regions, including the number of cycles, type of cycles, duration of cycles, and frost penetration depth [52].

3.3. F/T Methods and Setup

Many studies have been conducted to determine the effects of F/T cycles on the properties of concrete and natural soils. Since concrete structures exposed to air can undergo one F/T cycle per day, it is of great importance to investigate the changes in properties caused by F/T cycles [62–64]. In cold regions, the stability of the superstructure is reduced as a consequence of the deteriorated properties of natural soils under freezing conditions [39,58,61,65,66]. The results of Refs. [67,68] have been compiled and used to apply F/T cycles [34,50,62,64], but these standards focused on a rapid F/T process, which was not consistent with the situation for soilcrete.

Figure 2 shows two typical pieces of equipment used to conduct 3D F/T cycles in the lab for soilcrete study. In Ref. [61], the authors introduced a closed system (without a water supply) with a 3D freezing method to conduct F/T cycles in a refrigerator. The F/T processes were elongated to as long as one or two days to simulate the seasonal weather change. Recently, other similar equipments and testing methods have been adopted by studies related to soilcrete and soil subjected to F/T cycles [53,56,58]. Additionally, Ref. [69] reported that the difference between 1D and 3D freezing was negligible. Thus, a 3D freezing system with a container (refrigerator or other cells) has often been used in studies on soilcrete subjected to F/T cycles.

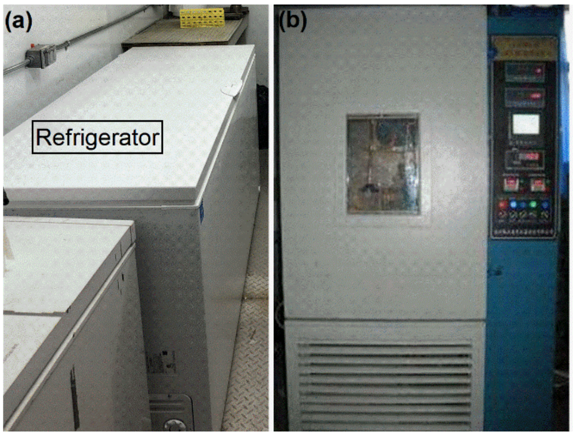

Figure 2. F/T setups: (**a**) a commonly used refrigerator and (**b**) a 3D F/T system (adapted from [70]).

3.4. Physical Properties of Soilcrete Subjected to F/T Cycles

Several studies have concluded that the height of the soilcrete specimen contracted and the radius remained stable, and thus the volume decreased under freezing temperature [52,56,58]. In the warming process, changes caused by freezing may not recover fully. Because the binder hydration and F/T cycles consume water, the water content of soilcrete changes vastly during F/T cycles [50,52]. Particles at the surface of specimens were observed to be destroyed. They became loose, resulting in the cumulative mass loss (ratio of the difference between the original mass and the mass after F/T cycles to the original mass of samples) after brushing increase with F/T cycles. Mass loss has often been used to estimate the degree of damage caused by the F/T cycles in concrete [71], which has also been adopted in studies on soilcrete [34,55,57].

Figure 3 shows typical mass loss change caused by F/T cycles. Figure 3a shows that a higher water/cement ratio causes an increase in mass loss, and the accumulated mass loss after 12 cycles of F/T for cement-treated silty sands is less than 5%. Figure 3b reveals that the accumulated mass loss of lime-treated clay increased significantly with the increase in F/T cycles, which reaches about 20% for soilcrete with 3% of lime at the 12th F/T cycle. Figure 3b also indicates that the increase in lime content enhances the resistance of soilcrete to F/T cycles. Figure 3c suggests a similar result to Figure 3b that the increase in cement content improves the resistance against F/T cycles.

Permeability is important when assessing the degree of improvement of soilcrete, especially in contaminant treatment. The authors of Refs. [8,72,73] analyzed the permeability of soilcrete subjected to F/T cycles in S/S. They observed that the permeability was affected by the freezing temperature, curing time, and the number of F/T cycles. In Ref. [74], the authors suggested that the change in permeability was not caused by the pore size distribution but by the cracking and macroscale pore deformation generated when subjected to F/T cycles.

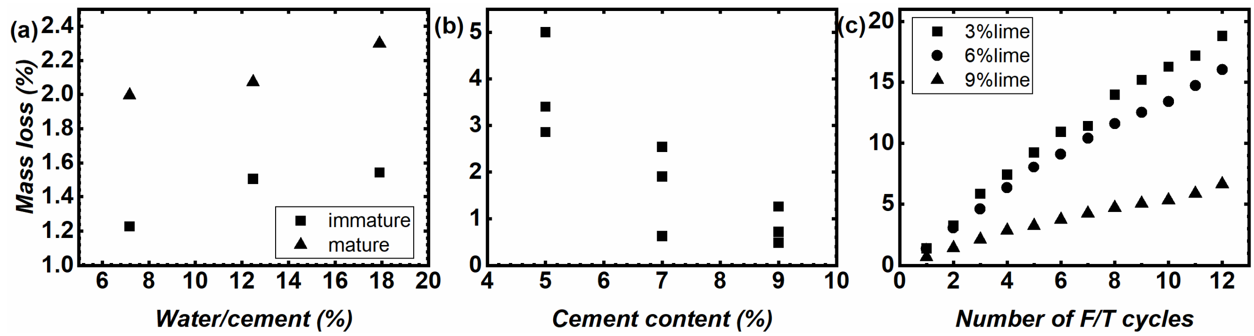

Figure 3. Mass loss caused by F/T cycles: (**a**) soilcrete with different water content under 12 F/T cycles (adapted from [55]), (**b**) soilcrete with different cement content under 12 F/T cycles (adapted from [34]), and (**c**) mass loss increases with the increase in F/T cycles (adapted from [57]).

Figure 4 shows the permeability of soilcrete versus water content before and after F/T cycles. Figure 4a shows that soilcrete samples exposed to F/T cycles have higher permeability than those not exposed to F/T cycles. Figure 4b reveals that the permeability of soilcrete increases after exposure to F/T cycles, while the magnitude of the increase is smaller than those in Figure 4a. The difference in permeability shown in Figure 4 may be attributed to the soil types, the number of F/T cycles, and the procedure of F/T cycles.

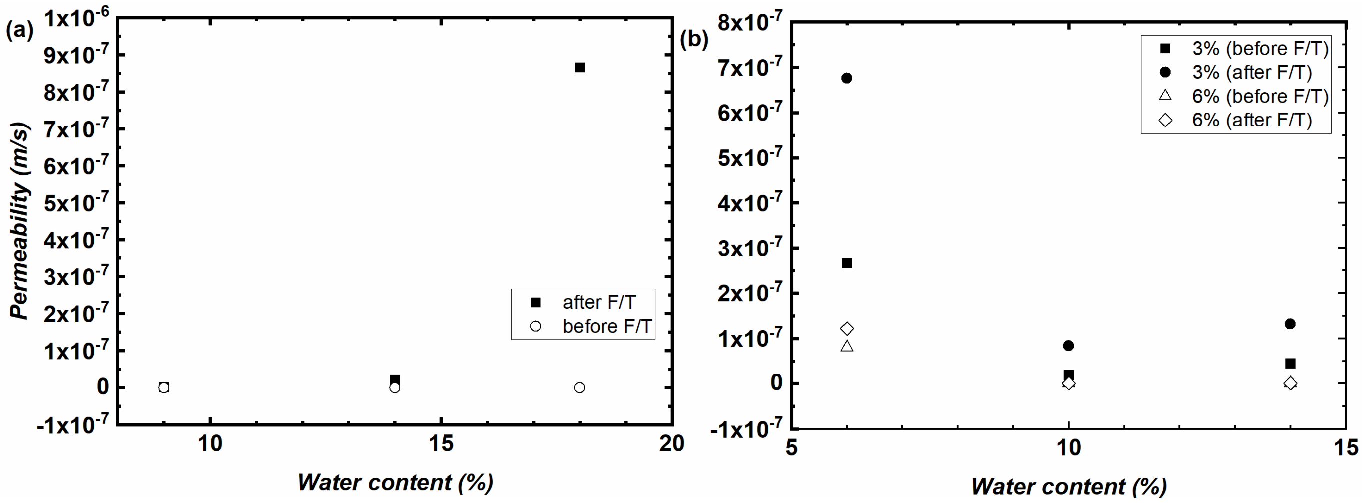

Figure 4. Permeability change caused by F/T cycles: (**a**) permeability versus water content for soilcrete after 12 F/T cycles (adapted from [73]) and (**b**) permeability versus water content for soilcrete after 3 F/T cycles (adapted from [75]).

3.5. Mechanical Properties of Soilcrete Subjected to F/T Cycles

The studies summarized in Table 2 show that the mechanical property of soilcrete subjected to F/T cycles is the primary concern of soil mixing practitioners. The UCS test is the first choice due to its speed and simplicity. The difference in UCS between specimens with and without F/T cycles has been used as an index to estimate the durability of soilcrete against freezing conditions [34,49,53,58]. Binders added to the natural soil could resist freezing damage to a certain extent due to the bonds generated between soil particles and clusters [49,50,56,57,76]. Generally, the strength of soilcrete decreased with F/T cycles. Researchers have observed that the most considerable change in UCS often occurred in the first or second F/T cycle [52,53,73,77]. After around ten cycles, the UCS would not change noticeably, although more cycles were applied [61,77].

Figure 5 shows the UCS of soilcrete under F/T cycles. It indicates that the UCS ratio (UCS after F/T to the original UCS) decreases significantly when F/T cycles increase from

4 to 12. The authors of Refs. [52,58] showed that the UCS of soilcrete decreases with more F/T cycles and the first cycle causes the most significant damage to the samples.

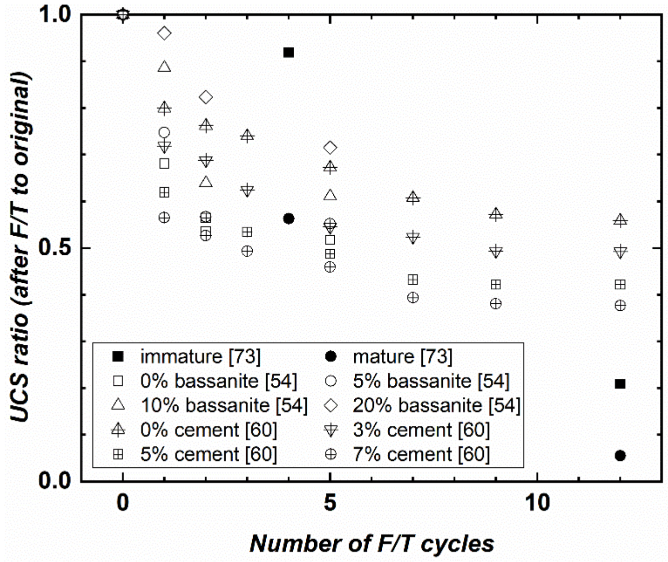

Figure 5. UCS ratio versus F/T cycles (adapted from [8,52,58]).

Triaxial testing has revealed that cohesion decreases with F/T cycles, while the friction angle increases in natural soils [61,66]. It is reasonable to anticipate that soilcrete would show a similar trend after F/T cycles, as the behavior of soilcrete is similar to an overconsolidated clay and studies on the triaxial behavior of soilcrete subjected to F/T cycles are scarce. In addition, detecting methods using pulse velocity [49] and resonant frequency [55] have been used to identify the damage caused by F/T cycles.

In recent decades, the use of artificial neural networks (ANNs) in geotechnical engineering studies has increased significantly, especially in modeling soil behavior, site characterization, earth retaining structures, slope stability, design of tunnels and underground openings, soil permeability, soil compaction, soil swelling, and classification of soils [78]. The authors of Ref. [79] introduced ANNs to predict the UCS of fiber-reinforced soilcrete under F/T cycles and found that ANNs performed better than the nonlinear regression method, especially the radial basis neural network approach.

3.6. Microstructure of Soilcrete Subjected to F/T Cycles

Several models of the microstructure of fine-grained soils have been proposed. Lambe's conceptual model is widely adopted, considering clay particles as single platelets. With the advent of experimental techniques, including scanning electron microscope (SEM) and computed tomography (CT) scanning, there have been many findings on the relation between the microscale properties and the engineering behavior of fine-grained soils.

The microstructure of soilcrete is affected by binders and water, which govern the macro-behavior. For example, the porosity changes of soilcrete due to micro-cracks or cavities can be related to mechanical properties. So far, many methods have been used to investigate the microstructure of soilcrete, such as X-ray diffraction (XRD), SEM, optical microscopy, mercury intrusion porosimetry (MIP), and CT. XRD can indicate the composition of the soilcrete and has been used to estimate the degree of hydration. SEM and optical microscopy have been used to show the details of the inner structure and dispersion of hydration products inside the soilcrete specimen [80,81]. MIP can estimate the pore distribution and pore connection in the soilcrete. CT has been used to estimate the pore distribution and the porosity of soilcrete [9]. The authors of Refs. [10,82] concluded that the porosity of soilcrete was affected by the addition of cement. The microstructure of soilcrete is affected by the clay–water/cement ratio or water/binder ratio [36,83]. Thus, the strength related to microstructure could be estimated by these ratios.

Table 3 lists several key studies that investigated the microstructure of soilcrete with the new techniques. Because cement and clay interact with water in soilcrete, clay and cement particles group together when preparing soilcrete specimens. Thus, the microstructure of soilcrete was determined from the connection of the clusters and single particles in the specimens by the hydration bonds. Microstructure changes due to F/T cycles have been investigated in several studies shown in Table 3.

Table 3. Key references on the microscale structure of soilcrete.

Reference	Application	Soil Type	Binders	Binder Dosage	Test Methods	F/T Method	F/T Cycles	Comments
[10]	Marine clay	Stabilization	Cement	10%, 30%, 50%	XRD, SEM, MIP, PSD by laser diffractometric	NA	NA	Microstructure mechanisms: flocculation of the illite clay particles, surface deposition and shallow infilling, etc.
[53]	Earthwork projects	clay with high plasticity	Cement, bassanite, coal ash	5 to 20%	UCS, SEM	Freezer, 3-D, 24 h + 24 h	5	Quantity and size of ettringite are improved by mixing bassanite and coal ash because of the pozzolanic reaction
[74]	Stabilization	Silty sand	Cement	3 and 6%	UCS, permeability, MIP, optical microscope, the resonant frequency	Freezer, 3-D, 24 h + 24 h	3	Damage in permeability is due to cracking and macroscale pore changes
[69]	Stabilization	Silty sand	Cement	10%	Permeability, UCS, optical microscope, longitudinal impact resonance test	Freezer, 1-D and 3-D, 24 h + 24 h	3	Optical microscopy can detect matrix disintegration for highly damaged specimens
[75]	S/S	Silty sand	Cement	3 and 6%	UCS, optical microscope, MIP	Freezer, 3-D, 24 h + 24 h	3	Thin section observations showed more voids and cracks in F/T exposed specimens relative to control samples

Soilcrete is vulnerable to F/T cycles due to the expansion of water during the freezing process. The initiation of the damage caused by F/T relies on the tensile strength of soilcrete and occurs through the weakest connections or bonds. Because of these damages, more cracks in the soilcrete specimens occur. Thus, the microstructure of soilcrete is altered by F/T processes. Many studies have been conducted on the microstructure changes in soilcrete caused by F/T cycles. Optical microscopy was used to observe the microstructure of soilcrete subjected to the F/T cycles in several studies [69,72,75], as well as other image-based methods such as SEM [56,77] and CT scanning [66]. The XRD test has been used to investigate the distribution of clay minerals in cement-treated clays. It has been confirmed by several studies that the matrix was destroyed, and the cracks were generated due to the F/T cycles. In contrast, the pore size distribution did not change much. The analysis of images could verify the strength results to a certain extent, whereas the quantitative assessment is still challenging.

Although XRD could provide the mineral amount in a powder sample of soilcrete with a specialized technique, the results may be questionable due to the small size of a single sample. Besides, the cement hydration product, i.e., CSH, is amorphous and is hard to detect with XRD. Thus, the component contents of soilcrete obtained from XRD are questionable and cross-checking with other testing methods is needed. As for the SEM and MIP methods, the sample size is relatively small compared to the cylinders for mechanical tests. Additionally, because the samples need to be dry, the sample preparation process for these tests may disturb the original microstructure, generating uncontrolled errors. With regard to SEM, a quantitative explanation of results has been lacking. Several studies introduced new methods to prepare samples with a relatively light disturbance. However, these tests are time-consuming and laborious. CT scanning is relatively new, and the results depend on soil and binder types. The major issue with the techniques mentioned above is the lack of quantitative relationships between the microstructure and the mechanical and physical properties.

3.7. Multiple Binders Used in Soilcrete Subjected to F/T Cycles

The accumulation of multiple industrial by-products, such as coal ash, silica fume, fly ash, and basanite, has become a crucial problem for practitioners. In addition, as climate change has become a major concern, plenty of research has been conducted to reduce the use of cement due to its high carbon footprint by adopting waste materials or industrial by-products. So far, many studies have been conducted on the effect of multiple binders or industrial wastes used in soil mixing.

The authors of Ref. [49] conducted UCS, California bearing ratio, ultrasonic wave, and resonant frequency tests on the cement-treated granular soils by adding silica fume, fly ash, and red mud to estimate the durability of soilcrete against F/T cycles. It was concluded that the waste materials could improve the durability of the granular soils and were suitable for road construction and earthwork applications. In Ref. [50], the authors used the UCS test to determine the optimum mixing rate of fly ash and cement for silty soils against F/T cycles with samples cast by the Standard Proctor test. The best dosage was 10% fly ash and 2% cement mixed binder. The samples after F/T cycles exhibited a crisp and brittle behavior and a higher strength which was attributed to the remarkable water loss in the curing process. The authors of Ref. [52] conducted a UCS test on soft clays stabilized with bassanite before and after exposure to F/T cycles. The strength results revealed that adding bassanite increased the strength and the durability against F/T cycles. In Ref. [70], the authors conducted a UCS test on cement-treated clays with the addition of pumice to verify the improvement of resistance against F/T cycles. It was concluded that the optimum cement content to enhance the strength was 16% and pumice could increase the resistance to F/T cycles of the cement-treated soils. Additionally, a proportion of 8% of pumice was decided as the optimum to resist F/T damage.

The authors of [53] conducted a UCS test on cement-treated clay with recycled bassanite and coal ash to investigate the resistance of soilcrete to F/T cycles. It showed that adding both additives enhanced the strength of soilcrete and the resistance to F/T cycles. In [56], the authors added cement, lime, and fly ash to the subgrade loess to improve its resistance to F/T cycles. It was concluded that the additives could prevent damage caused by F/T cycles in a certain range. There was an optimum additive content, and higher or lower dosage could hardly bear the attack by F/T cycles. The authors of Ref. [57] investigated the properties of clay blended with coal fly ash and carbide lime subjected to F/T cycles. In [57], the accumulated mass loss was used as the indicator to analyze the effects of F/T cycles, which was revealed to increase with more F/T cycles. In Ref. [76], the authors used the UCS test to investigate the effects of F/T cycles on the clay–sand mixed with cement and fly ash. It was concluded that cement-treated soil has a higher resistance to F/T cycles than fly ash-treated soil, which was attributed to the difference in the hydration and pore-filling efficiency. The increase in F/T cycles did not weaken the resistance of cement-treated soils considerably.

Recently, additives formed by the cold-bonded geopolymerization method have been adopted to stabilize the soilcrete used in grouting and deep soil mixing projects [84,85]. The authors of Ref. [84] used cold-bonded geopolymer stabilizers (consisting of metakaolin and slag) for grouting. It was found that cold-bonded stabilizers had adequate flowability and could satisfy the bearing capacity requirement for grouting. In Ref. [85], the authors deployed cold-bonded stabilizers made with limestone and bottom ash and concluded that the cold-bonded stabilizers could meet the strength requirements for grouting and deep soil mixing and provide excellent workability in projects. Thus, the cold-bonded geopolymerization is promising for grouting and deep soil mixing.

Although various additives, including coal ash, silica fume, fly ash, metakaolin, red mud, and basanite, have been introduced into the soil mixing technique to substitute cement, lower the cost, and enhance the treatment effect of cement, cement is the dominant binder in most soil mixing projects. Generally, these additives are just supplementing materials and enhance the performance of cement in the soilcrete.

Figure 6 shows several typical studies of soilcrete mixed with additives. Figure 6a concludes that adding bassanite increases the resistance of soilcrete against F/T cycles, especially at 20% usage. Meanwhile, it shows that the UCS increases with more bassanite. Figure 6b,c show that fly ash significantly affects the increase in UCS. Moreover, the combined use of fly ash and cement in natural soils significantly enhances the resistance of soilcrete to F/T cycles.

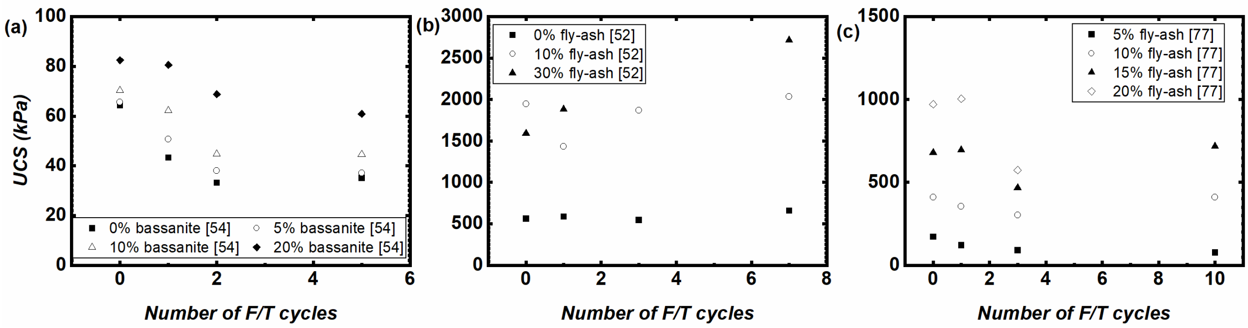

Figure 6. The effect of binders on the performance of soilcrete subjected to F/T cycles: (**a**) UCS of soilcrete subjected to F/T cycles with varying bassanite content [52], (**b**) UCS of soilcrete subjected to F/T cycles with varying fly ash content [50], (**c**) UCS of soilcrete subjected to F/T cycles with varying bentonite and fly ash content [76].

4. Research on Soilcrete with Deep Soil Mixing Method Subjected to F/T Cycles

4.1. Deep Soil Mixing Technique

In the deep soil mixing (DSM) technique, binders are blended with natural soils to strengthen the soft soil. The strengthening effect is mainly due to the reaction of binders with water. Blocks, columns, and panels are three basic patterns used in the DSM technique. Figure 7 shows the details of these patterns. Among these patterns, the cylindrical column is most common for DSM construction. Figure 8 illustrates DSM construction with a wet mixing method. The DSM columns can penetrate as deep as 70 m for offshore sites and 30 m for inland operations.

DSM was first used in the USA in 1954 [86]. Subsequently, DSM was adopted by practitioners from Japan, Europe, and America [1–4]. Lime was the first binder used by projects worldwide, and afterward, other binders were adopted, such as cement, fly ash, and slag [1,4]. Since cement hydration products have high stiffness and a strong bonding effect, cement has become predominant in DSM.

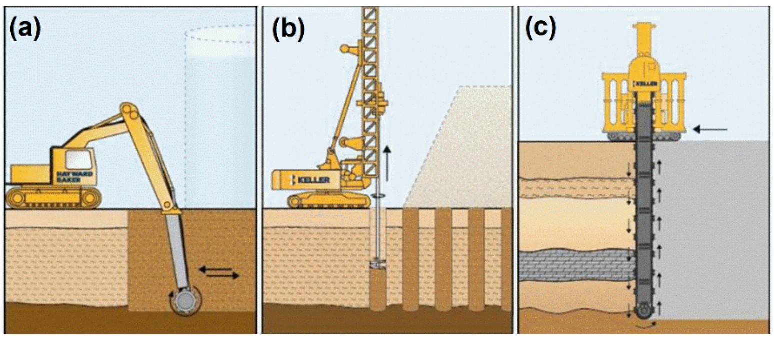

Figure 7. DSM technique: (**a**) DSM blocks, (**b**) DSM columns, and (**c**) DSM panels (courtesy of Keller).

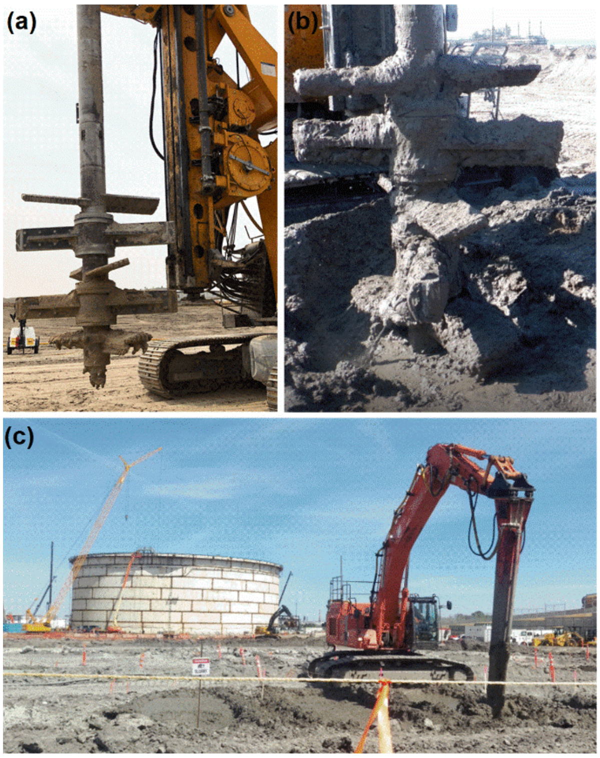

Figure 8. Construction of DSM columns with the wet mixing method: (**a**) before drilling and (**b**) retrieval and mixing, and (**c**) block construction by wet mixing.

Since the 1970s, DSM has been adopted for the rapid development of offshore and onshore infrastructure, remediating the soft marine clay and other poor soils. For onshore sites, DSM has been used in the pavement and subgrade of the road system for embankments and the foundations of various structures. DSM is also an important and widely-used method in coastal projects such as docks and bridge foundations. Marine clay was the most problematic soil type in these projects, and many studies on marine clay have been conducted [10,31,87]. DSM was used in contamination treatment or S/S [88,89], land reclamation [22], and landfill liner [90]. DSM could increase strength and stiffness and reduce compressibility when dealing with soft, cohesive soils. Stiff clays may also need improvement when particular requirements are mandatory, for instance, the enormous load applied on the foundations by oil tanks [7]. The usage of DSM in cohesionless soils is not frequent. However, DSM is suitable for improving cohesionless soils in several conditions, such as mitigating the liquefaction risk and cutting off the groundwater flow. In [26], the authors mitigated the damage caused by the dilation in silt with cement. In a road subgrade project, cement strengthened the weak lateritic soils [91]. In the embankment of a high-speed railway, cement–fly ash–gravel piles were used to pass through the soft marine clay layer [92].

Several kinds of unique soils have been mixed with cement in certain areas. For example, [13,93] conducted mechanical and physical tests to investigate the behavior of cement-treated peat in Sweden.

4.2. Sample Preparation and F/T Cycles

In the present study, the specimens were made by the laboratory mixing of natural Edmonton clay and general Portland cement. Table 4 summarizes the properties of the natural Edmonton stiff clay. The compositions of natural soil and cement were examined in [9].

Most studies on soilcrete have concentrated on the low cement content (lower than 20%), but recent studies have commonly adopted high cement contents. In DSM columns installed to support oil storage tanks in eastern Edmonton, 225 kg/m^3 (cement mass to the volume of natural soils and slurry) was selected to mix the soilcrete in situ. Three dosages were adopted to validate that the choice of cement content could meet the required loading conditions and study the effect of cement content on the changes in the mechanical behavior of soilcrete in the high cement range. Table 5 details the mixing plan used in the present study.

Table 4. Natural soil characteristics.

Property	Value
Sand content	33%
Silt content	43%
Clay content	24%
Unified Soil Classification System (USCS)	Sandy CL
Water content	21.8%
Liquid limit	40.9%
Plastic limit	12.5%
Plasticity index	28.4%
Shear strength	63–72 kPa (vane shear), 50 kPa (UCS)
Specific gravity	2.54

Table 5. Parameters of different specimens.

Property	C1	C2 and CS2	C3
W_c [%]	55.57	53.84	52.14
C_c [%]	17.50	22.39	27.47
W_c/C_c	3.18	2.40	1.90
Binder content [kg/m^3]	175	225	275

Note: W_c: water mass to solids mass; C_c: cement mass to solids mass; binder content: binder mass to the volume of natural soils and slurry.

The authors of Ref. [94] suggested that tapping, rodding, dynamic compaction, static compaction, and plain mixing without compaction were five common methods to cast soilcrete specimens in the lab. The specimen preparation method developed in [94] was adopted in the present study, which was modified with the help of industrial collaborators. Figure 9 illustrates the details of the specimen preparation process. The cement and tap water were mixed with an electrical blender. The natural soil was crushed into small lumps by hand and poured into a large container. Then, the slurry was sprinkled into the lumped soil. After about 5 min, the slurry and natural soil were mixed with a dough mixer using a dough blender hook for 2 min. Then, the paste was filled into the plastic mold layer by layer. The bottom of each mold was drilled with a small hole for extruding. Before filling, the hole was sealed with waterproof tape. For each layer of filling, the mold was tapped against the hard surface of the test bench to remove the trapped air. After three layers of filling, the surface of the completed specimen was leveled. The specimens were covered with plastic film and sealed with a lid. Then they were stored in a rubber container filled with about 20 cm of tap water. The container was covered with a plastic lid to keep the moisture. The specimens were kept at room temperature (20 ± 1 °C) and left to cure for 1 to 300 days. Figure 9f–i show the cured specimens with a diameter-to-height ratio of 0.5, with diameters of 75 mm and 50 mm, respectively.

An F/T control system was designed and assembled for the present study. The equipment is located in the cold room facility with a constant room temperature of about −2 °C. Figure 10 illustrates the setup details. A steel cell circulated by spiral pipes was used as the main container, and a temperature chiller was connected to the cell by two cyclic pipes. The glycol was circulated to take away the heat from the soil. Several specimens enclosed by dry sand in the container were uniformly spread to allow the axisymmetric transition heat flows. In the present study, −20, −10, −5, and −2 °C were used to freeze the specimens. After 24 h of freezing, the chiller was set to 23 °C to warm the specimens for another 24 h, forming a complete F/T cycle.

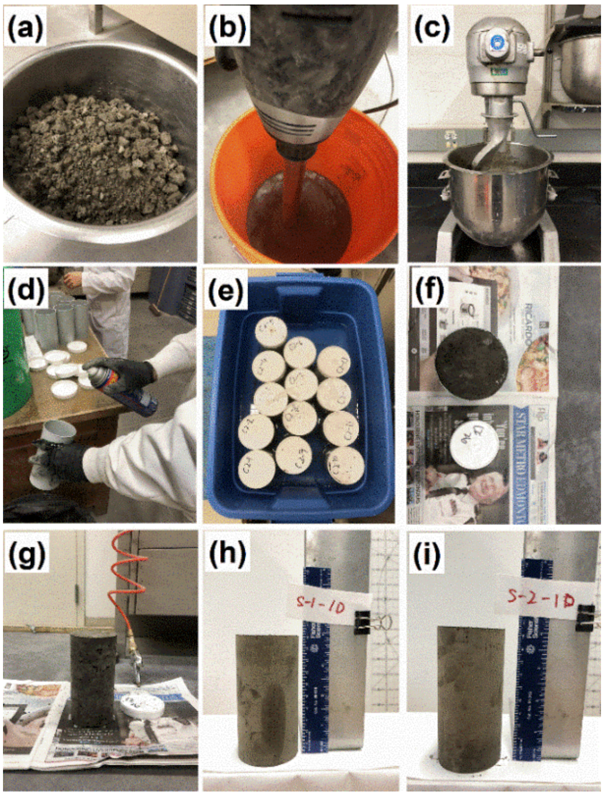

Figure 9. Specimen preparation: (**a**) lumped stiff clay in a container, (**b**) making cement slurry, (**c**) mixing slurry with soils, (**d**) lubricating the plastic molds, (**e**) curing in a rubber container filled with water, (**f**,**g**) cylinder specimens with a diameter of 75 mm, and (**h**,**i**) cylinder specimens with a diameter of 50 mm.

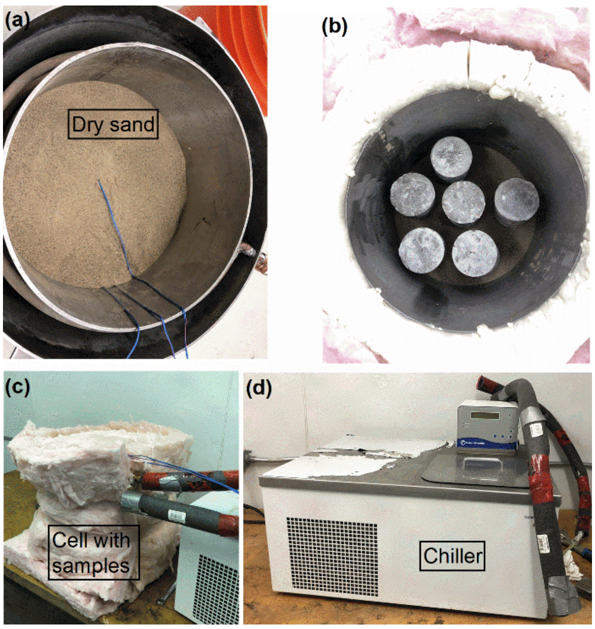

Figure 10. Temperature control system: (**a**) steel container where the samples were kept, (**b**) samples kept in the cell, (**c**) the cell containing samples and sand wrapped for insulation, and (**d**) chiller used to conduct the heat transfer.

4.3. Mechanical Testing of Soilcrete Subjected to F/T Cycles

Most studies choose a curing age of 28 and 56 days [4], representing the maturation of soilcrete specimens and the end of hydration. However, studies have shown that the development of the strength of soilcrete specimens lasted for a long time, up to two years [12,55]. It is important to learn the strength development process of soilcrete with curing time. Thus 1 to 300 days of curing was selected in the present study. After a certain curing time, the cylindrical specimens were removed from the mold through pressurized air injected into the bottom hole. Table 6 summarizes the tests conducted on the cured soilcrete specimens.

Table 6. Test matrix.

Type	Curing (D, Day)	Temperature (T, °C)	Number of F/T Cycles (N)	Test Methods
C225 (C2 and CS2)	1, 7, 14, 28, 110, 300	−2, −5, −10	0, 1	UCS, CU, Permeability, Brazilian test (BT), CT, SEM
	56	−2, −10	0, 1	
		−5	0 to 20	
C175 (C1) and C275 (C3)	14, 28, 56, 110, 300	−2, −5, −10	0, 1	

The UCS test was the most common method used by many researchers to determine the strength of the soilcrete. Before the UCS test, the specimen was capped on both ends by gypsum to obtain even surfaces for loading. The UCS test was conducted on three duplicated specimens at a strain rate of 0.5 mm/min for 75 mm specimens and about 1 mm/min for 50 mm specimens. The load and displacement were recorded until failure or 10% strain. The shear plane and failure pattern of each specimen were observed.

The CU test with the constant confining pressure was selected. Since [7] reported that soilcrete gained most of its strength in 28 days or longer, specimens for CU tests were cured for 56 days. Specimens were extruded after curing and exposed to the designed F/T cycles. They were then placed in a cylindrical cell with a designated confining limit of 4 MPa. Entrapped air in the pumps and the connection pipes were removed by water fluid. Distilled water is used in the back pump, and tap water is used in the confining pump. To ensure the saturation of soilcrete, a back pressure of 600 kPa and an initial confining pressure of 625 kPa were used and kept for 48 to 72 h. After saturation, B values were measured, all being larger than 0.9. As [38] suggested, geomaterial with a stiff microstructure was fully saturated when B was over 0.8. The permeability of the specimen was measured after saturation. The yielding pressure of soilcrete was about 1400 kPa [7]. Therefore, the saturated specimens were consolidated under different pressures varying from 100 to 1000 kPa. After consolidation, the specimen was subject to axial displacement under the undrained condition at a strain rate of 0.5% strain/hour (or 0.0125 mm/min). The specimen was compressed under an axial load until its strain reached about 15%. The pore water pressure and deviator stress were recorded every 30 s during the shearing.

The difficulties associated with the direct tension test have led to the development of several alternative indirect test methods, such as BT, the ring test, the axial fracturing test (also known as the double punch test or unconfined penetration test), bending test or flexure beam test, hydraulic fracturing test, and hoop test [95,96]. BT is common among these testing methods due to its low cost and because combining compressive stress during the test mimics the field stress. Hence, BT was chosen to determine the inter-particle or splitting strength of the soilcrete in the present study.

A thickness-to-diameter ratio of 0.5 was adopted to fabricate the specimens. A curved load strip was used in the BT, and the loading strain rate was 0.5 mm/min. The tensile strength of the BT is calculated as follows

$$\sigma_t = \frac{1.272P_{max}}{\pi t\phi} \quad (1)$$

where P_{max} is the maximum applied load, t is the thickness of the specimen, and ϕ is the diameter of the specimen.

Other studies suggest that the specimen size and loading rate could greatly affect the result. Thus, it is important to ensure the specimens have a similar size and keep the loading rate steady. The tensile strength of the soilcrete was primarily related to the cohesion stemming from the clay and cement. Therefore, the tensile strength change was an indicative method to verify the microscopic changes caused by the damage to cementitious bonds.

4.4. Results of Lab Tests of Soilcrete Subjected to F/T Cycles

The soilcrete specimens were reasonably identical in terms of density, although it was difficult to prepare samples with the same mass because the mixing was not ideally uniform. The mass of C samples after curing ranged from 1207 to 1271 g. The difference in mass of most C samples was relatively marginal (<5%). The density of C samples ranged from 1.82 to 1.91 g/cm^3. Similarly, the density of CS2 samples ranged from 1.57 to 1.80 g/cm^3.

With an increasing F/T cycle, mass loss increased from 1.19% to 2.17% for C2 samples and from 0.88% to 9.83% for CS2 samples. As the freezing temperature decreased from −2 to −20 °C, the mass loss did not change significantly, ranging from 1 to 2%. The samples had more resistance to the mass loss for the same cement dosage but were cured for longer.

Figure 11 shows typical examples of C2 samples under different F/T cycles, indicating that mass loss is due to the cavities and cracks on the sample surface. The mass loss was progressive. As the number of F/T cycles increased, the cracks penetrated the samples, causing more clusters to burst into small debris.

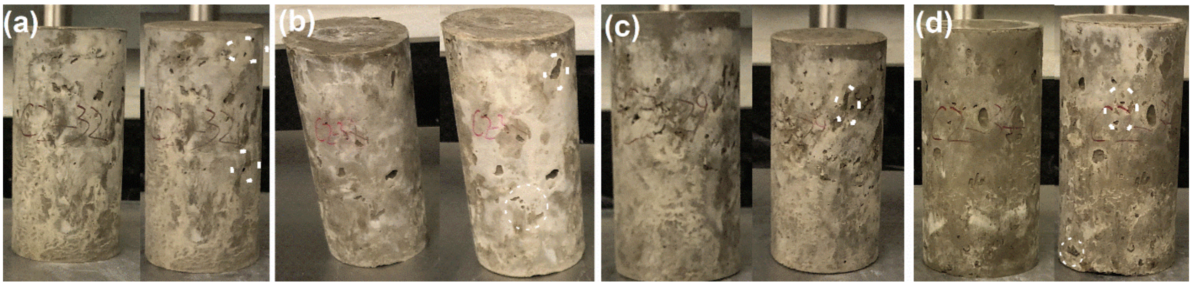

Figure 11. Photos of soilcrete samples before and after F/T cycles: (**a**) C2-D56T5N1, (**b**) C2-D56T2N1, (**c**) C2-D56T10N1, and (**d**) C2-D56T5N4.

Based on the UCS testing results, it was concluded that UCS deteriorated significantly because of the freezing temperature. Moreover, the decrease from −5 to −10 °C was much more significant than other temperature changes. Secondly, the decrease in UCS was progressive as the number of F/T cycles increased, exhibiting a different trend from that in [55], whose conclusion was that the first and second cycles damaged the soilcrete most, and more cycles did not continue to reduce the strength. Although the loss of strength due to the first F/T cycle was as large as 30 percent of the sample's normal UCS without F/T cycles, the damage continued to evolve after two and more F/T cycles were applied, which is significant.

Brazilian tests were conducted with disk soilcrete specimens at a 0.5 mm/min rate. As F/T cycles damaged the bonds in the soilcrete samples, σ_t was heavily affected by F/T cycles. The BT results show the change in σ_t subjected to F/T cycles. As the freezing temperature decreased, σ_t decreased. When one to five F/T cycles were applied to the soilcrete, σ_t decreased significantly. But as 10 and 20 cycles were applied, σ_t became larger than in the samples without F/T cycles. The unexpected σ_t subjected to 10 and 20 cycles may be related to the healing effect. The authors of [97] studied the healing effect of soilcrete via the recovery in the compressive strength of soilcrete after crushing, indicating that 28 extra days of healing after crushing increased the compressive strength of soilcrete by about 27%. In [98], the authors found that the permeability of soilcrete recovered to the original value due to the healing effect of superabsorbent polymer, although the soilcrete went through aggressive environments. In these studies, the healing effect was defined as the additional cementitious products generated in soilcrete from the existing binder or external additives to cure the damaged soilcrete by filling cracks. Thus, in the aforementioned study, the long thawing period could have allowed the formation of extra hydration products, strengthening the soilcrete samples.

CT scanning images were used to estimate the overall porosity and the distribution of void ratio along soilcrete specimens [9]. Figure 12 shows that the void ratio from scanned images is close to that calculated by physical measurement. The standard deviation of the data points in Figure 12 is as small as 0.155, indicating that CT scanning is a potential method for estimating the void ratio in soilcrete. Furthermore, Figure 12 indicates that the void ratio distribution along the sample can also be obtained. The shape and volume of the cracks in the sample can be estimated by combining these photos. Thus, in the present study, CT scanning was chosen to study the microstructure of soilcrete subjected to F/T cycles.

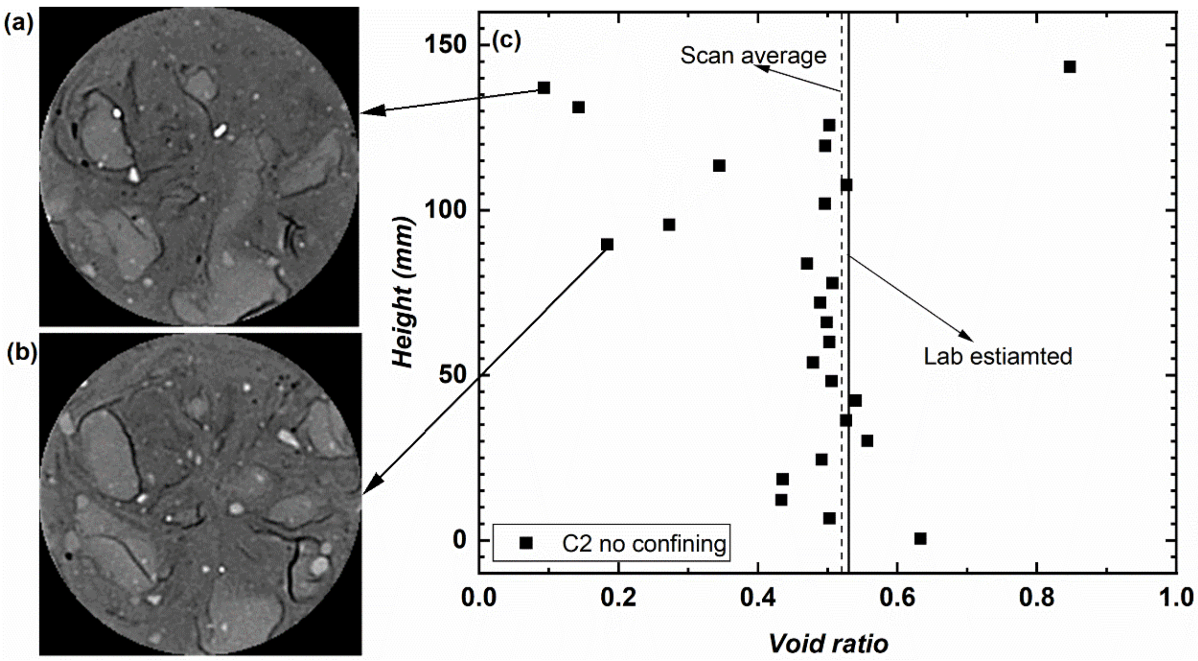

Figure 12. Void ratio calculated from CT scans: (**a**,**b**) cross-section slices from different locations and (**c**) void ratio distribution along the sample (adapted from [9]).

5. Summary

According to an analysis of recent studies and the present study on DSM used in Canada, the current understanding of and potential research on soilcrete subjected to F/T cycles may be summarized as follows:

1. Soil mixing has become a common ground improvement method for practitioners and researchers worldwide, including in cold regions.
2. Mechanical and physical studies on soilcrete in temperate conditions revealed that the strength and compressibility of soilcrete have been significantly improved by adding different binders, such as fly ash, silica fume, bassanite, etc.
3. F/T cycles have been considered in many soil mixing studies where the practice was employed in cold regions. Soil mixing applications in cold regions are common, including embankments, S/S, foundations, etc.

4. F/T cycles have mostly been conducted in 3D freezers, in which the standards for concrete and compacted cement-treated clay have been adopted in several cases. Modifications of the F/T method have been conducted in many studies to meet the unique requirements for soilcrete materials used in cold regions, such as the increase in freezing time and the variation of the freezing temperature.
5. It has been generally accepted that the strength of soilcrete decreases with more F/T cycles, which the UCS could decrease by over 30% in some cases. Meanwhile, the mass loss increased with more F/T cycles, which has become an indicator of F/T destruction in soilcrete samples. Similarly, for S/S applications, the permeability of soilcrete decreased significantly after exposure to F/T cycles.
6. Although various binders have been employed in soil mixing projects, cement is the major binder used in most areas. In order to reduce the cost and deal with the increasing amount of industrial by-products or waste materials, soil mixing with new additives and industrial wastes has become popular. The studies on these binders show promising results, which can be used to substitute part of the cement, enhance the cement's efficiency, and improve the resistance of soilcrete to F/T cycles.
7. The study on DSM used in Canada reveals that the freezing temperature significantly impacted the compressive and tensile strength of soilcrete. As temperature decreased from -2 °C to -20 °C, the magnitude of compressive strength decrease changed from 5% to about 15%. Noticeably, the damage caused by increasing F/T cycles was more important than freezing temperature.

6. Recommendations for Future Research

In summary, cement was still the most commonly used binder despite several substitutive and supplemental binders. Research on soilcrete with high cement content (over 20%) is insufficient. Consequently, UCS, triaxial tests, oedometer, and ultrasonic wave tests have been used in research to investigate the mechanical properties of soilcrete, and the permeability of soilcrete has already been determined for a few projects. So far, most studies have only focused on the compressive behavior of the soilcrete, while the tensile behavior of soilcrete has not been thoroughly understood. It has been reported that cement addition can increase the tensile strength of soilcrete, but the bonds due to cement hydration do not prevent the tensile cracks from happening when soilcrete is subjected to F/T cycles. Given that tensile strength is of great importance for soilcrete designs, particularly for soilcrete columns used for earth-retaining structures, understanding the development of soilcrete tensile strength is essential.

First, as the usage of soil mixing becomes prevalent in cold regions and thus soilcrete performance is heavily affected by F/T cycles, it is important to study the physical, hydraulic, and mechanical behavior of soilcrete subjected to F/T cycles. Moreover, the study on the performance of the soilcrete subjected to freezing temperatures becomes vital for the design and quality control/quality assessment. Although several researchers have investigated the mechanical and physical properties of soilcrete exposed to F/T cycles in contaminant treatment, road subgrade, and embankments, most studies were site-specific and concentrated on certain types of soils, and the behavior of soilcrete under severely cold weather is insufficient. Additionally, 3D freezers and standards for concrete and compacted cement-treated soil were the common methods adopted by most researchers to conduct F/T cycles. But these methods were specified for certain materials and specific freezing temperatures (depending on locality) and were not universal, resulting in difficulty in comparing the results from different studies. The need to formulate a universal method for employing F/T cycles is becoming urgent.

Secondly, almost all studies concentrated on the effect of the number of F/T cycles on the properties of soilcrete, while the freezing temperature was not taken into consideration. Remarkably, temperature plays an important role in determining the speed of the freezing process, which is assumed to be the major direct cause of the F/T damage. Thus, studying the effect of freezing temperature becomes necessary.

Thirdly, in almost all studies on soilcrete subjected to F/T cycles, the major reason for the damage was assumed to be the volume change due to water transforming to ice. However, the variation in volume change from different minerals may also contribute to the cracks and cavities from F/T cycles. In order to thoroughly understand the mechanism of F/T damage, the study of dry soilcrete samples subjected to F/T cycles should attract researchers' attention.

Moreover, as addressed in past studies, the pozzolanic reaction between clay minerals and the binders occurs in soilcrete at a late stage of curing. It can strengthen the soilcrete to some extent based on the amount of the binder hydration product. However, several types of soils contain minerals other than clay minerals, so the potential reactions between these minerals and the binder are unclear.

In addition, many studies have investigated the microstructure changes in soilcrete caused by the binder hydration and F/T cycles. However, there is no overall pattern for all types of soils treated with the same binder, and the findings from different studies vary depending on the soil type, binder type, and casting methods. Furthermore, the studies on microstructure are mostly qualitative. Thus, it is necessary to develop a method to quantify the microstructure of soilcrete and unify the damage patterns in soilcrete caused by F/T cycles.

Finally, since conduction dominates the heat transfer in soilcrete and natural soils, thermal conductivity becomes the most important factor determining the temperature distribution in soilcrete samples. However, information on the thermal properties of soilcrete is scarce, especially under freezing temperatures.

Author Contributions: Conceptualization: C.L., C.B. and L.D.; writing—original draft preparation: C.L.; writing—review and editing: C.L., C.B. and L.D.; supervision: L.D.; funding acquisition: L.D. All authors have read and agreed to the published version of the manuscript.

Funding: The research is funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) under the Collaborative R&D program (CRDPJ 493088-2015).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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