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A Study on Uniaxial Compressive Strength and Ultrasonic Non-Destructive Analysis of Fine-Grained Soil in Seasonally Frozen Regions

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Abstract: Understanding the physical and mechanical properties of soils subjected to freeze-thaw cycles, including both micro and macrostructures, is critical for achieving the required performance of structures employing it as a structural or support material. An experimental study was carried out on clay soil with varying water content (18%, 21.5%, and 23%) after repeated freeze-thaw cycles (0, 2, 5, 7, 12, and 15). The performance of soil was evaluated using unconfined compressive strength (UCS) and ultrasonic pulse velocity (UPV) tests. The experimental results demonstrated that UCS peak values were observed at the lowest water content before and after the freeze-thaw cycles. The stress-strain curves exhibited strain-softening behavior, and this condition transitioned to strain hardening behavior after freeze-thaw cycles with increment in the water content. Moreover, the highest values of UPV were observed to increase UCS values due to capillary forces at minimum water content. Also, an increase in the number of freeze-thaw cycles resulted in a decrease in the UPV. According to correlations between UPV and UCS values, the highest correlations for water contents were obtained at optimum water content, and a decreasing trend was observed after experiencing a number of freeze-thaw periods. In addition, the Grey Correlation Analysis was performed to show the degree of correlation between the UCS and UPV, water content as well as the freeze-thaw cycles. The results demonstrated that the UPV values have a greater impact on the UCS than other parameters.

Key words: Clay soil, uniaxial compression test, ultrasonic pulse velocity test, seasonally frozen region.

Mevsimsel Donmuş Bölgelerde İnce Taneli Zeminlerin Tek Eksenli Basınç Dayanımları ve Ultrasonik Tahribatsız Analizleri Üzerine Bir Çalışma

Öz: Mikro yapı ve makro yapı dahil olmak üzere donma-çözülme döngülerine maruz kalan zeminlerin fiziksel ve mekanik özelliklerini anlamak, onu yapısal veya destek malzemesi olarak kullanan yapıların gerekli performansını elde etmek için kritik öneme sahiptir. Bu sebeple, 0, 2, 5, 7, 12 ve 15 donma-çözülme döngüsünden sonra farklı su içeriklerine sahip (%18, %21,5 ve %23) killi zemin üzerinde deneysel bir çalışma yapılmıştır. Zeminin performansı, serbest basınç dayanımı (UCS) ve ultrasonik dalga hızı (UPV) testleri ile değerlendirilmiştir. Deneysel sonuçlar, donma-çözülme döngülerinden önce ve sonra en düşük su içeriğinde UCS pik değerlerinin gözlemlendiğini göstermiştir. Gerilme-şekil değiştirme eğrileri, kırılgan davranış sergilemiş ve bu durum, donma-çözülme döngülerinden sonra ve su içeriğindeki bir artışla kırılgandan sünek davranışına doğru değişiklik göstermiştir. Ayrıca, minimum su içeriği değerlerinde kılcal kuvvetler nedeniyle artan UCS değerlerinde en yüksek UPV değerleri gözlenmiştir. Ayrıca, donma-çözülme döngülerinin sayısındaki artışla UPV'de bir düşüş gözlemlenmiştir. UPV ve UCS değerleri arasındaki korelasyonlara göre, optimum su içeriğinde su içerikleri için en yüksek korelasyonlar elde edilmiş ve artan donma-çözülme döngü sayısı ile azalma eğilimi gözlenmiştir. Ayrıca, serbest basınç dayanımı ile ultrasonik darbe hızı, su içeriği ve ayrıca donma-çözülme döngüleri arasındaki korelasyon derecesini göstermek için Grey korelasyon analizi yapılmıştır. Sonuçlar, UPV değerlerinin UCS üzerinde diğer parametrelerden daha büyük bir etkiye sahip olduğunu ortaya koydu.

Anahtar kelimeler: Killi zemin, serbest basınç dayanımı, ultrasonik darbe hızı testi, mevsimsel donma bölgeleri.

1. Introduction

Fine-grained soil is a difficult material to work with in a variety of civil engineering applications. High clay content in a fine-grained soil tends to shrink and expand as the volume of water changes. The change in volume can lead to structural problems for buildings hence posing critical threats to geotechnical engineers [1-2]. Due to the variation of mechanical properties exhibited by these soils, frost susceptibility, excessive compression, high swelling potential, low strength, and collapse behavior are examples of possible structural damages to be encountered [3-5]. Dry density and water content were proved to significantly impact the unconfined compressive strength (UCS), shear strength, and brittle against plastic behavior of these soils [6-7]. Furthermore, the water content is said to strongly influence the strength and structural stability of the soil grains [8-11]. Depending on the

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moisture content of a fine-grained compacted soil, it may behave brittle or plastic under loading. The water content at which softening to hardening behavior transitions happen is based on the plasticity level of clay and the type and amount of clay minerals [7].

Freezing and thawing cycles throughout the changes in seasonal temperature have destructive effects on soil behavior. Mineral composition, moisture content and dry density all influences the physical and mechanical behavior of the frozen soils. The arrangement and structure of soil particles changes as a result of the freezing-thawing cycles, hence the changes in the soil's physical and mechanical properties [12-17]. According to studies of previous tests on the soils after repeated freezing-thawing cycles, compacted soil would become loose and thaw settlement would increase after thawing or vice versa [12, 18, 19]. The volume of water increases to about 9% when it freezes in fine-grained soil, exerting great pressure on the pore walls of the fine-grained soil, also changing its physical and mechanical properties [20]. Destruction of these soils by freezing and thawing occurs as water migrates into the soil. The extent of the destructive effect depends on factors such as freezing depth, surface freezing temperature, duration of freezing, and negative variations in the amount of snow on the surface during the winter [21, 22].

In seasonally frozen regions, the occurrence of variations in freezing-thawing cycles should be taken into account while determining stability analysis parameters and deformational problems. While utilizing UCS tests, deformation changes in the soil, changes in the mass due to changes in water content and passing wave velocity, and the influence of freezing-thawing cycles on the mechanical behavior of soils were investigated in this study. Also, the most significant parameters affecting the UCS values of the soil were revealed with the Grey correlation analysis.

2. Materials and Method

2.1. Soil

The soil specimens were collected from Ataşehir district, Elazig city (Turkey), and fine-grained soil was used in the experiments. Grain Size Distribution Test, Atterberg Limit Tests, and Proctor Tests were carried out to obtain the soil's physical properties. The maximum dry density is 1.656 gr/cm³, the optimum water content is 21.50% and the plasticity index has been found 45.67%. The collected samples were found to be high plasticity clay (CH) soils according to the Unified Soil Classification System (USCS). Also, the grain size distribution is presented in Figure 1.

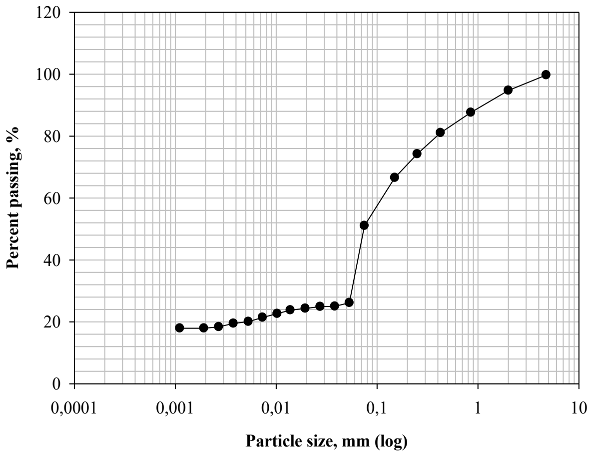


Figure 1. Grain size distribution of the studied soil.

2.2. Specimens preparation

Physical, uniaxial mechanical properties and non-destructive analysis results were determined on the fine-grained soil for various water contents and after experiencing a number of freeze-thaw cycles. While preparing the soil specimens, the following steps were followed; (i) The soil specimens were put in an oven at 105±5 °C for 12 hours in order to obtain specimens with desired water content and to prevent water loss. After the required drying, all soils were placed in the humidity cabinet to cool. (ii) According to the optimum water content determined by the Proctor test, water was slowly added to the soil specimens and mixed. (iii) Then, the soil-water mixture was placed in plastic bags and kept for 24 hours in order to ensure homogeneous distribution of the water content in the mixture. (iv) The water contents of the soils were checked again before starting the experiments. (v) Soil-water mixtures were compacted in three layers with the apparatus for preparing the test specimens shown in Figure 2(a), 3.80 cm in diameter and 7.60 cm in height, as in Figure 2(b). The first layer of the specimens is placed in the mold and compacted. Then, the remaining two layers were added and placed separately and compacted in the same way, and the test sample was prepared as in Figure 2 (c). (vi) After preparation of the samples, they were quickly covered with plastic wraps and placed in humidity cabinets to preserve the water contents. Table 1 depicts the experimental plan of the test specimens.

Figure 2. Preparation of soil specimens.

Table 1. The experimental plan for the specimens.

Test/Series	Dimension of test specimen		Soil Type	Water contents	N	Temperature		TT°
	D (mm)	H (mm)				F	T	
Physical properties	-	-	CH soil		Unfrozen condition	-	-	~20 ºC
UCS tests	38	76		18%, 21.5%, 23%	0, 2, 5, 7, 12, 15	-18 ºC	20 ºC	~20 ºC
UPV tests	38	76		18%, 21.5%, 23%	0, 2, 5, 7, 12, 15	-18 ºC	20 ºC	~20 ºC

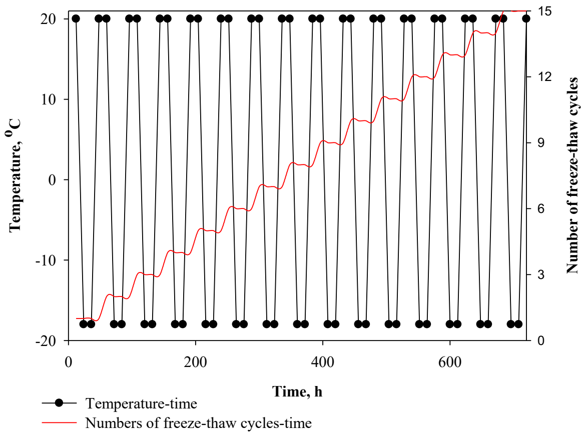
Note: UCS is uniaxial compression test, UPV is ultrasonic pulse velocity test, F is the freezing, T is the thawing, D is the diameter, H is the height, N is the number of freeze-thaw cycles, TT° is the tested temperature.

2.3. Freeze-thaw test

As presented in Table 1, for all series in the tests in this study, the freeze-thaw tests were operated at 0, 2, 5, 7, 12, and 15 freeze-thaw cycles. For all tests, the freezing temperature was -18 °C, the thawing temperature was 20 °C. Also, the experiments for all specimens were conducted at about 20 °C. Due to the continental climate affecting eastern Turkey, most of the region is exposed to the effects of freezing. Considering the average annual temperatures, the freezing periods of the region are between November and March [23].

The prepared soil specimens were subjected to various numbers of freeze-thaw cycles (0, 2, 5, 7, 12, and 15) by placing them in a closed system freezing cabinet without water before their UCS and UPV tests. Freezing temperatures were chosen considering the approximate mean minimum temperature of the region ($T_{freezing}$= -18 ºC). As seen in (a) to (d) as in Figure 3, the soil samples were frozen for 12 hours at a temperature of -18 ºC in a freezing cabinet. The temperature of the freezing cabinet was maintained for 12 hours after it reached the predetermined degree to maintain the temperature balance between the specimens and the environment. Then, the soil specimens were put in humidity cabinets and exposed to the thawing process for 12 hours. All these processes were considered as one freeze-thaw cycle. In addition, Figure 3 (e) shows the time-dependent variations of temperature control processes and freeze-thaw cycles of soil specimens.

(a) Freezing cabinet, (b) Test specimens during freezing, (c) and (d) Test specimens during thawing



(e) Temperature control processes

Figure 3. Freeze-thaw tests.

2.4. Principle of uniaxial compression behaviors of the soil

In this study, the uniaxial compression test was carried out according to ASTM D2166 [24]. After freezing-thawing cycles, the uniaxial compression strengths of the specimens were determined with a Triaxial test machine (ELE brand) at the Fırat University- Faculty of Technology-Civil Engineering Department-Soil Mechanics Laboratory. The same machine was also used for uniaxial compression tests. A strain rate of 0.760 mm per minute was used to apply the load to the specimens. The loading procedure was repeated until either the specimen failed or the strain reached 25.0% (presented as Figure 4).

Figure 4. The appearance of the specimen before and after the UCS test.

2.5. Principle of UPV behaviors of the soil

An ultrasonic non-destructive digital tester apparatus was utilized to determine the ultrasonic pulse velocity (UPV) of the specimens. The Ultrasonic Wave tests were conducted in accordance with ASTM C 597-09 [25] after 0, 2, 5, 7, 12, and 15 freeze-thaw cycles (Figure 5). The transducers were positioned at appropriate positions on the circular surface of the specimens once the apparatus had been calibrated. The measurements of the UPV were taken with an accuracy of 0.1µs. Previous research has found that ultrasonic wave frequencies in the 40-80 Hz range are effective for evaluating stabilized soils. The goal of this experiment was to find a link between the UCS of the soil and the UPV. According to the display unit, the pulse frequency and the pulse transmission time were 54 Hz and 0.1 microseconds, respectively. The UPV for the specimen can be computed using Eq. (1) taking into account the sample length:

$$V = \frac{L}{t} x10^{6} \tag{1}$$

where V is the ultrasonic wave velocity (m/s), L is the sample's pulse transmission path distance (m), and t is the sample's pulse transmission time.

Figure 5. The appearance of the specimen during the UPV test.

2.6. Grey correlation analysis

Grey correlation analysis is a method for determining how different sequences inside a structure approach each other geometrically [26]. The relationship between water content, freeze-thaw cycles, and UPV was derived using the Grey correlation theory to reveal the primary parameters impacting the UCS of clayey soil. The UCS values were taken as the reference sequences (RefSeq) and water contents, freeze-thaw cycles, and UPV values were used as the comparison sequences (ComSeq). Eqs. (2) and (3) can be used to define the reference and comparison sequences, respectively:

$$x_0(f_k) = \{x_0(f_1), x_0(f_2), .., x_0(f_n)\} \tag{2}$$

$$x_i(f_k) = \{x_i(f_1), x_i(f_2), .., x_i(f_n)\} \tag{3}$$

where $x_0(f_k)$ and $x_i(f_i)$ are the RefSeq, the ComSeq, respectively and *k* shows the number of RefSeq or ComSeq.

The RefSeq and ComSeq were normalized using Eqs. (4) and (5) since the parameters in the sequences had different dimensions.

$$x_0^{'}(f_k) = x_0^{'}(f_k) / x_0(f_1) = \{x_0^{'}(f_1), x_0^{'}(f_2), ..., x_0^{'}(f_n)\} \tag{4}$$

$$x_i^{'}(f_k) = x_i^{'}(f_k) / x_i(f_1) = \{x_i^{'}(f_1), x_i^{'}(f_2), ..., x_i^{'}(f_n)\} \tag{5}$$

where $x_0^{'}(f_k)$ and $x_i^{'}(f_k)$ the normalized reference and comparison sequences, respectively. Eq. (6) was used to calculate the correlation coefficient after normalizing the sequences.

$$\xi_i(f_k) = \frac{\min\limits_i \min\limits_k \left| x_0(f_k) - x_i(f_k) \right| + \rho \max\limits_i \max\limits_k \left| x_0(f_k) - x_i(f_k) \right|}{\left| x_0(f_k) - x_i(f_k) \right| + \rho \max\limits_i \max\limits_k \left| x_0(f_k) - x_i(f_k) \right|} \tag{6}$$

where ξ shows the correlation coefficient and taken equal to 0.50 in this study. The Grey correlation degree (r_{0i}) can be determined from Eq. (7), using the correlation coefficient calculated from Eq. (6):

$$r_i = \frac{1}{n}\sum_{k=1}^{n}\xi_{0i}(f_k) \quad (7)$$

3. Results and Discussions

3.1. Evaluation of unconfined compression test results and effects of water contents

Figure 6 shows the compressive strength - strain behavior of the soil specimens with various water contents before and after freeze-thaw cycles. The UCS failure strength of clayey soil declined with an increment in water content. Some researchers [27] found a similar trend in water content, however, some of them [28, 29] presented that as water content increases, the compressive strength rises at first and then decreases. Their results showed that the maximum UCS was observed at the optimum moisture content value. Further, the UCS of all specimens after freeze-thaw cycles decreased. Moreover, in clayey soil, the stress-strain curves exhibited strain- softening behavior, and this condition transitioned from strain- softening to strain- hardening behavior after freeze-thaw cycles and with an increment in water content.

Also, Figure 7 depicts the variation of peak values of UCS versus freeze-thaw cycles (N) for different water content (w). The UCS of the soil with an 23.0% water content was observed little less than the soil with a 18.0% water content before freeze-thaw cycles, but after the maximum freeze-thaw cycle, it was observed that this ratio approached each other. Moreover, the compressive strength decreased at the rate of 62.03% for an increase in the water content to 21.5%, and 59.25% for a 23.0% water content. Generally, when the water content rises, the friction resistance and interfacial force between soil grains decrease. This drop could be attributed to a decrease in soil absorption, which happens simultaneously as the water content rises and the potential for the formation of excess pore water pressure [30].

3.2. Influence of the freeze-thaw cycles on the UCS strength

Due to probable moisture movement and ice development below 0 ºC, soil engineering qualities change significantly after the repeated freeze-thaw cycles. As a result, the determination of engineering features is a requirement for stability analysis and solutions in seasonally frozen regions [20]. Figure 6 shows the UCS-strain relationships prior to and following repeated freeze-thaw cycles. As shown in Figure 6, the soil compressive strength is greatly affected by water content and freeze-thaw cycles. Before freeze-thaw cycles, UCS peak values varied from 442.45 to 1085.63 kPa with an increase in water content from 18.5% to 23.0%. However, after the 15th freeze-thaw cycle, UCS peak values decreased from 183.20 to 159.88 kPa with an increase in water content from 18.5% to 23.0%. The pore water within the soil freezes when it is exposed to a freezing process. Soil particles separate from one another due to the ice force, raising pore water pressure. The increased pore water pressure, on the other hand, cannot return to its original state during thawing. As a result, freeze-thaw cycles frequently weaken soil [31].

In this study, to demonstrate the impacts of freeze-thaw cycles on soil failure strength, a ratio (qu-N/qu-0) was calculated by dividing the UCS peak values of the soil after the freeze-thaw cycles (qu-N) by the UCS peak values of soil that had not been experienced to any freezing-thawing cycles (qu-0). Figure 8 depicts the failure strength ratio of all specimens experienced with freeze-thaw cycles at different water contents.

The failure strength ratio of the clayey soil reduced as the number of freeze-thaw cycles increased, as illustrated in Figure 8. Also, the compressive strength of the soil decreased by 40.82% to 80.09% for 18.0% water content; this drop was about 14.44 % to 58.57 % for 21.5% water content and 38.18% to 63.87 % for 23.0% water content between 2 and 15 freeze-thaw cycles.

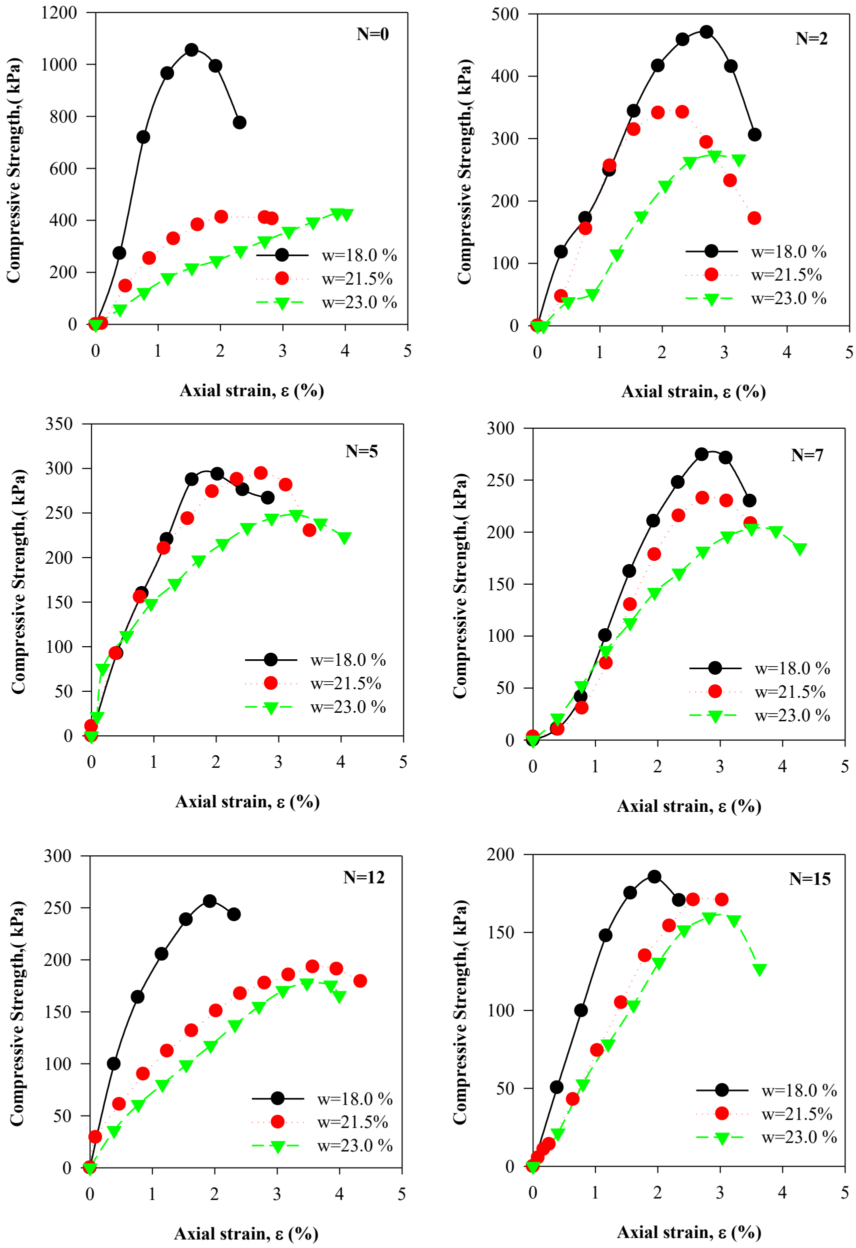


Figure 6. The UCS versus axial strain of the specimens for different w and N.

3.3. Effects of the freeze-thaw cycles and water contents on the ultrasonic pulse velocity

The UPV is regarded to be a useful tool for determining the material's overall quality and elasticity [32]. As presented in Figure 9, the water content and UPV of the specimens were inversely proportional. That is, the water content rises while the UPV of the soil specimen's decreases. Since velocities of solids are greater than velocities of liquids, which are greater than air velocities, the velocity of ultrasonic pulses are transmitted rapidly in voids and a high frequency is more easily transmitted in the clay soil with lower water and air content. The UPV measurements before the freeze-thaw tests varied from 593 to 916 m/s, indicating the degree of very low velocity suggested by prior research. This low degree of strength and elasticity could be related to the material type (clay) used in this study. According to other research, ultrasonic velocities are higher in clayey soils at low water content

[33, 34], which confirms the findings of this study. This is due to the fact that waves propagate at a fast speed in low-water-content soils [35]. This could be because voids in soil samples reduce as water content decreases, resulting in higher UPV.

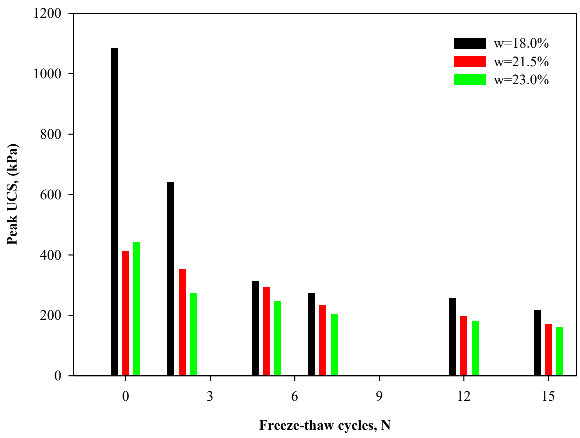


Figure 7. Change of peak values of UCS versus N for different w.

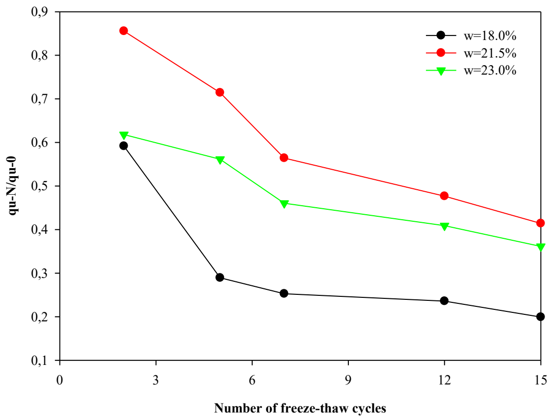


Figure 8. Variation of qu-N/qu-0 ratio with freezing-thawing cycles for different *w*.

In addition, when the number of freeze-thaw cycles increases, the UPV values decline. Soil samples showed a velocity variation of 515 m/s for samples with 18.0% water content, 490 m/s for samples with 21.5% water content, and 406 m/s for samples with 23.0% water content after the freeze-thaw tests with the maximum number of cycles. As previously explained by [36, 37] the soil has a decrease in the UPV during thaw cycles, while the soil has a slight rise in the UPV during freeze cycles. The water inside the pores and voids between the soil particles tends to freeze when the temperature is lowered to negative during the freezing process, reducing the volume and raising the internal pressure on the soil particles. The UPV is increased by filling the pores in the soil with ice, resulting in a more compacted soil with improved interlocking. By allowing the ultrasonic waves to pass through the soil sample in a shorter time, a higher UPV value is obtained. Micro-cracks occur as the ice melts, resulting in a drop in the UPV.

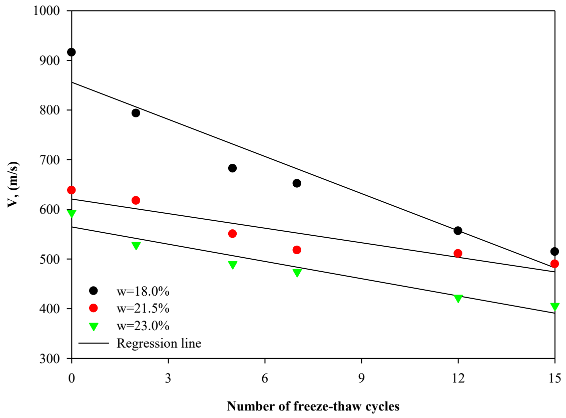


Figure 9. Comparison of the impact of freeze-thaw cycles on the UPV.

As Figure 10 shows, an increase in the UCS values was observed with increasing the UPV values for clayey soil. This conclusion is in agreement with that of [33]. Figure 10 further shows that for all soil specimens, the UCS against the UPV relationships result in good correlations (R^2>0.87). The number of freeze-thaw cycles (N) and water contents (w) have a clear impact on the relationships. The highest correlations for water contents were obtained at optimum water content. On the other hand, low correlations were obtained with the increasing number of freeze-thaw cycles. The correlations for the 15th freeze-thaw cycle were lower, whereas the correlations for the 2nd freeze-thaw cycle were higher.

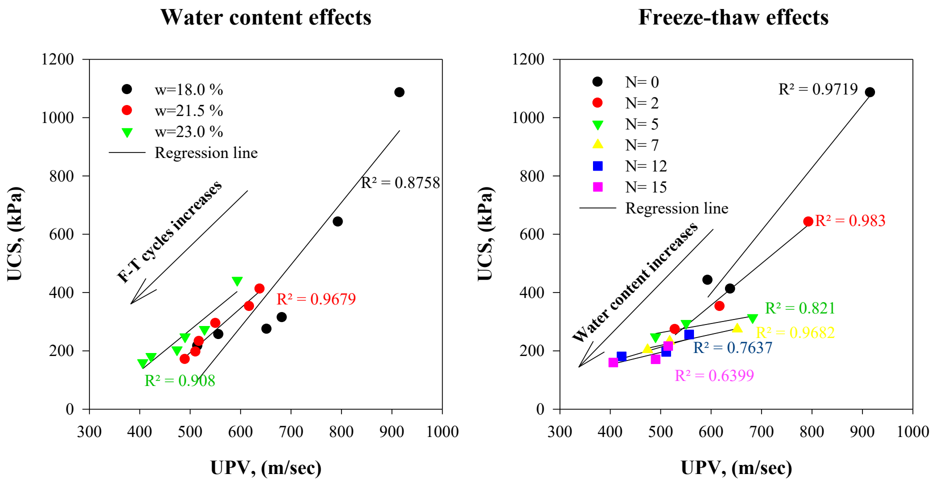


Figure 10. The correlations of UCS versus UPV for different w and N.

3.4. Results of Grey correlation analysis

Temperature changes in a year significantly influence the water migration of soils. Because a significant quantity of latent heat must be removed in soil with high unfrozen water content, the freezing phase takes longer to penetrate. Describing the soil water conditions can make it easier and is essential for specifying the strength properties of soil in the seasonally frozen region. The strength characteristics and water content of the subgrade soil are not directly considered in evaluating the performance or usability of the pavement. However, the increased water content in subgrade soil in seasonal freezing regions, coupled with increased pavement loads often leads to pavement problems. In this study, the UCS was described as the reference sequence, and the water content, the ultrasonic pulse velocity, and freeze-thaw cycles, (w, UPV, and N) were used as the comparison sequences. While soil water content is related to internal properties, ultrasonic wave velocity, temperature, and freeze-thaw cycle are external parameters for the soil. Therefore, Grey correlation analysis was used to assess the significance of these parameters on the UCS of the soils. Table 2 presented the Grey correlation coefficients.

Table 2. Grey correlation coefficients.

Reference sequences	Comparison sequences		
	w	*F-T*	*UPV*
q_u	0.898	0.604	0.958

qu: Unconfined compressive strength, w: water content, F-T: number of freeze-thaw cycles, UPV: ultrasonic pulse velocity

The sequence of Grey correlation for several parameters was found to be UPV > w> F-T. It is clear that the UPV has more influence on the q_u than the freeze-thaw cycles and water contents for clayey soil. The UPV values are mainly related to the composition of soils, namely the mineralogical structure. The soil's composition is proportional to the lower number of voids, thus the higher its strength. In contrast to freeze-thaw cycles, the water content has a greater impact on the q_u. This was due to the limits enshrined by the soil's inherent properties exhibited while experiencing both the freezing and thawing processes.

Moreover, the highest mean correlation coefficients of the reference sequence, ξ_{max}, were calculated as ξ_{max1}=0.9479, ξ_{max2}=0.9261, ξ_{max3}=0.9686. Thus, the best gradation for the reference sequences (q_u) of clayey soil under the examined condition is proved for 18%, 0 freeze-thaw cycles, and 916 m/sec respectively.

4. Conclusions

In this study, the impact of water content and freeze-thaw cycle on the unconfined compressive strength and non-destructive testing behavior using the UPV test of the soil specimens was investigated. Conclusions were made within the scope of the study. These are as follows:

The UCS of specimens prepared with water contents less than the optimum water content was greater than the other values. Also, UCS peak values were observed at the lowest water content prior to and post the freeze-thaw cycles. The stress-strain curves exhibited a strain-softening behavior, and this condition transitioned from brittle to ductile behavior after the freeze-thaw cycles, with an increment in the water content.

According to the unconfined compression test results, the soil's strength decreases with an increase in the freeze-thaw cycles. A decrease in the UCS of soils due to freeze-thaw cycles was derived with the highest values of the samples prepared below the optimum water content, while it was seen the least values in the soil specimen prepared at the optimum water content. After the maximum freeze-thaw cycle, with a water content rise from 18.5% to 23.0%, UCS peak values decreased from 183.20 to 159.88 kPa.

To show the impacts of freeze-thaw cycles on the soil failure strength, a ratio (qu-N/qu-0) was determined and a decline in the compressive strength was found by 80.09% for 18.0% water content; 58.57 % for 21.5% water content, and 63.87% for 23.0% water content after maximum freeze-thaw cycles, respectively.

The highest values of UPV were observed for UCS values increasing due to capillary forces at minimum values of water content. Moreover, a decrease in the UPV was observed with increments in the number of freeze-thaw cycles. According to correlations between UCS and UPV values, the highest correlations for water contents were obtained at 21.5% (optimum water content), and a decreasing trend was observed with the increasing number of freeze-thaw cycles.

The Grey correlation sequence of various parameters on the UCS values was determined to be ultrasonic pulse velocity > water content > freeze-thaw cycles.

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