FREEZE-THAW EFFECT ON THE RESILIENT MODULUS AND ACCUMULATIVE DEFORMATION OF SILTY CLAY

By

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ABSTRACT

The behavior of subgrade soils with different water contents under freeze-thaw conditions is a significant factor to be considered in pavement engineering, since freeze-thaw cycles substantially affect deformation of subgrade under cyclic loading, which in turn influence the performance of pavements.

In this study, the resilient modulus tests were performed on unfrozen silty clay before and after the first freeze-thaw cycle. Resilient modulus tests were carried out at various water contents including 5%, 8%, 10%, 12% and 15%. The behavior and response of the samples were monitored and recorded, and are compared through this report. In addition to resilient modulus tests, the accumulative deformation of the samples under cyclic loading was investigated. The results reveal that freeze-thaw cycles have the potential to have significant impact on permanent deformation of silty-clay under cyclic load.

ACKNOWLEDGEMENTS

I would like to express my profound gratitude to Dr. Peijun Guo for his encouragement, guidance and technical support throughout the research program.

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M_r – Resilient modulus;

S_1 – Axial stress;

S_3 – Confining pressure;

$S_{contact}$ – Contact stress;

S_{cyclic} – Cyclic axial stress;

S_{max} – Maximum axial stress;

p – Mean stress $p = (S_1 + 2S_3)/3$;

θ - Bulk stress $\theta = 3p = S_1 + 2S_3$;

ε_r – The resilient (recovered) axial strain due to S_{cyclic};

w - Water Content;

θ^0 – Temperature;

$\dot{\varepsilon}$ - Resilient Strain Rate;

S_d- Deviator Stress;

CHAPTER 1: INTRODUCTION

1.1 Frost and Heave

When water freezes and expands in a soil such as silty clay and silt, frost heave may occur, in which the ground surface moves upward due to the expansion of the freezing zone. Generally, frost heave is accomplished by the formation of ice lenses, which is due to moisture migration from unfrozen soil into the freezing zone. As the frozen ground thaws in spring time, an excess of water is developed, which contributes to softening the soil and hence results in a loss of bearing capacity and decrease in stiffness. In other words, the ice lenses become a source of the significant weakening of the soil during thawing process.

There are three significant conditions for frost heave to occur (Voller and Sterling, 2003):

- Water must be available at all the time even during freezing,
- There should be freezing temperature, and
- The soil must be frost susceptible.

Taber (1929) showed that when soil column freezes, additional moisture is drawn up into the freezing zone, which in turn increases the level of heave. Taber performed the experiment in which the water in the soil was replaced by other liquids such as benzene and nitrobenzene in order to prove that the phenomenon of frost and heave is not because of the water expansion due to freezing since the benzene and nitrobenzene contract upon freezing. Frost heave is related to moisture migration into freezing zone and ice growth (segregated ice lenses), and not to the fluid expansion upon phase changes.

1.2 Influences of Frost Heave

The pore water in soil near the ground surface freezes when the air temperature drops below zero for extended period of times. Frost action results in the following engineering consequences:

- 10% of volumetric expansion of water upon freezing
- Formation of ice crystals and lenses in the soil.

The ice lenses can be seen as the dark bands within the soil. These lenses can grow to several centimeters in thickness and cause heaving and damage to highway pavement structures and small building owing to the low vertical stress in soil induced by these structures. At the same time, due to uneven volume changes in soils due to freezing, the soils have differential movement that may induce damage to the structures.

In the spring time, the ice lenses usually melt and subsequently the water content of soil increases. As water content increases, the soil strength and stiffness both decrease. This thaw weakening of soils may result in rapid damage to the pavement structures under cyclic traffic loading. There are some methods for reducing frost induced damage in cold regions such as lowering the water table, removal of frost susceptible soils, use of impervious membranes, chemicals additives, foam installation under highways, etc. (Voller and Sterling, 2003).

1.3 General Frozen Ground Engineering Approach

The deformation behavior of frozen soil is relevant to the practical aspects of engineering in cold regions. It is crucial to know this behavior to predict under what circumstances a structure may fail or how the deformation develops. In North America particularly, development of the permafrost regions is advancing rapidly, and engineering design and construction principles need to be formulated that will ensure structural and environmental stability over the long term (Parapeswaran and Jones, 1981). However, the mechanical properties of frozen soil are perhaps the most variable and difficult of all geomaterials to understand and model (Andersen et al., 1995). The uncertainty regarding its stress-strain time-temperature interaction consequently restricts the construction and maintenance of structures built on frozen soil.

Climate effects on pavement structures have been extensively studied by Johnson (1952), Johnson et al (1978), Berg and Wright (1984), and Grandahl (1987). The deterioration of the pavement structure is caused not only by commercial vehicles (traffic load) but also by climate. The deterioration in spring time appears when the thaw phenomena occur in the soil. During spring time, subgrade and some subbase materials may become water-saturated through the melting of excess ice which significantly reduces bearing capacity and stiffness (or resilient modulus). This may initiate large settlements and deformations of the pavement structure. Consequently, to attain satisfactory all-season service and long-term performance of pavement in cold regions, climate effects must be addressed.

Some fine-grained soils such as silty clay, when exposed to freezing and thawing cycles, generally experience volume changes (Chamberlain and Gow 1979; Knutsson 1984), loss in shear strength (Graham and Au 1985) and sometimes alternations in their hydraulic conductivities (Chamberlain and Gow 1979; Wong and Haug 1991; Othman and Benson 1994). Such alternations of engineering properties during cyclic freezing and thawing are of practical significance for geotechnical engineering structures.

For instance, the increase in permeability and compressibility, and loss in strength and stiffness in clays at shallow depth because of cyclic freezing and thawing, are main considerations when designing clay liners, retention dikes and other barriers in cold climates. Volume changes in clays due to cyclic freezing and thawing are important for the performance of the shallow structures based in freshly exposed soft clay deposits (e.g. in the case of highway cuts).

Konrad and Roy (1999) mentioned that "Pavement design in cold regions characterized by seasonal variations in properties of each soil layer of the pavement structure including subgrade soils below the frost front is complex and needs to consider basic soil mechanic principle. Frost heave is related to the segregation potential of frost susceptible subgrade soils. Below the water table, the segregation potential is mainly a function of soil type and overburden pressure. Above the water table, the segregation potential of a saturated subgrade is a function of capillary rise and associated suction. Frost heave may be negligible if the subgrade is unsaturated with degrees of saturation less than 70%". They further specified that "The pavement structure heaves when it is frozen, the pavement heave longitudinally along the pavement length was uneven in freeze-thaw test. At the start of the thaw period, a few load repetitions resulted in a very large permanent deformation. Part of this deformation was due to the settlement of the frost heave, and part of it was due to additional permanent deformation. From the plastic strains measurements which is done on top of the subgrade, the permanent deformation in the subgrade can be determined. It can be determined that 60% of the surface rutting is due to the permanent deformation of the subgrade."

In addition to understating the frost-heave behavior of soils and its influence on soil properties, it is important to observe the soil behavior after freeze-thaw cycles in order to determine the performance of engineering structures. For example, when the soils are under cyclic loads, freeze-thaw cycles may have significant influences on the durability of the engineering structures.

It should be mentioned that frozen ground engineering is also useful for utilizing the artificial ground freezing as a construction purposes for providing temporary support for excavations, tunnels, mineshafts, underground utilities and buildings (Voller and Sterling, 2003). The groundwater control for large excavations can be established through controlled ground freezing. However, the artificial ground freezing may not be effective all the time due the various in the mechanical behavior of the resulting soil-ice material and the influence of temperature on its behavior are difficult to predict.

1.4 Research Objectives

The objectives are to investigate the effect of frozen-thaw on the resilient modulus and the accumulative deformation of soil specimens under cyclic loading. In this study, unfrozen silty-clay samples and specimens of the same soil after one frozen-thaw cycle are tested under cyclic load at different water contents. The research focuses on the following tasks:

- Understanding the unfrozen silty-clay soil behavior at different water contents.
- Understanding the silty-clay soil behavior at different water content after one freeze-thaw cycle.

- Obtaining accumulative deformation of samples under cyclic loading and comparing the results under two different conditions: unfrozen and after one freeze-thaw cycle.
- Comparing the results obtained through the cyclic tests under two mentioned different conditions considering various water contents.

1.5 Scope of the Report

This report is divided in to five chapters. Following the introduction of this Chapter, Chapter 2 provides a brief literature review on the following subjects:

- Frozen and unfrozen soil silty clay under repeated load
- Compressive strength of frozen soil versus strain rate
- Resilient properties of unbound material during seasonal frost conditions

Chapter 3 addresses the test set up, which includes the testing material, equipment, sample preparation and testing procedure. The results are represented in Chapter 4. Finally the conclusions and recommendation are summarized in Chapter 5.

CHAPTER 2: LITERATURE REVIEW

2.1 The Behavior of Frozen and Unfrozen Silty Clay under Repeated Load

The behavior of soil subjected to repeated loading such as earthquake and traffic loads is important to the performance of structures. Such repeated loads may cause significant decreases in the strength of soils, endangering life and property (Togrol et al., 1982). The consequences of repeated loading on the performance of unfrozen soils have been studied by many researchers such as Seed and Chan (1966) and Lee and Focht (1976). It was observed that the strength of unfrozen soils decreases under repeated load and this reduction is usually caused by the increase of pore water pressure (Togrol et al., 1982).

The structure of the frozen soil is more complex than that of unfrozen soils. Existence of an ice phase and ice cementation bonds play an important role in the behavior of a frozen soil (Togrol et al., 1982). Porkudin and Zhinkin (1973) carried out dynamic triaxial tests on frozen saturated specimens at temperatures between 0 and -2.4^{0}C by changing the cell pressure in a sinusoidal form and found that strength decreases under the effect of vibrodynamic loads as compared to static loading.

Tsevetkova (1960) compared the strengths of frozen and unfrozen soils. They found that under repeated loading, the strength of their silty-clay decreased 22 percent for the frozen samples tested under dynamic loads at -0.8 to -1.0 ^{0}C , yet no change in the strength of unfrozen samples was observed.

Nadezhdin and Sorokin (1975) found that the strength properties of frozen soil were affected by preloading. The long-term strength was shown to increase and the instantaneous strength was shown to be decrease by preloading.

The influence of repeated loading on the mechanical behavior of frozen soils can be explained by the existence of unfrozen water in the frozen soils and by the increase of the pore-water pressure as well as the destruction of the structural bonds of ice under cyclic loading. The strength change of frozen soil under repeated loading is more pronounced at temperatures just under 0 ^{0}C (Togrol et al., 1982).

The monotonic loading stress-strain curve of frozen soil is influenced by previous history of repeated loading as per Figure 1. The samples previously subjected to cyclic stresses reach failure at smaller strains than virgin specimens (Togrol et al., 1982).

Togrol et al., (1982) also reported that the influence of cyclic loading on the shear strength of frozen soil varies with temperature. The shear strength of frozen soil when subjected to repeated loading decreases by about six percent at temperature near -1 ^{0}C but shows no difference at lower temperatures, i.e. -2 or -3 ^{0}C as per Figure 2. The deformation modulus ($Es = 33\theta + 0.3$ MPa where θ is absolute of the negative temperature of degree Celsius) of frozen soil increases when subjected to repeated loading. This increase is found to be 200 percent at -1 ^{0}C and 75 percent at -3 ^{0}C for the soil tested as per Figure 3.

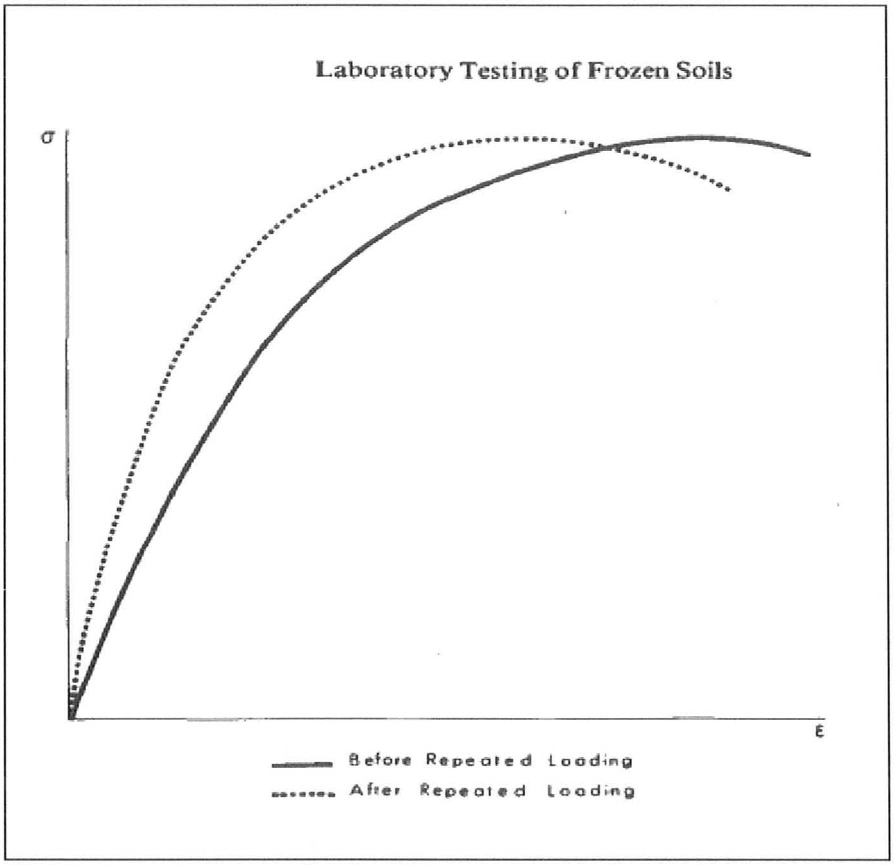


Figure 1 Influence of Repeated Loading on the Stress-Strain Curve (Togrol et al., 1982)

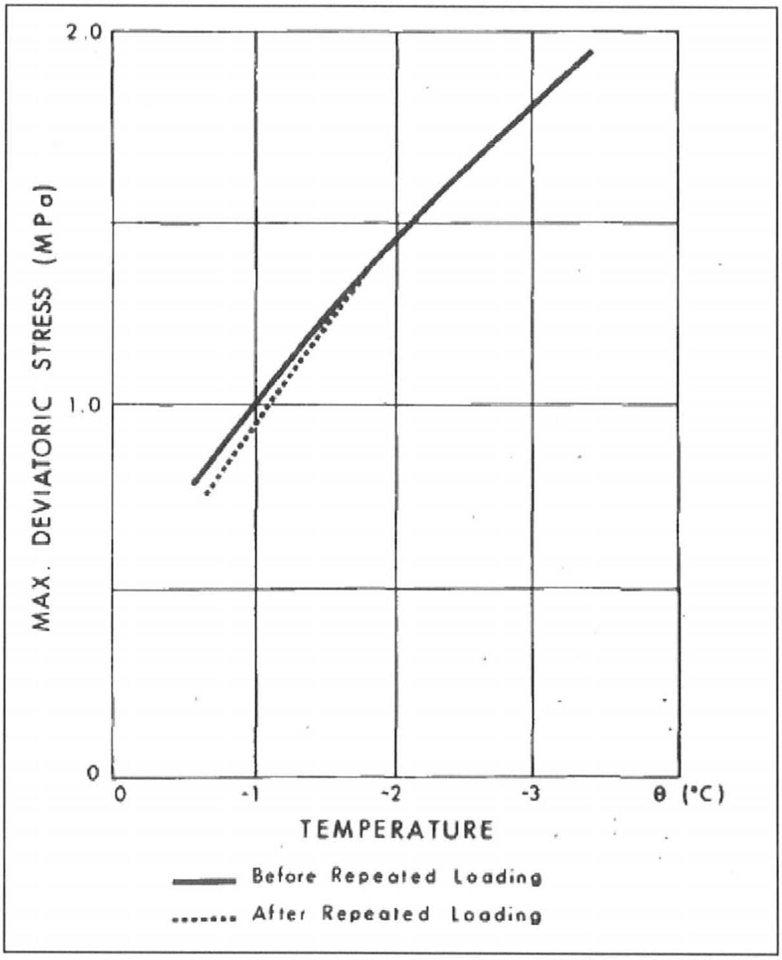


Figure 2 Influence of Repeated Loading on the Shear Strength at Various Temperature (Togrol et al., 1982)

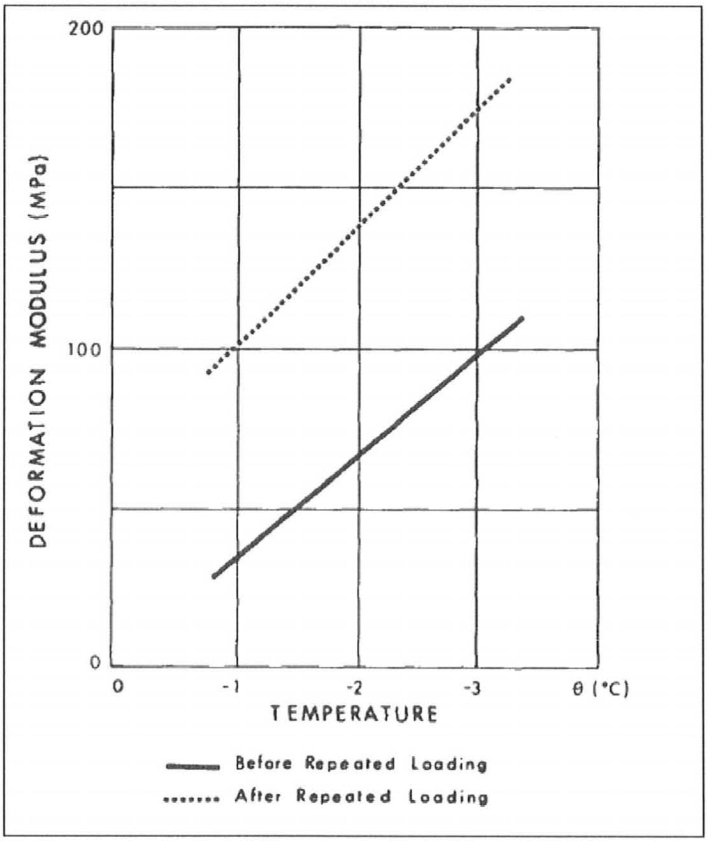


Figure 3 Influence of Repeated Loading on the Deformation Modulus at Various Temperatures (Togrol et al., 1982)

2.2 Compressive Strength of Frozen Soil versus Strain Rate

At a certain temperature, the relationship between stress and strain varies with a change of strain rate. Therefore, the compressive strength of frozen soil will be different for different strain rates. This can be observed in Figure 4 and Figure 5 (Li, et al. 2001).

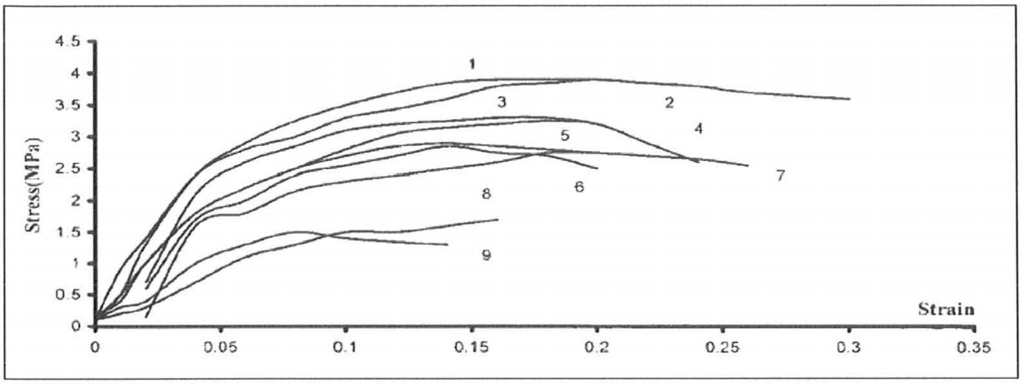


Figure 4 Effect of Strain Rate on Stress-Strain Curves of Frozen Soils

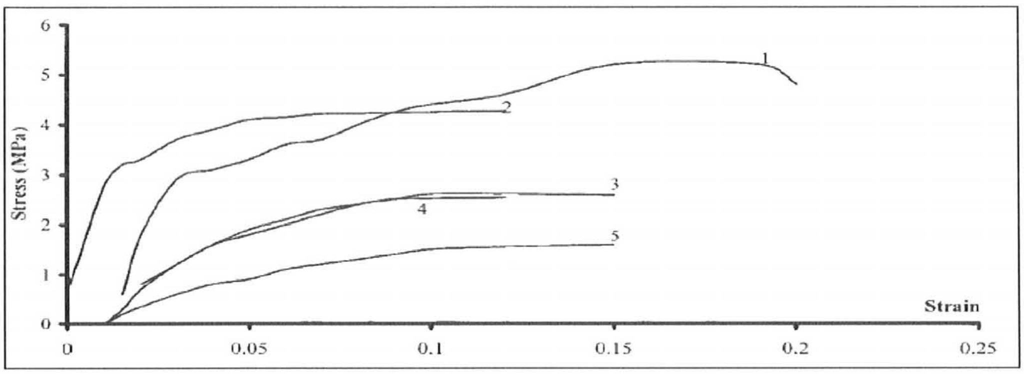


Figure 5 Stress-Strain Curves at Different Temperatures

The numbers in Figure 4 and Figure 5 represent the samples with the following conditions, with $\acute{\varepsilon}$ (1/s) representing strain rate and σ_c (MPa) the confining stress.

from 1 to 9, represent ($\theta = -5°C$)

(1) $\dot{\varepsilon} = 4.13 \times 10^{-3}$, $\sigma_c = 3.94$
(2) $\dot{\varepsilon} = 2.82 \times 10^{-3}$, $\sigma_c = 3.75$
(3) $\dot{\varepsilon} = 1.54 \times 10^{-3}$, $\sigma_c = 3.21$
(4) $\dot{\varepsilon} = 2.30 \times 10^{-3}$, $\sigma_c = 3.21$
(5) $\dot{\varepsilon} = 4.30 \times 10^{-4}$, $\sigma_c = 2.90$
(6) $\dot{\varepsilon} = 4.10 \times 10^{-4}$, $\sigma_c = 2.80$
(7) $\dot{\varepsilon} = 3.61 \times 10^{-4}$, $\sigma_c = 2.80$
(8) $\dot{\varepsilon} = 7.74 \times 10^{-5}$, $\sigma_c = 1.73$
(9) $\dot{\varepsilon} = 4.75 \times 10^{-5}$, $\sigma_c = 1.62$

from 1 to 5

(1) $\dot{\varepsilon} = 9.90 \times 10^{-6}$, $\theta = -20°C$, $\sigma_c = 5.05$
(2) $\dot{\varepsilon} = 1.12 \times 10^{-5}$, $\theta = -20°C$, $\sigma_c = 4.65$
(3) $\dot{\varepsilon} = 2.50 \times 10^{-5}$, $\theta = -10°C$, $\sigma_c = 2.77$
(4) $\dot{\varepsilon} = 1.63 \times 10^{-5}$, $\theta = -10°C$, $\sigma_c = 2.62$
(5) $\dot{\varepsilon} = 1.74 \times 10^{-5}$, $\theta = -5°C$, $\sigma_c = 1.73$

The compressive strength of frozen soil increases with decreasing temperature for a given strain rate, as shown in Figure 5 (Li, et al. 2001) in which curve (1) is at the temperature of θ = -20 ^{0}C and Curve (5) is at θ = -5 ^{0}C. It was also observed that the compressive strength of frozen soil is closely related to the stain rate. For silty soil, it is less sensitive to strain rate when strain rate is less than 10^{-4}/s and becomes more sensitive when the strain rate is in the range of 10^{-4}/s to 10^{-3}/s. The sensitivity of compressive strength against strain rate is the highest when the strain rate is greater than 10^{-3}/s (Li, et al. 2001).

2.3 Resilient Properties of Unbound Material during Seasonal Frost Condition

The concept of resilient modulus found in the mid 1950 (Seed et al., 1955) is important in the mechanistic design procedures for pavement structures. The resilient properties of soils in the cold region tend to vary over a wide range due to seasonal frost (Simonsen, 2002).

Johnson et al (1978), Cole et al (1986) and Berg et al. (1996) investigated the resilient properties of granular materials from frozen to thawed conditions. The following are the primary findings from these researches:

- Significant loss of strength upon thaw for most soils tested;
- A gradual regain of strength as moisture drained from the soil during the recovery period;
- A two-to-three order magnitude increase in strength of all materials at subfreezing temperatures.

Fredlund et al (1975) found a significant reduction in matric suction after freeze-thaw cycling, which was associated with a reduction in resilient modulus. The reduction in matric suction was substantial below the optimum water content, diminishing above optimum. Bergan and Fredlund (1972) found the similar reductions in matric suction occurred in undisturbed subgrade sample during spring thaw (Bergan and Fredlund, 1972). Lee et al (1955) investigated the resilient properties of cohesive soils and found that the stress level at 1 % ($S_{U1.0\%}$) strain in the unconfined compression test could be used to estimate the resilient modulus. They concluded that cohesive soils with $S_{U1.0\%}$ (stress level at 1 % strain) lower than 55 kPa would exhibit negligible freeze-thaw effects. In contrast, a soil with $S_{U1.0\%}$ (stress level at 1 % strain) higher than 103 KPa would exhibit a decrease of over 50% in resilient modulus due to freeze thaw (Lee, et al., 1995).

At subfreezing temperatures, the stress dependence of resilient modulus varied between the soils. Higher stress dependence was found in the fine-grained soils. Depending on soil type, the resilient modulus increased by a factor of 100-600 from room temperature down to -10 ^{0}C. As it can be seen in Fig. 6, the resilient modulus for the soils is a function of temperature (Simonsen, et al., 2002).

A significant stress-strain hysteresis was observed for a clay soil at subfreezing temperatures (Simonsen, et al., 2002). Generally, the clay displayed a higher resilient modulus during warming than cooling at lower temperatures (less than -5^{0}C). At higher temperatures (-2 to -0.5 ^{0}C), the clay displayed a lower resilient modulus during warming than cooling. It is suggested that consolidation is the cause of the initial stiffness increase, and the mechanisms controlling the redistribution of melting moisture affect the subsequent stiffness reduction. The freezing and thawing modulus paths are illustrated in Fig 7.

After freeze-thaw, coarse gravelly sand containing only 5% fines can display decrease of approximately 20-60% in resilient modulus. A 50% decrease in resilient modulus for fine sand was also observed. Both Figures 8 and 9 show typical experimental results for coarse gravelly sand. It is suggested that the volume of a very dense soil might increase due to freeze-thaw, making the soil slightly looser and weaker than it was prior to freezing. However, further research is required to verify these observations.

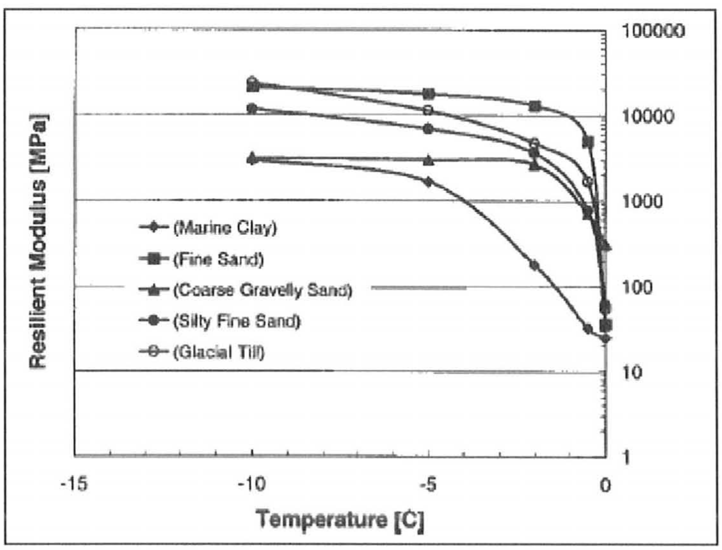


Figure 6 Resilient Modulus for Soils as a Function of Temperature
(Simonsen, et al., 2002)

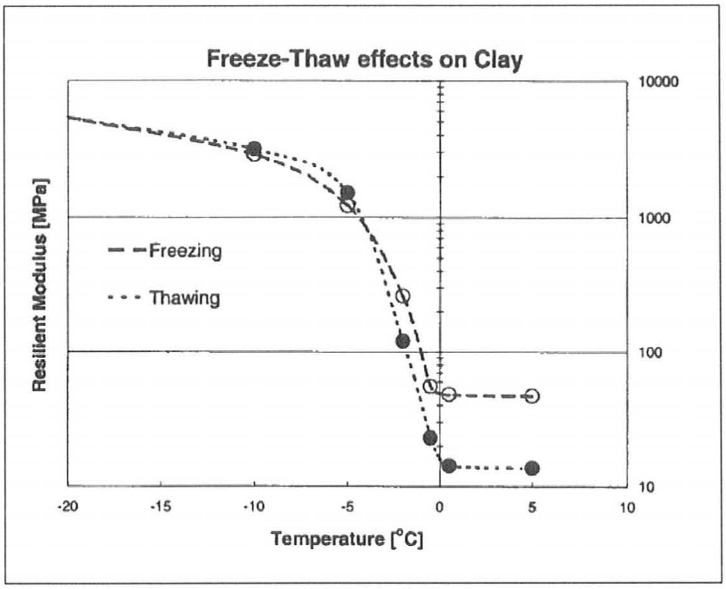


Figure 7 Resilient Modulus Freezing and Thawing Paths for Marine Clay (Simonsen, et al., 2002)

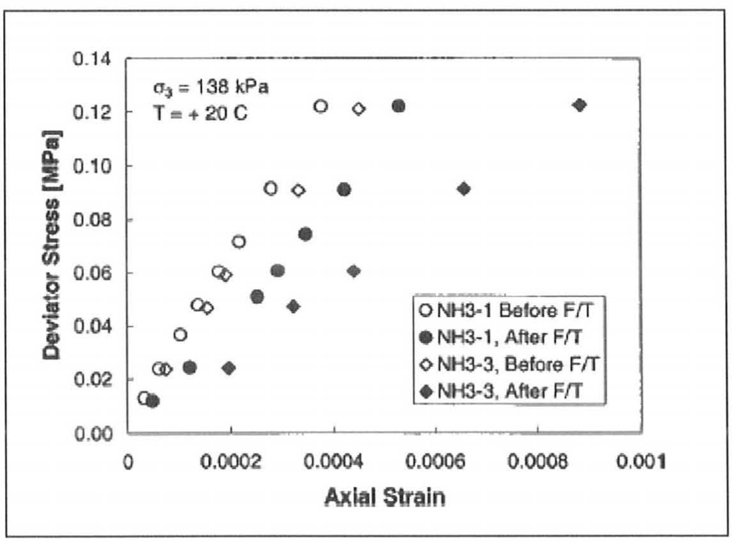


Figure 8 Resilient Modulus for Coarse Gravelly Sand before and after Freeze-Thaw (Simonsen et al. 2002)

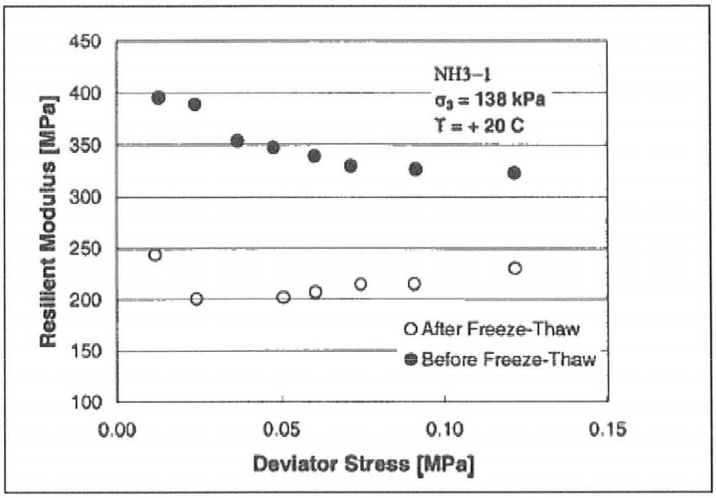


Figure 9 Typical Stress-Strain Behavior for Coarse Gravelly Sand before and after Freeze-Thaw (Simonsen et al., 2002)

2.4 Effects of Cyclic Freezing and Thawing on Volume Changes and Permeability of Soft, Fine-Grained Soils

Fine-grained soils when exposed to freezing and thawing, will generally experience volume changes (e.g., Chamberlain and Gow 1979; Knutsson 1984; Leroueil et al. 1991), loss in shear strength and increases in compressibility (Graham and Au 1985), and frequently alterations in their hydraulic conductivities (e.g., Wong and Huag 1991; Benson and Othman 1993). Such alternations of soil properties during cyclic freezing and thawing, increases of permeability and compressibility and loss in strength in clays at shallow depth due to cyclic freezing thawing are important for the design of clay liners, retention dykes, and barriers in cold climates. Volume changes in soft clays as the result of cyclic freezing and thawing, often called " freeze-thaw consolidation" (e.g., Chamberlin and Gow 1979), are important for the performance of shallow structures constructed in freshly exposed soft clay deposits or in the case of highway cuts (Roy et al. 1992).

Volume changes and strength properties after one freeze-thaw cycle have been determined for Chamberlin Sea clays, which could be relevant to the initial liquidity index (Leroueil et al.1991). Eigenbrod et al. (1996) measured the pore-water pressures and volume changes during one-dimensional freezing of soft grained soils and observed considerable fluctuation of negative and positive pore-water pressures during initial freezing. The maximum negative pore-water pressures measured during initial freezing could be correlated to the compression observed in the soft clay specimens subsequent to freezing and thawing (Eigenbrod, 1996). Both Figures 10 and 11 present typical soil deformations during freezing and thawing of soil 3 (as per Table 1) for fast and slow-freezing conditions as reported by Eigenbrod (1996). It may be seen that the net height of samples at the end of each cycle decreased and eventually after five to six cycles reached a fairly stable value (Eigenbrod, 1996).

Table 1. Characteristic Soil Properties (Eigenbrod 1996)

Soil type:	Mixed grey clay 1	Kam red clay 2	Yellow clay 3	Rosslyn blue clay 4
W_P (%)	24.8	23.6	16.1	20
W_L (%)	35.8	50.0	30.0	35
Clay size (% < 2 μm)	55	45	68	40
% illite	29	12	20	18
% chlorite	19	10	4	33
% montmorillonite	18	55	0	12
% kaolinite	19	15	65	23

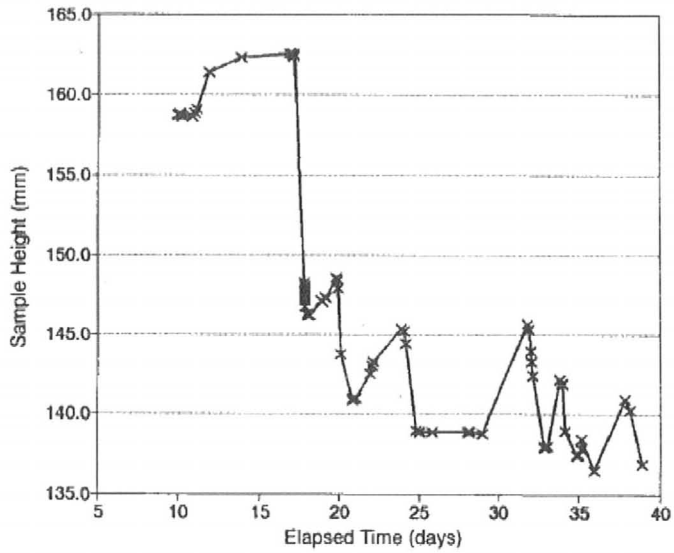


Figure 10 Deformations during Cyclic Freezing and Thawing for Fast Freezing (approx 30 mm/h) of Soil

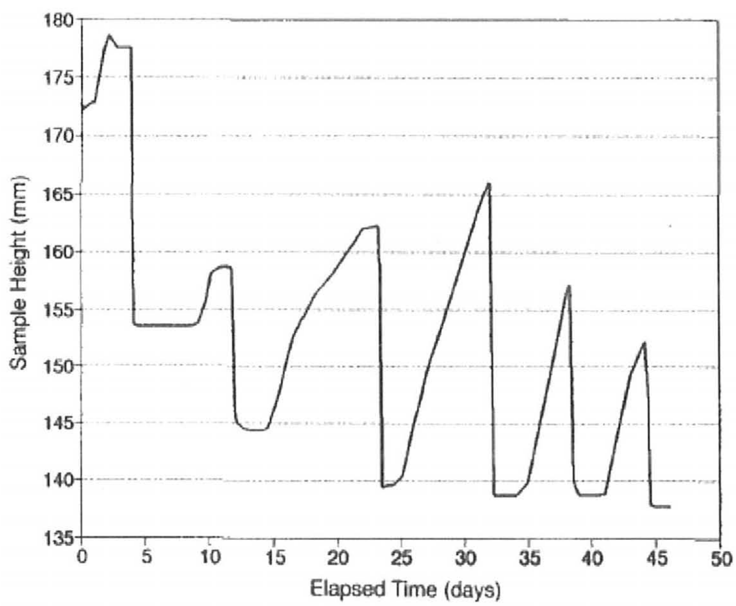


Figure 11 Deformations during Cyclic Freezing and Thawing for Slow Freezing (approx 0.8 mm/h) (Eigenbrod 1996)

The volumetric strains and the liquidity indices after each freeze-thaw cycle are plotted versus number of freeze-thaw cycles for the fast-freezing tests in Figures 12 and 13 and for slow-freezing conditions in Figures 14 and 15, respectively. It appears that volume changes decreased with each freeze-thaw cycle, and eventually, after about six cycles approached zero. This indicates that the magnitude of the volume change subsequent to freezing and thawing depends on the water content of the specimen prior to freezing and thawing (Eigenbrod, 1996). The results for soil 2 (Table 1)are compared for 20-30 day and 7 days freezing periods in terms of volumetric strain and liquidity index. These results are plotted in Figures 16 and 17. It can be noticed that apart from the fact the long freezing tests were started with higher initial water contents than the shorter tests, the data are much more scattered for the longer tests than for shorter tests (Eigenbrod, 1996).

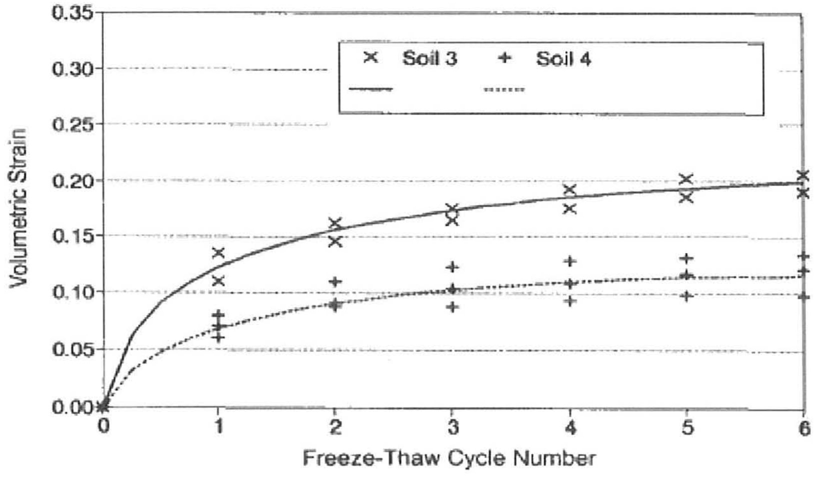


Figure 12 Fast-Freezing Tests: Volumetric Strains versus Number of Freeze-thaw Cycles. (Eigenbrod 1996)

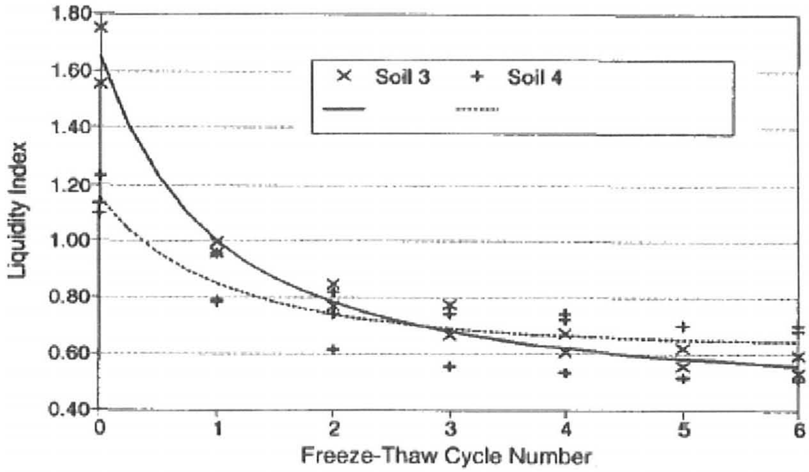


Figure 13 Fast-Freezing Tests: Liquidity Indices after Each Freeze-Thaw Cycles versus Number of Freeze-Thaw Cycles. (Eigenbrod 1996)

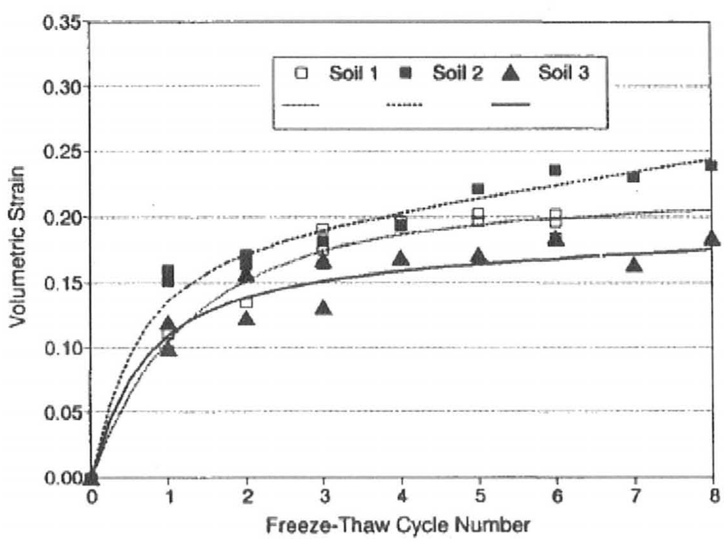


Figure 14 Slow-Freezing Tests: Volumetric Strains versus Number of Freeze-Thaw Cycle (Eigenbrod 1996)

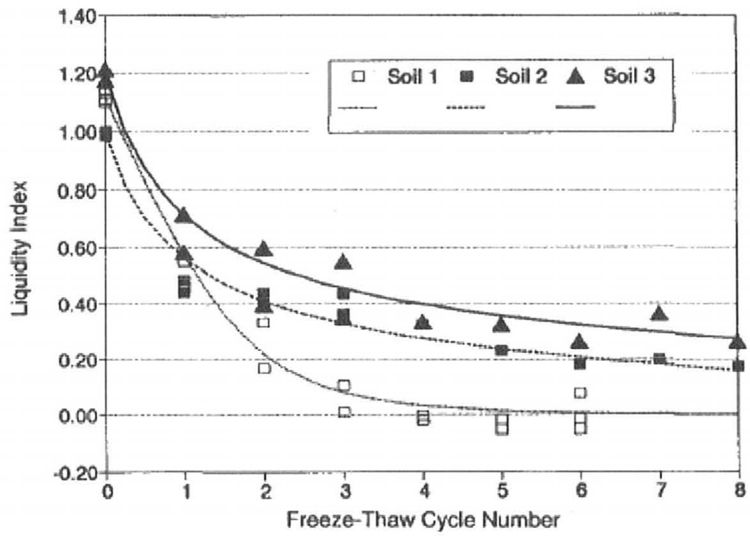


Figure 15 Slow-Freezing Tests: Liquidity Indices after Each Freeze-Thaw Cycles versus Number of Freeze-Thaw Cycles. (Eigenbrod 1996)

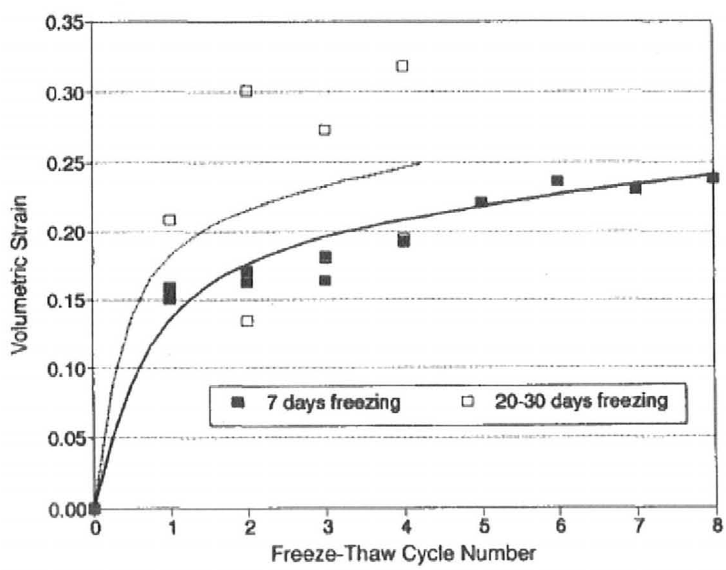


Figure 16 The Test Results for Soil 2 for 7 Days and 30 Days Freezing Periods. Volumetric Strain versus Freeze-Thaw Cycle Number (Eigenbrod 1996)

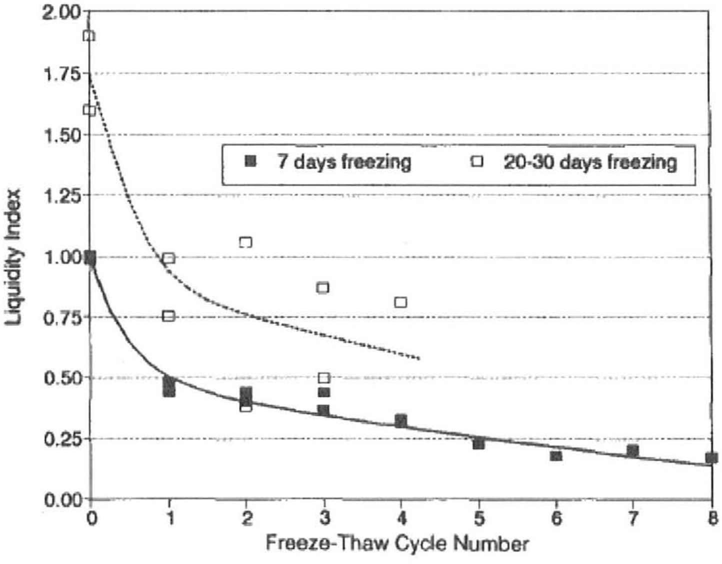


Figure 17 The Test Results for Soil 2 for 7 Days and 30 Days Freezing Periods. Liquidity Index after Each Freeze-Thaw Cycles versus Number Freeze Thaw Cycle. (Eigenbrod 1996)

To identify the effects of freezing rate, the volumetric strains at a given initial water content (liquidity index = 1.0) are plotted in Figure 18 versus rate of freezing (Eigenbrod, 1996). The results clearly show that slower freezing tends to induce larger volume change than fast freezing.

The volume changes subsequent to freezing and thawing depend on primarily on soil type and soil consistency, the number of freeze-thaw cycles, freezing rate and the mode of freezing. The magnitude of the final volume changes is larger in cold climates, as the depth of frost penetration will be much larger (Eigenbrod, 1996).

In 1996, Eigenbrod proved that typically after four freeze-thaw cycles, the magnitude of frost heave decreased with increasing freeze-thaw cycles, suggesting that the potential for frost heave in clayey soils may decrease with time. More data are needed, however, to confirm this behavior.

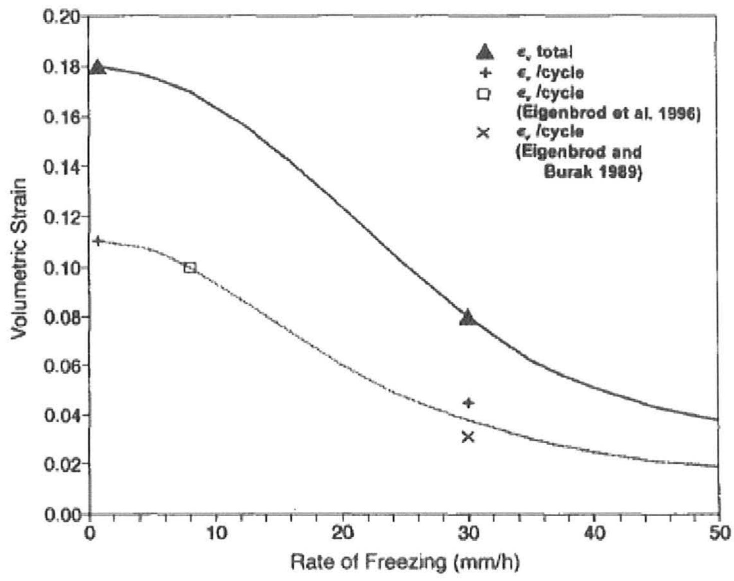


Figure 18 Volumetric Strain for (Initial Liquidity Index) I_{LO} =1.0 versus Rate of Freezing (Eigenbrod 1996)

Also, in 1996, Eigenbrod established that soft fine-grained soils were exposed to cyclic one-dimensional, open system freezing and thawing, resulting in maximum volume changes of up to 30%, depending on the initial water content and plasticity of the clay as well as on the rate of freezing. A linear relationship between the net volume change subsequent to freezing and thawing and the liquidity index prior to freezing and thawing was identified. This correlation was found to be unique, but depends on rate and mode of freezing. However, the settlements from freeze-thaw consolidation in the field can be predicted from such tests if the rate and mode of freezing are the same as in the field. During cyclic freezing and thawing the soil was found to become fissured and jointed, which resulted for most clay in large increases in their bulk permeability that increased with an increasing number of numbers of freeze-thaw cycles (often by more than two orders of magnitude). For some materials, however, little change in permeability occurred.

In a study of Eigenbrod in 1996, the coefficients of permeability for Materials 1, 2, and 3 were tested in rigid-wall permeameters at zero effective stress and are plotted versus number of cycles in Figure 19. For Materials 1 and 2, increases in permeability by two orders of magnitude are indicated, when compared with permeability of soft clay specimens prior to freezing and thawing. Material 3 did not show any changes.

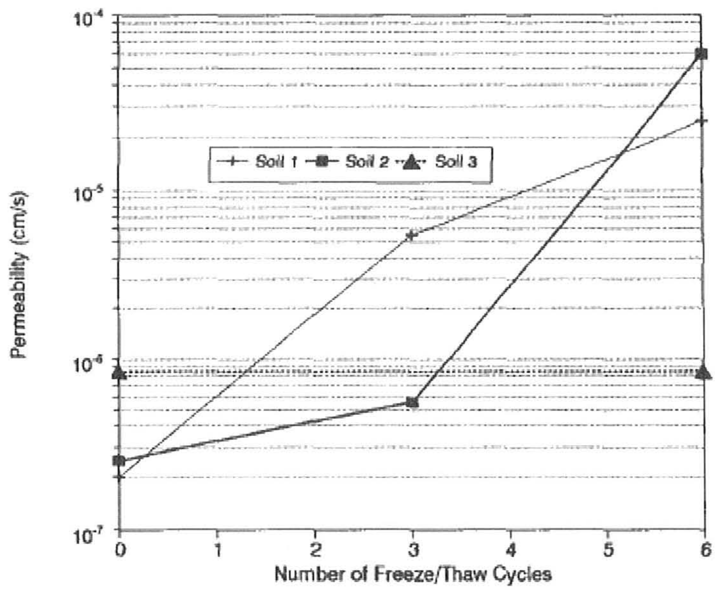


Figure 19 Permeability's versus Number of Freeze-Thaw Cycles. (Eigenbrod 1996)

2.5 Conclusion

For understating the unfrozen and frozen soil behavior under cyclic or static load, there is numerous research reported in the literature. The literature considers different types of soil such as sand, clay, silt and gravel. It has been shown that soil samples have different behavior under different temperature and the strength of soil varies with change in temperature. In conclusion, the soil behavior with different water content under freeze-thaw condition is an important factor in the pavement studies. The deflection measurement of the subgrade under cyclic load can assist geotechnical engineers for preventing the future pavement's failures from happening.

CHAPTER 3: LABORATORY TESTS

3.1 Introduction

Resilient modulus tests were performed to explore the influence of freeze-thaw on the resilient modulus of a subgrade material. Ten samples were prepared with different water contents. The resilient modulus tests were carried out on 5 unfrozen samples and 5 samples subjected to one freeze-thaw cycle, following the standard resilient modulus loading sequences of AASHTO T307-99. After performing the resilient modulus test on the samples, the accumulative deformation was established by placing these samples under 2000 load repetitions at different deviator stress levels though three stages.

3.2 Testing Material

A silty clay was selected for this study since this type of soil is a common subgrade material in North America and is known to be frost susceptible. Large blocks of the dry material were broken into small ones using a hammer so that the size of the maximum soil blocks was no larger than 4.75 mm. Figures 20 and 21 show the material before and after breaking up.

Figure 20 Original Material, Silty Clay before Breaking up.\

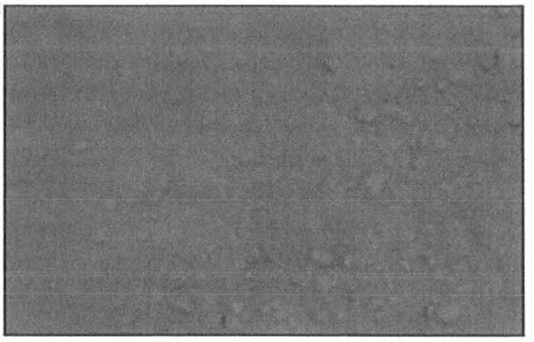


Figure 21 Original Material, Silty Clay after Breaking up

3.3 Equipment

The loading device for the resilient modulus testing is a closed-loop, servo-controlled electro-hydraulic MTS testing machine with a function generator that is capable of applying repeated cycles of a haversine load pulse, following a history supplied by the microcomputer control software. Figure 22 shows the loading frame together with the triaxial cell that is capable of hosting the specimen, the devices for specimen preparation as well as the transducers, including a load cell and two linear differential transducers (LVDT) used externally to measure the deformation of the specimen.

3.4 Sample Preparation

Soil passing sieve No.4 (4.75mm) was used to prepare specimens for resilient modulus testing. Specimens with the target dry unit weight γ_d = 16.5 kN/m^3 were fabricated at different water contents (w =5%, 8%, 10%, 12% and 15%) for the resilient modulus test. The bulk density of the samples was calculated by:

$$\gamma = \gamma_d\,(1+w) \qquad (1)$$

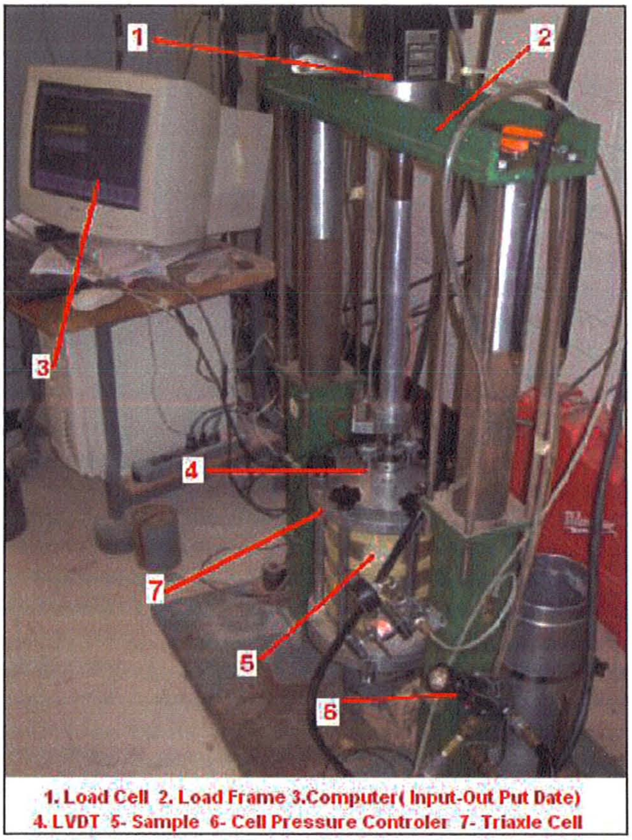


Figure 22 Triaxil Cell and Other Accessories Used for Resilient Modulus Test

Prior to fabricating soil specimens, water was added to 3000 g of dry soil samples in small amount and mix thoroughly after each addition. Afterwards, the samples were stored in plastic bags and left in a moisture room for 24 hours in order to allow a more uniform distribution of the moisture through the sample.

3.5 Compaction of Soil

The samples were taken out from the moisture room after 24 hours. The specimens were prepared as per AASHTO T307-99.

3.5.1 General

The compaction method for the samples of this study is as per AASHTO T307-99 (2003). This method discusses the compaction of type 2 soils (such as clay, silty clay, etc). It is based on static compaction (a modified version of the double plunger method). Specimens were compacted in a 71 mm diameter by 152 mm in height mold; as shown in Figure 23.

3.5.2 Compaction Procedure

Five layers of equal weight soil were used to compact the specimens using the following five steps that are illustrated in Figure 24. The total weight of wet soil was determined and divided by five for weight of each layer. The spacer plugs were placed in to the specimens mold as per Figure 24. Full details of the procedure can be found in the AASHTO T307-99 (2003) and also LTPP-Protocol P46 (1996). A MTS Testing Machine was used to compress the spacers into the sample as shown in Figure 25. After making the samples, the samples were injected out of the mold by the extruders as shown in Figure 26.

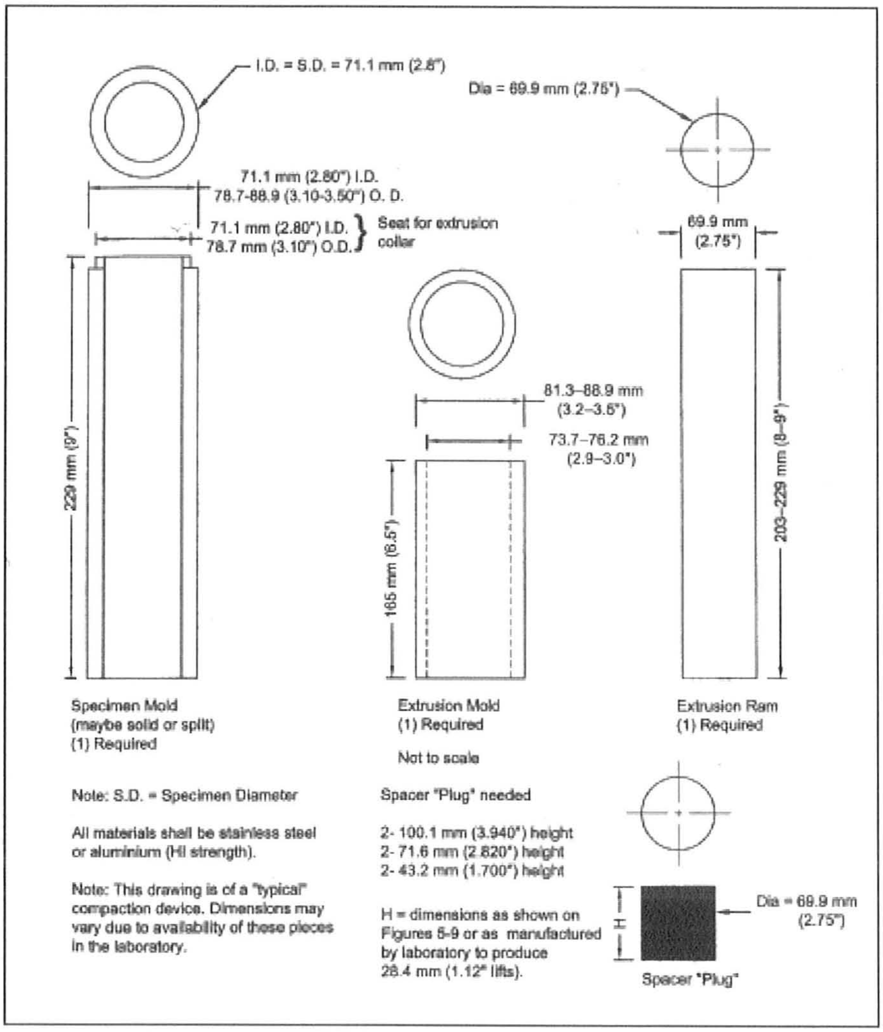


Figure 23 Typical Apparatus for Static Compaction of Type 2 Material (AASHTO T307-99 & Protocol P46-LTPP-August 1996)

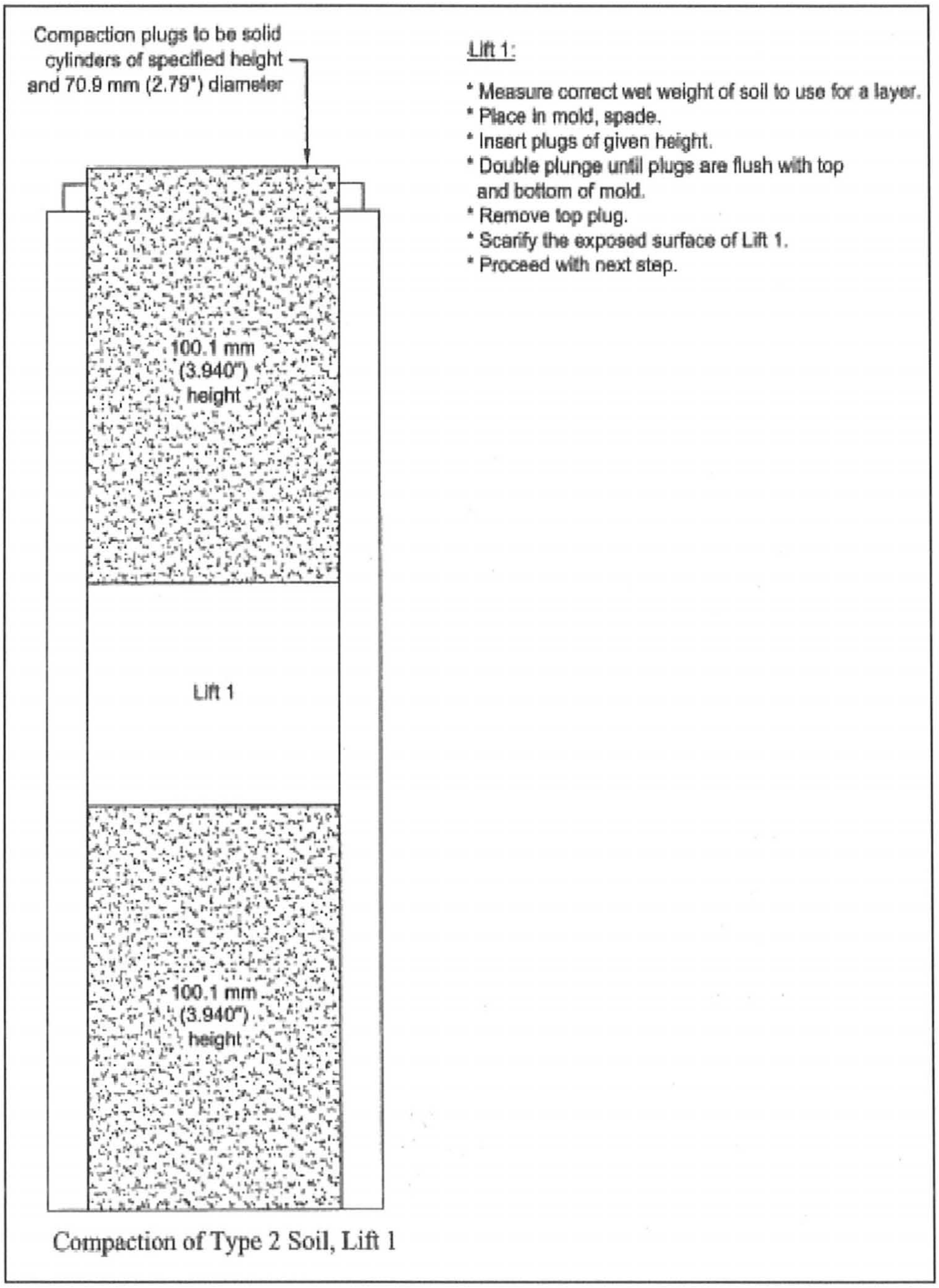
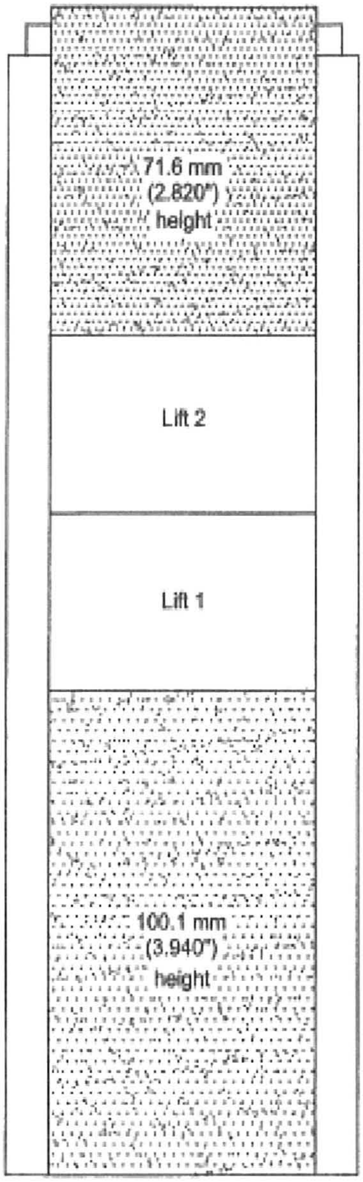


Figure 24.a-Step 1

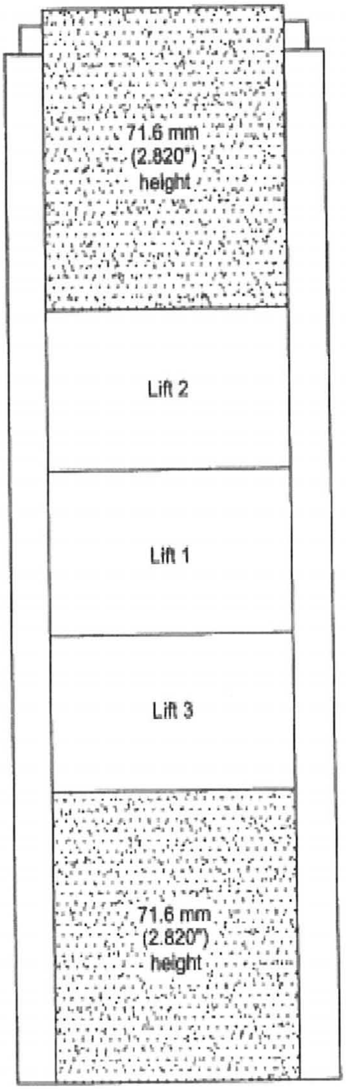


Compaction of Type 2 Soil, Lift 2

Lift 2:

* Measure correct wet weight of soil to use for a layer.
* Place in mold, spade.
* Insert 71.6 mm (2.820") plug.
* Plunge until plugs are flush with top and bottom of mold.
* Flip mold over and remove 100.1 mm (3.940") plug, keeping the 71.6 mm (2.820") plug in place.
* Scarify the exposed surface of Lift 1.
* Proceed with next step.

Figure 24.b-Step 2



Lift 3:

* Measure correct wet weight of soil to use for a layer.
* Place in mold, spade.
* Insert 71.6 mm (2.820") plug.
* Plunge until plugs are flush with top and bottom of mold.
* Flip mold over and remove 71.6 mm (2.280") plug, from the top of Lift 2, keeping the 71.6 mm (2.820") plug (on Lift 3) in place.
* Scarify the exposed surface of Lift 2.
* Proceed with next step.

Compaction of Type 2 Soil, Lift 3

Figure 24.c-Step 3

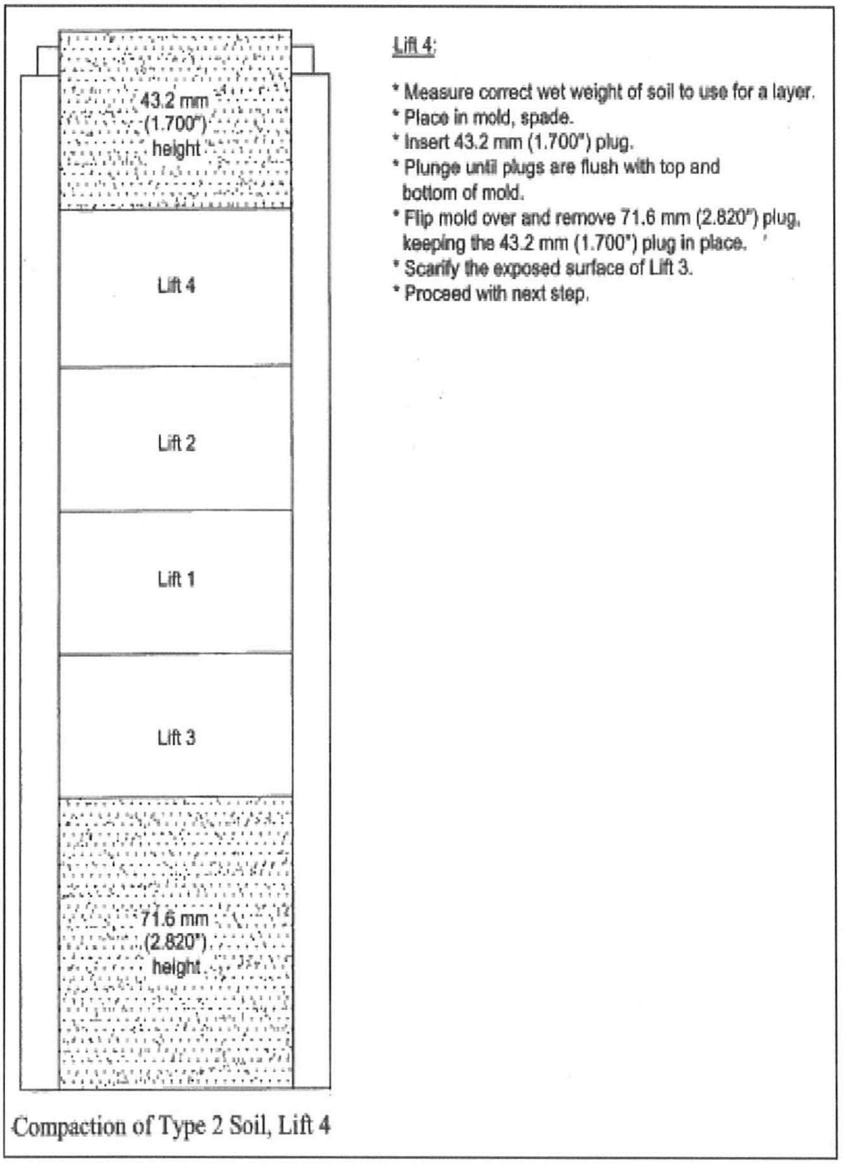
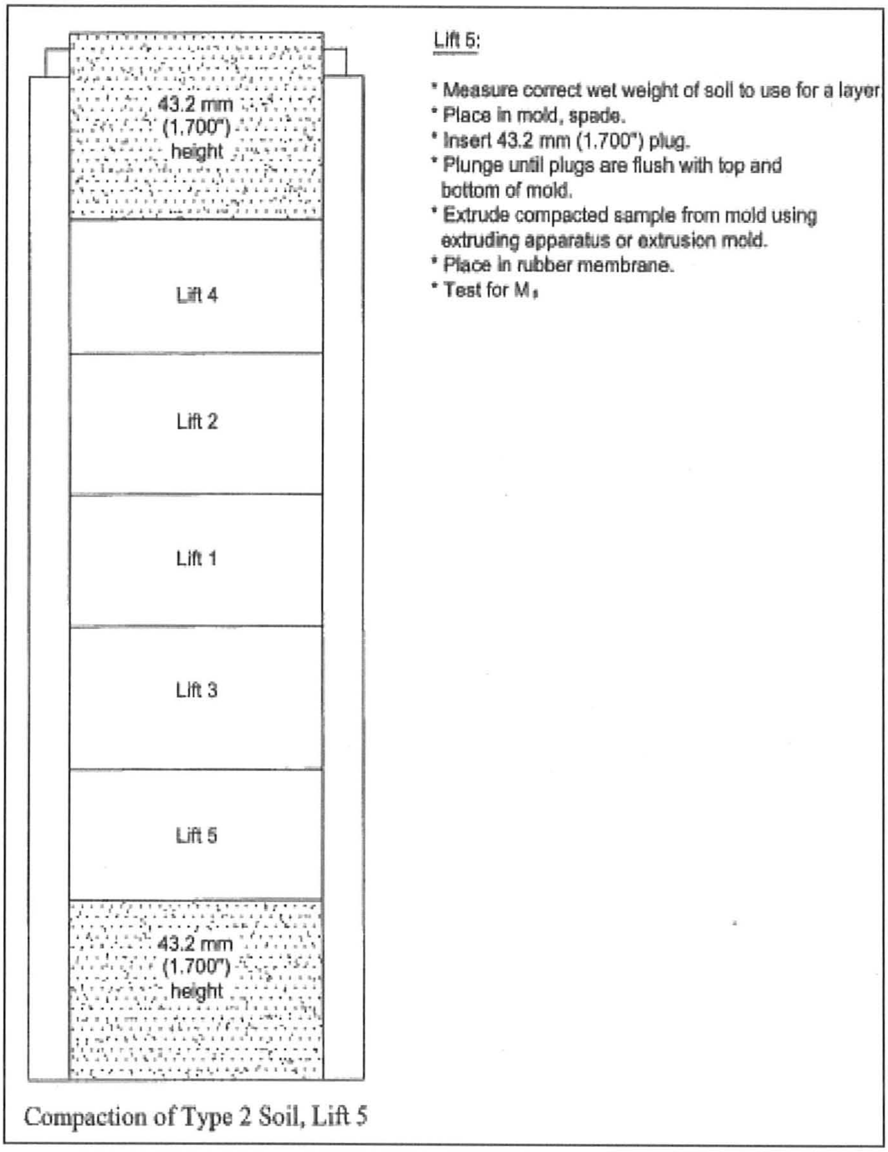


Figure 24.d-Step4



Compaction of Type 2 Soil, Lift 5

Figure 24.e-Step5

Figure 24 a, b, c, d, e, f. Typical Compaction Procedure for Type 2 Material (AASHTO T307-23-2003 & Protocol P46-LTPP 1996)

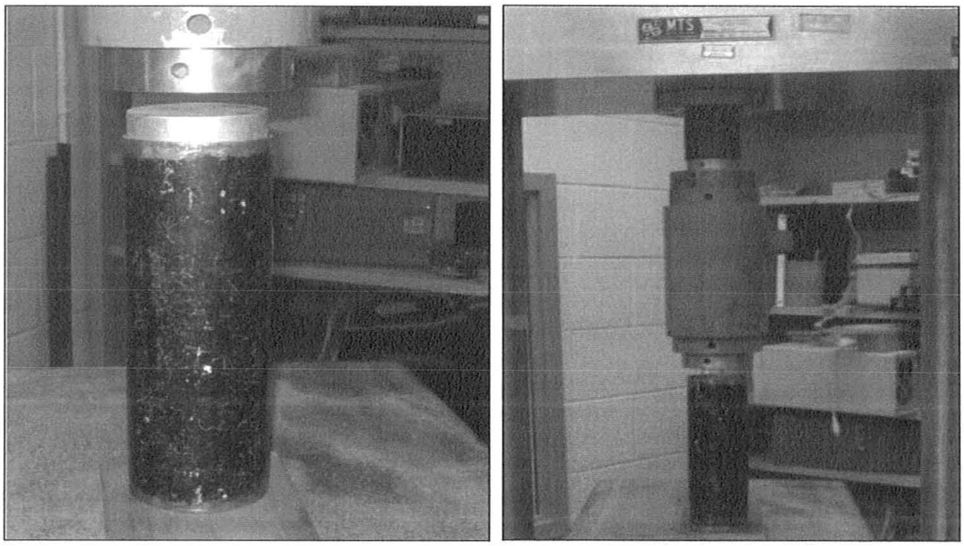


Figure 25 MTS Machine to Compact the Samples

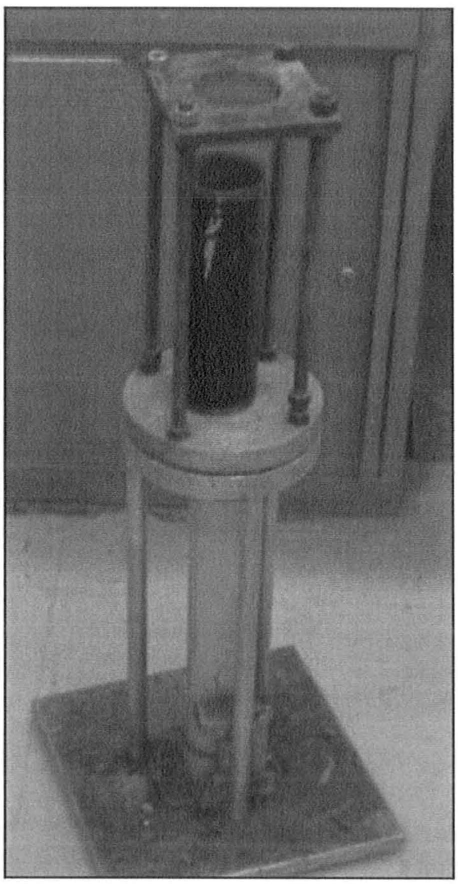


Figure 26 Extruder Machine for Injecting the Samples Out of the Mold

3.6 Testing Procedure

3.6.1 Resilient Modulus Test

3.6.1.1. Introduction

The resilient modulus of materials is influenced by many factors, which can be generally classified according to stress state and physical properties of materials. Various relationships have been used to describe the dependency of the resilient modulus M_r on stress level. Early studies recommend the use of a simple relation between resilient modulus and bulk stress, commonly known as the *K-θ* model (e.g., Hicks and Monismith, 1971)

$$M_r = K_1 p_a \left(\frac{\theta}{p_a} \right)^{K_2} \qquad (2)$$

where

p_a = atmospheric pressure (100 kPa);

θ = bulk stress: $\theta = S_1 + S_2 + S_3$ with S_1, S_2 and S_3 being principal stresses;

K_1 , K_2 = regression constants

The *K-θ* model fails to account for the effects of deviatoric stress (or shear stress) on the resilient modulus and is therefore only applicable over a small range of stress variations and for coarse aggregates, in which the resilient modulus is not sensitive to the applied deviator stress. The influence of deviatoric stress on the resilient modulus is taken into account in the universal model proposed by Uzan (1985, 1992); that is,

$$M_r = K_1 p_a \left(\frac{\theta}{p_a} \right)^{K_2} \left(\frac{s_d}{p_a} \right)^{K_3} \qquad (3)$$

or

$$M_r = K_1 p_a \left(\frac{\theta}{p_a}\right)^{K_2} \left(\frac{\tau_{oct}}{p_a}\right)^{K_3} \tag{4}$$

where k_1 , k_2 , k_3 are regression constants,

$$\tau_{oct} = \frac{1}{3}\sqrt{(s_1 - s_2)^2 + (s_1 - s_3)^2 + (s_2 - s_3)^2}$$

with τ_{oct} being octahedral shear stress. Under triaxial stress conditions, the octahedral shear stress is related to the deviator stress via

$$\tau_{oct} = \sqrt{2} s_d / 3$$

with $s_d = s_1 - s_3$ being the deviator stress.

In general, the universal model yields better results than the *k-θ* model. However, it tends to underestimate the resilient modulus when the material is subjected to small shear stresses, which correspond to low s_d or τ_{oct}. It is important to recognize that the regression constants in Eqs. (3) and (4) must be determined for the stress range of interest.

In order to eliminate this shortcoming of the universal model, the AASHTO 2002 design procedure, taking into account the LTPP (Long Term Pavement Performance) M_r test data, recommends a modified version of Eq. (4) (see, e.g., Yau and Von Qu, 2002)

$$M_r = k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3} \tag{5}$$

where k_1 , k_2 , k_3 are regression constants,

3.6.1.2. Resilient Modulus Test Procedure

After preparing the samples, the samples designated for unfrozen condition were left in the moisture room for a day in order to develop a more even moisture distribution through the sample. The samples designated for testing after first freeze-thaw cycle were placed in fridge in -32 ^{0}C for 24 hours. These samples after freezing were put in the moisture room in order to allow them to thaw. The resilient modulus test was performed on both type samples as per AASHTO Designated T307-99-2003. The results are presented in Chapter 4. For the sake of simplicity, the samples after one freeze and thaw cycle are called frozen through the entire report.

As per AASHTO T 307-99 (2003), a certain contact load must be maintained to keep contact between the specimen and the loading plate. When calculating the stresses applied on the specimen, adjustment on the load measured by the load cell should be made to compensate the resultant force created by the chamber pressure (upward force) and the weight of the chamber piston rod, including the LVDT holder (downward force) prior to conduct of the resilient modulus test.

3.6.2 Test Procedure for Accumulative Deformation under Cyclic Loading

After completion of the resilient modulus test on a sample, the same sample was tested under constant confining pressure 13.8 kPa (2psi) under cyclic load (2000 load repetitions at different deviator stress levels though three stages). The accumulative axial deformation of the samples was measured and recorded. The axial deformation history of the samples as shown in Figure 27 was monitored and recorded.

Figure 27 The Accumulative Deformation Observed during the Cyclic Triaxial Test

CHAPTER 4: EXPERIMENTAL RESULTS

4.1 General

This chapter summarizes the results of resilient modulus testing according to stress conditions and the dependency of resilient modulus on various factors including applied stresses. The development of accumulative permanent deformation is also analyzed.

4.2 Experimental Results

4.2.1 Experimental Resilient Modulus

This part is divided in to two sections. Section 4.2.1.1 discusses the resilient modulus of unfrozen soil and Section 4.2.1.2 discusses the resilient modulus of the soil after one freeze - thaw cycle (frozen).

4.2.1.1 The Resilient Modulus of Unfrozen Soil

This section focuses on the relationship between the resilient modulus and the bulk stress for soils at different water contents. Also, it demonstrates how this relationship may vary according to cell pressure. Details for both the resilient modulus vs. deviator stress relationship and the stress-strain relationship and their dependency on water content and cell pressure are presented.

As per Figures 28, 29 and 30, under the constant cell pressure, the resilient modulus Mr corresponding to different stress deviators decreases significantly as the bulk stress increases when the water content is 5% and 8%, respectively. With the increase of water content, the influence of bulk stress on resilient modulus decreases. For all cases, Mr approaches a constant when the bulk stress exceeds a threshold of approximately 40 to 45 kPa. It should be noted that in each individual figure, the variation of bulk stress is induced by changes in the deviator stress since the confining pressure is kept constant.

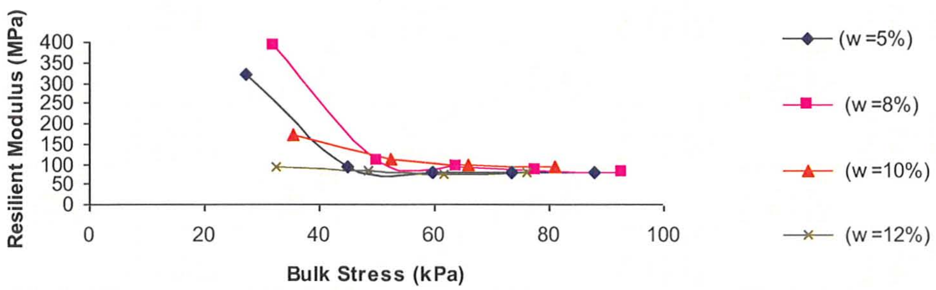


Figure 28 Resilient Modulus vs. Bulk Stress for S_3= 41.4 kPa (6 psi) (Unfrozen)

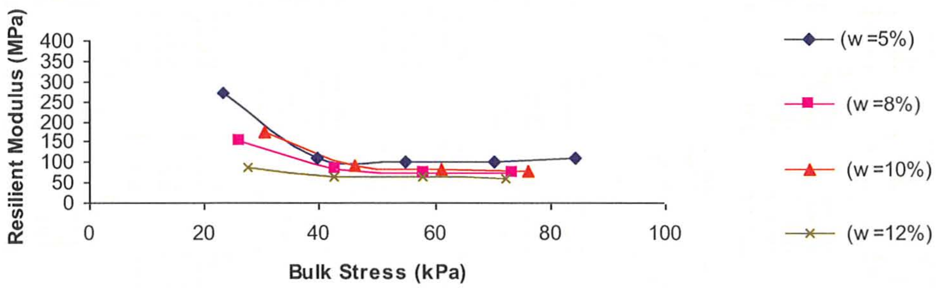


Figure 29 Resilient Modulus vs. Bulk Stress for S_3= 27.6 kPa (4 psi) (Unfrozen)

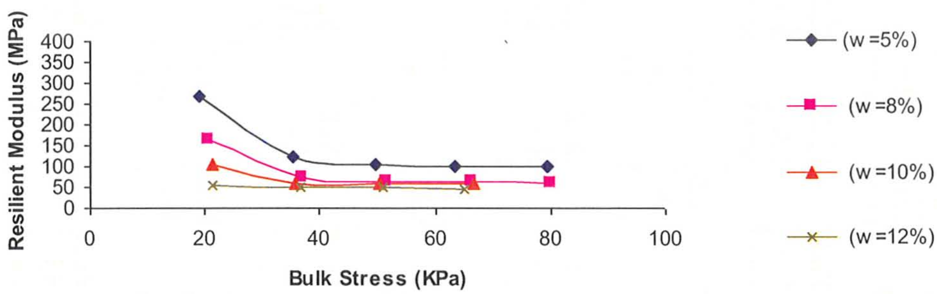


Figure 30 Resilient Modulus vs. Bulk Stress for S_3= 13.8 kPa (2 psi) (Unfrozen)

As per Figures 31, 32, 33 and 34, for a constant water content, the resilient modulus decreases as the bulk stress increases. It should be noted that the resilient modulus decreases significantly with increasing bulk stress under higher cell pressure at the water content of 5% and 8% (as can be seen in Figures 31 and 32), which means that the influence of deviator stress is more pronounced under higher confining pressure . For increased water content of 10% and 12%, the dependency of Mr on the bulk stress tends to decrease.

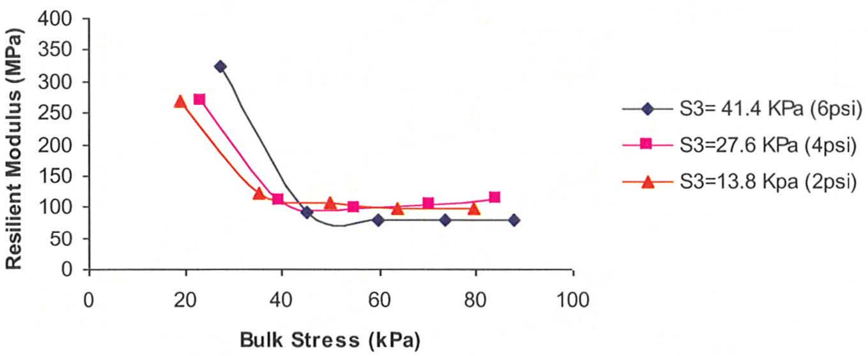


Figure 31 Resilient Modulus vs. Bulk Stress for w=5% (Unfrozen)

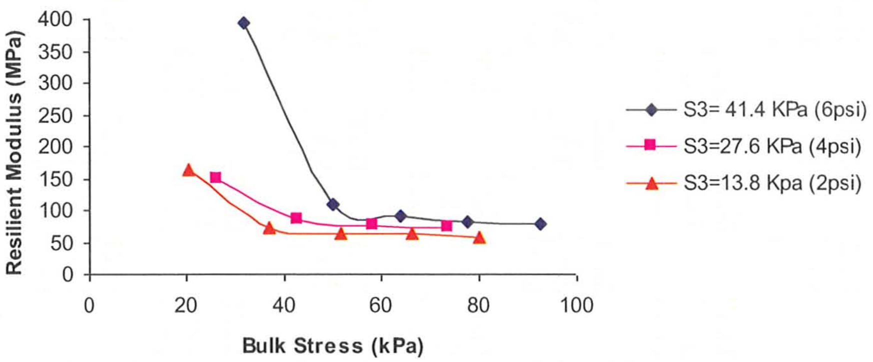


Figure 32 Resilient Modulus vs. Bulk Stress for w=8% (Unfrozen)

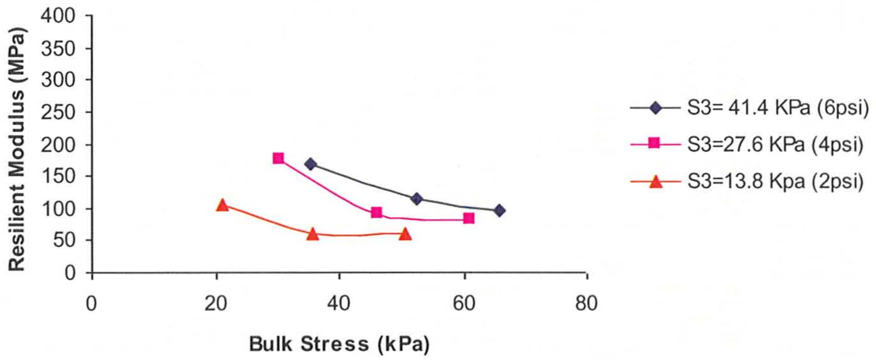


Figure 33 Resilient Modulus vs. Bulk Stress for *w*=10% (Unfrozen)

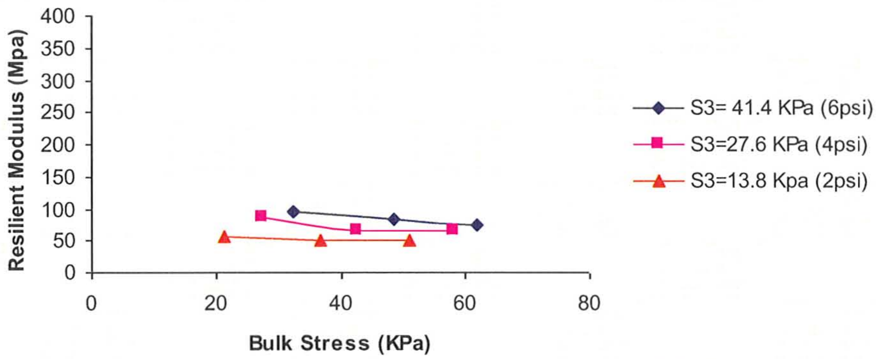


Figure 34 Resilient Modulus vs. Bulk Stress for *w*=12% (Unfrozen)

Figures 35, 36 and 37, show more clearly the influence of deviator stress on Mr. Under a constant cell pressure, the resilient modulus decreases as the deviator stress increases. It should be noted that the resilient modulus decreases significantly when the specimen has less water content. With higher water content, the resilient modulus decreases gradually when the deviator stress increases. One observes that when stress deviator is greater than 30 kPa, Mr becomes almost independent of both the bulk stress and stress deviator.

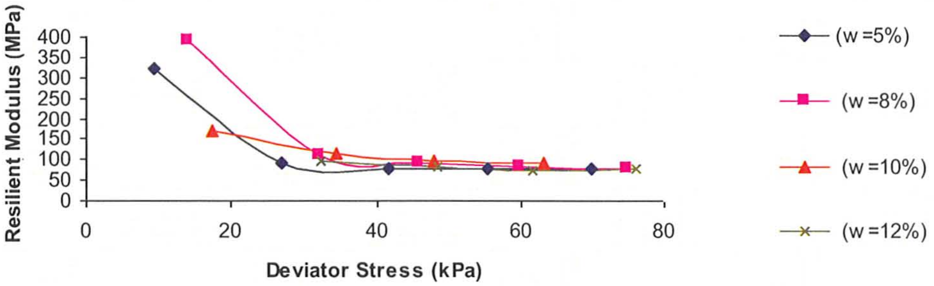


Figure 35 Resilient Modulus vs. Deviator Stress for S_3= 41.4 kPa (6psi) (Unfrozen)

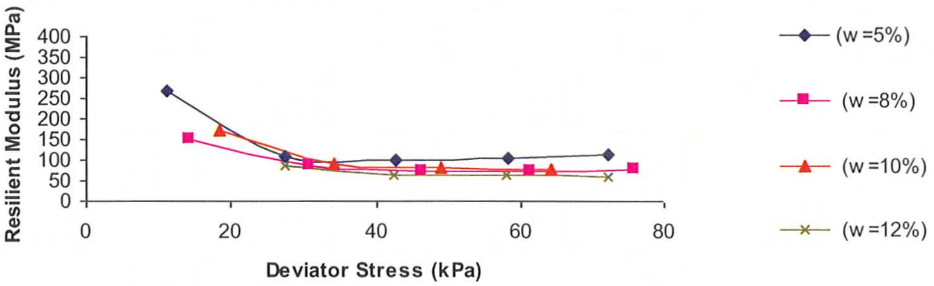


Figure 36 Resilient Modulus vs. Deviator Stress for S_3= 27.6 kPa (4psi) (Unfrozen)

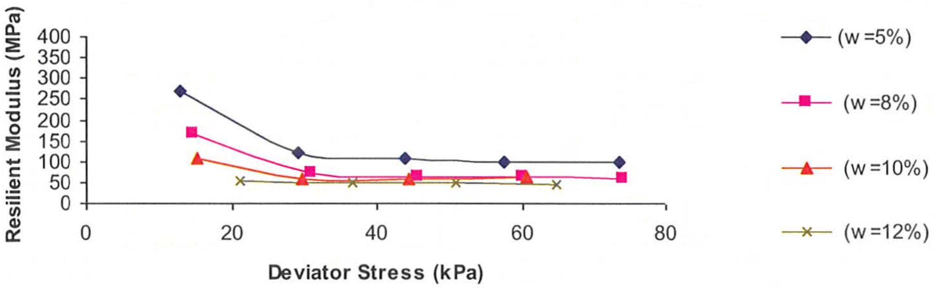


Figure 37 Resilient Modulus vs. Deviator Stress for S_3= 13.8 kPa (2 psi) (Unfrozen)

As per Figures 38, 39, 40 and 41, under the constant water content, the cyclic axial stress amplitude increases as the resilient strain increases. However, the increase of the maximum stress with a given resilient strain increment tends to decrease under low confining pressure or when the water content is increased, which implies that increased cyclic strain level tends to reduce the stiffness of the specimen under low confinement or high water content.

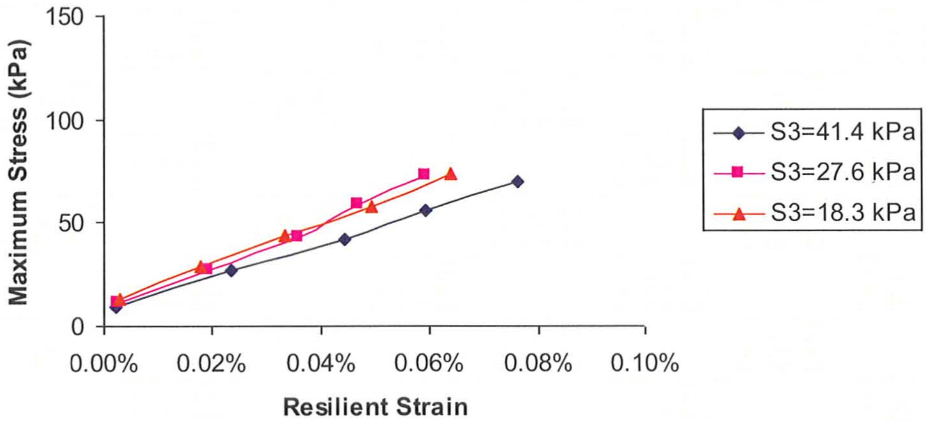


Figure 38 Stress vs. Resilient Strain, *w* =5% (Unfrozen)

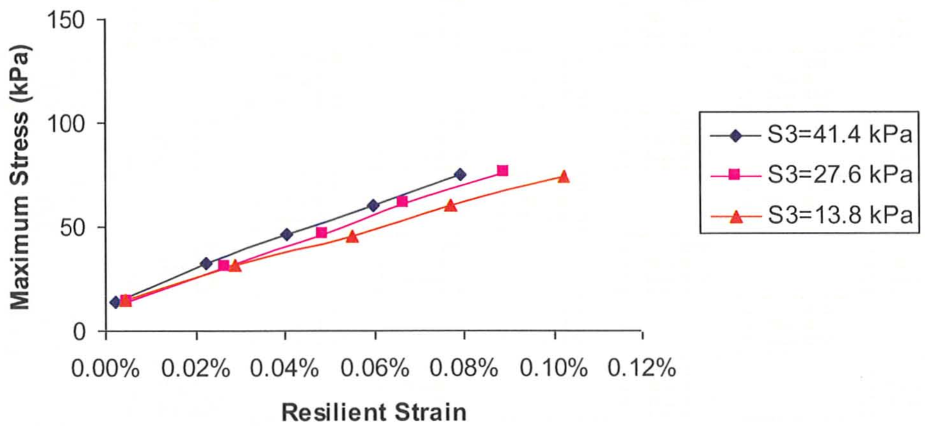


Figure 39 Stress vs. Resilient Strain, *w* =8% (Unfrozen)

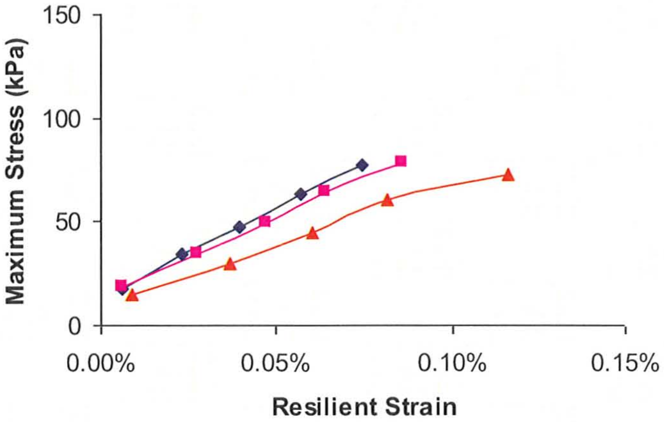


Figure 40 Stress vs. Resilient Strain, *w*=10% (Unfrozen)

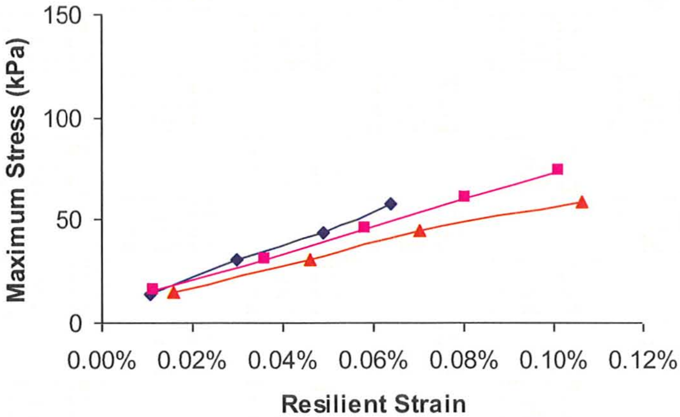


Figure 41 Stress vs. Resilient Strain, *w* =12% (Unfrozen)

Figures 42, 43, 44 and 45, it can be observed that the stress ratio (deviator stress/bulk stress) increases as the average resilient strain in each cycle increases. The samples, unfrozen with higher water content (10%, 12%), have higher stress ratio when they are under smaller cell pressure 13.8 kPa (2 psi) than those with the same water content but under larger cell pressure.

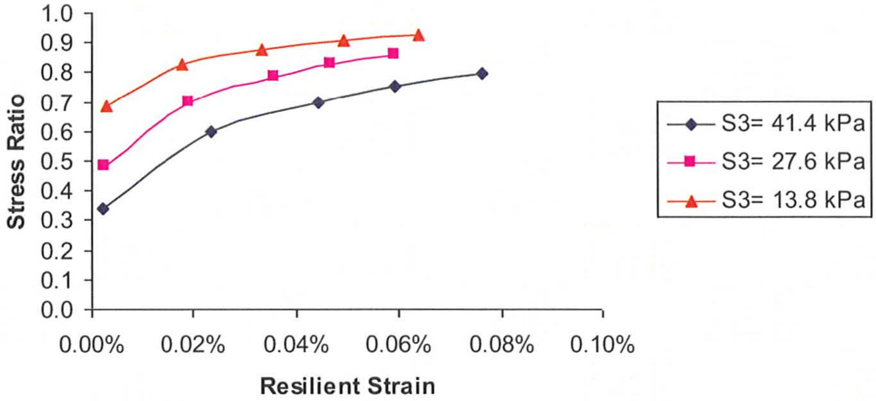


Figure 42 Stress Ratio vs. Resilient Strain *w*=5% (Unfrozen)

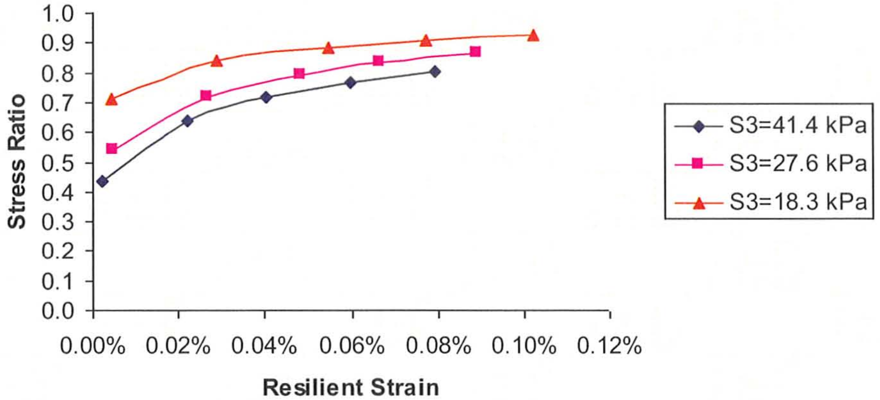


Figure 43 Stress Ratio vs. Resilient Strain *w*= 8% (Unfrozen)

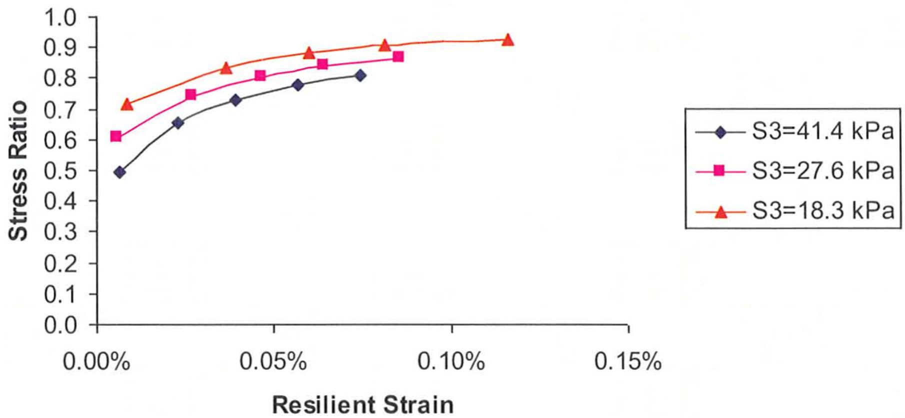


Figure 44 Stress Ratio vs. Resilient Strain *w* =10% (Unfrozen)

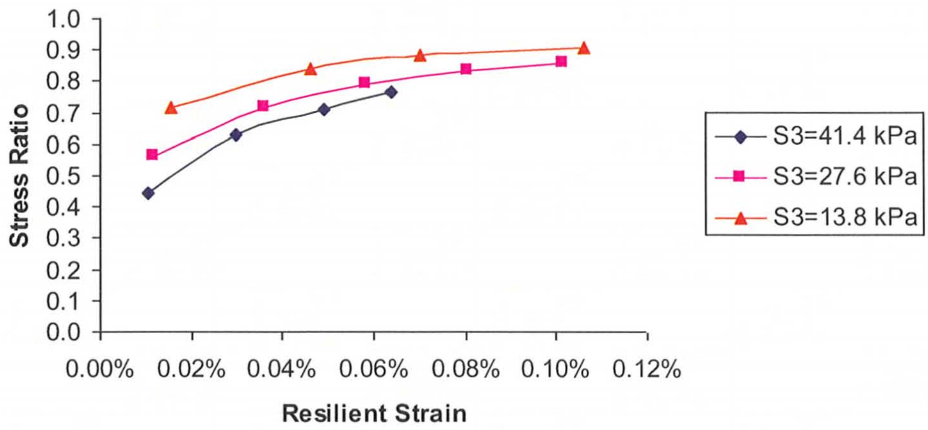


Figure 45 Stress Ratio vs. Resilient Strain *w* =12%, (Unfrozen)

Figure 46 presents the relation between resilient modulus and confining pressure. As it can be seen, the resilient modulus increases as confining pressure increases. Figure 47 shows that as water content increases the resilient modulus decreases. This could be the result of increase of pore water pressure during testing.

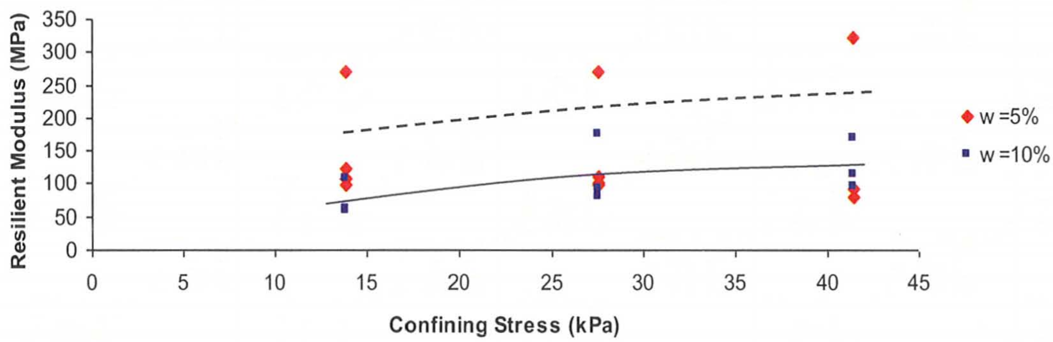


Figure 46 Resilient Modulus vs. Confining Stress (Unfrozen)

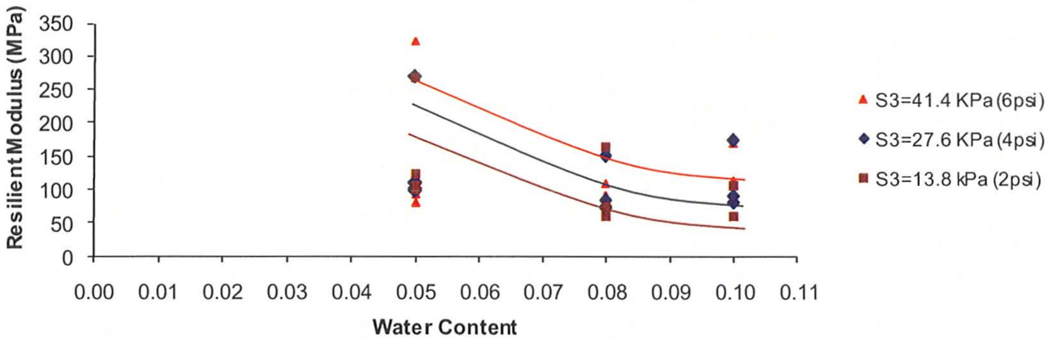


Figure 47 Resilient Modulus vs. Water Content (Unfrozen)

4.2.1.2 Resilient Modulus of Soil after One Freeze-Thaw Cycle

In the previous section, the behavior of unfrozen soil was discussed. The same soil under different stress conditions, after one freeze- thaw cycle, has different behavior which is presented as follows.

Figures 48, 49 and 50 present the variation of Mr with the bulk stress under constant cell pressures when the water content is changed. One observes that under a constant cell pressure, the resilient modulus of frozen soil decreases as the bulk stress increases, which is the same as the unfrozen soil. As the water content increases, the resilient modulus decreases. The resilient modulus tends to reduce more with an increase in the bulk stress at low water content. For example, at w = 5%, Mr decreases from 250 MPa to 100 MPa when S_3 = 13.8 kPa (2psi). However, when w = 10%, Mr decreases from 60 MPa to 45 MPa when S_3= 13.8 kPa (2psi).

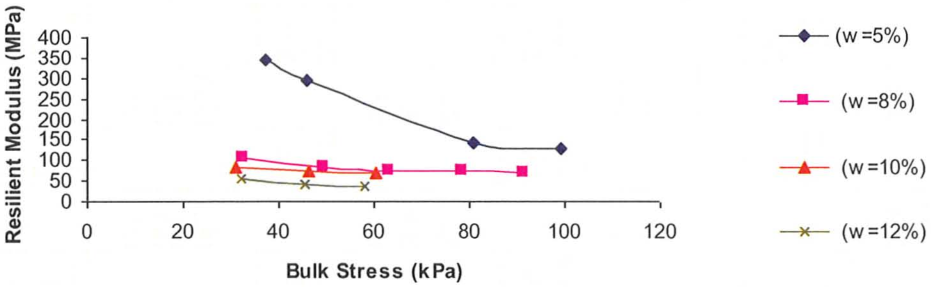


Figure 48 Resilient Modulus vs. Bulk Stress for S_3= 41.4 kPa (6 psi) (Frozen)

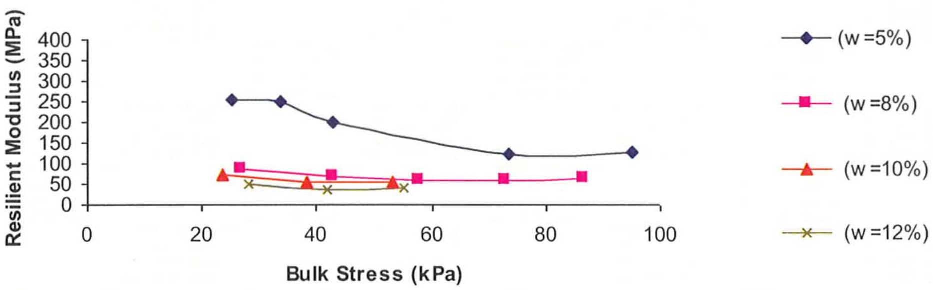


Figure 49 Resilient Modulus vs. Bulk Stress for S_3= 27.6 kPa (4 psi) (Frozen)

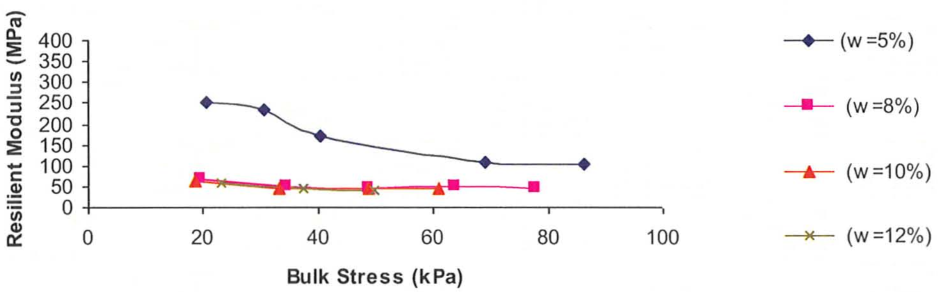


Figure 50 Resilient Modulus vs. Bulk Stress for S_3= 13.8 kPa (2 psi) (Frozen)

Figures 51, 52, 53 and 54 show the result of Mr for specimens having the same water content under different confining pressures. As shown in these figures, under the constant water content, the resilient modulus decreases as the bulk stress increases. In Figure 51, it is observed that the resilient modulus decreases significantly as bulk stress increases when the specimen is subjected to a frozen-thaw cycle at the water content of 5%. The influence of confining pressure tends to decrease as the water content is increased. The relations between the resilient modulus and the bulk stress under different cell pressures (13.8, 27.6 and 41.4 kPa) become close when the water content is 12%, as per Figure 54. This could be the result of increase in pore water pressure as the cell pressure was increased, which corresponded to lower effective confining pressure.

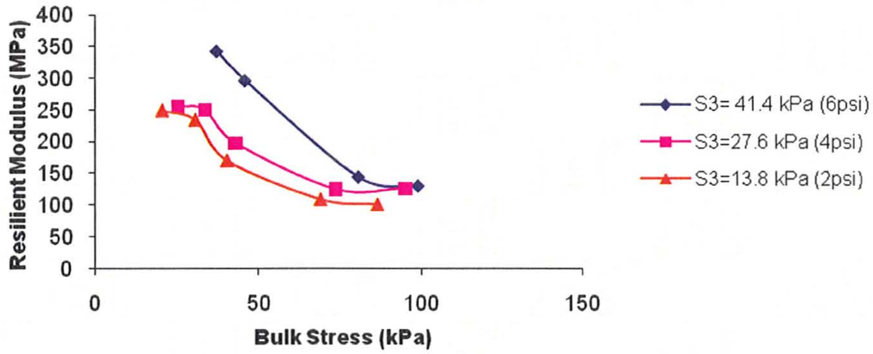


Figure 51 Resilient Modulus vs. Bulk Stress *w*=5% (Frozen)

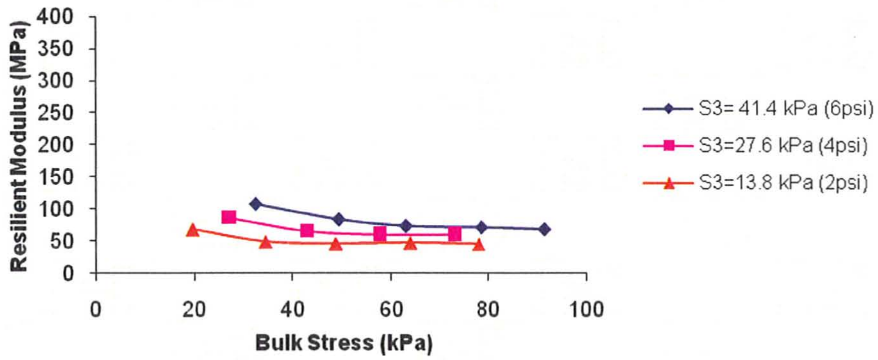


Figure 52 Resilient Modulus vs. Bulk Stress *w*=8% (Frozen)

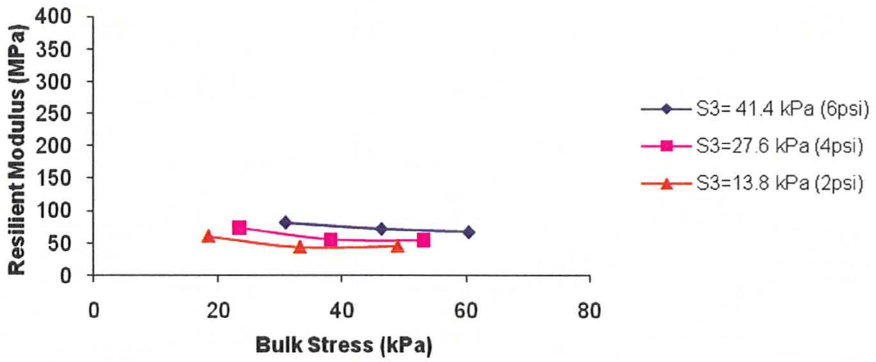


Figure 53 Resilient Modulus vs. Bulk Stress, *w*= 10% (Frozen)

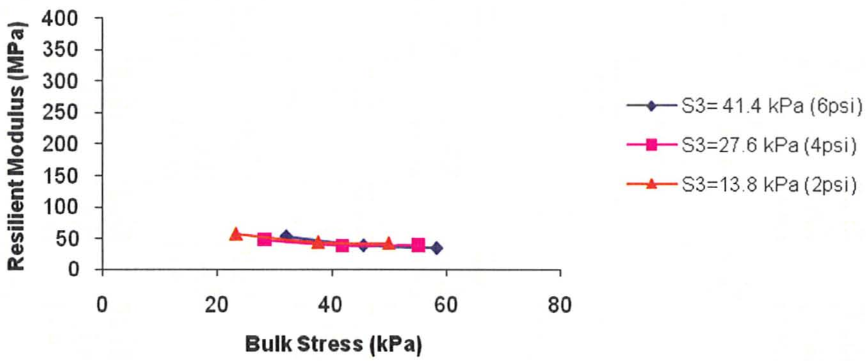


Figure 54 Resilient Modulus vs. Bulk Stress, *w*=12% (Frozen)

As per Figures 55, 56 and 57, under constant water content, the resilient modulus decreases as the deviator stress increases. Mr decreases more significantly when the deviator stress is increased under small water content (5%). As it can be seen, the decrease of Mr with the stress deviator becomes insignificant when the water content is high (12%) under different cell pressures.

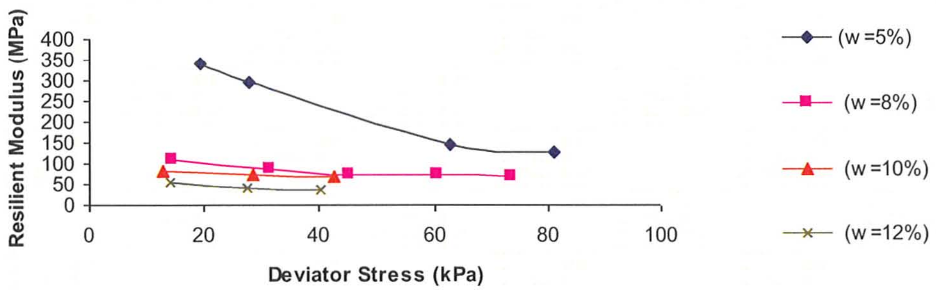


Figure 55 Resilient Modulus vs. Deviator Stress for S_3= 41.4 kPa (6 psi) (Frozen)

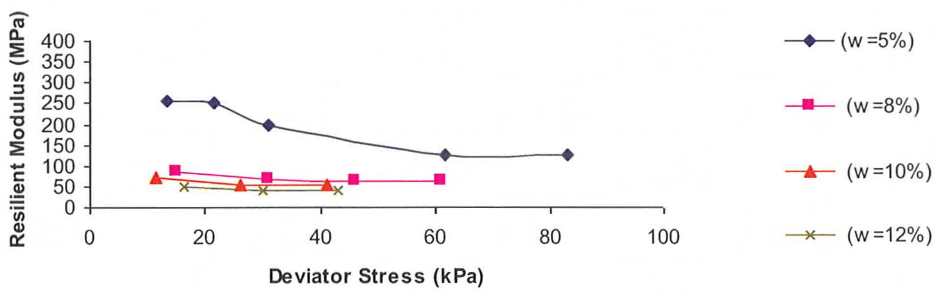


Figure 56 Resilient Modulus vs. Deviator Stress for S_3= 27.6 kPa (4 psi) (Frozen)

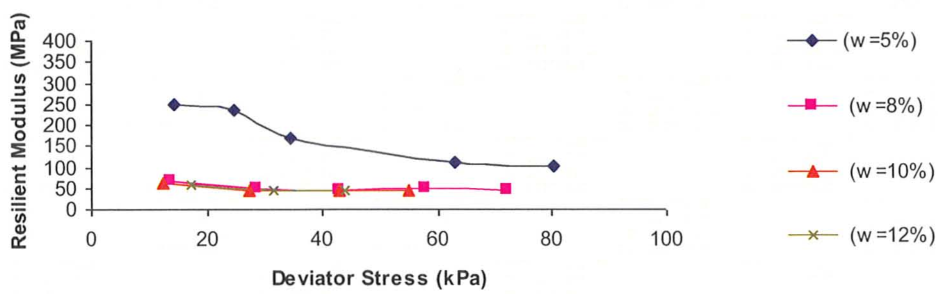


Figure 57 Resilient Modulus vs. Deviator Stress for S_3= 13.8 kPa (2psi) (Frozen)

As per Figures 58, 59, 60 and 61, under the constant water content, the cyclic axial stress amplitude increases as the resilient strain increases. However, the increase of the maximum stress with the resilient strain tends to decrease under low confining pressure when the water content is 12% as it can be seen in Figure 61.

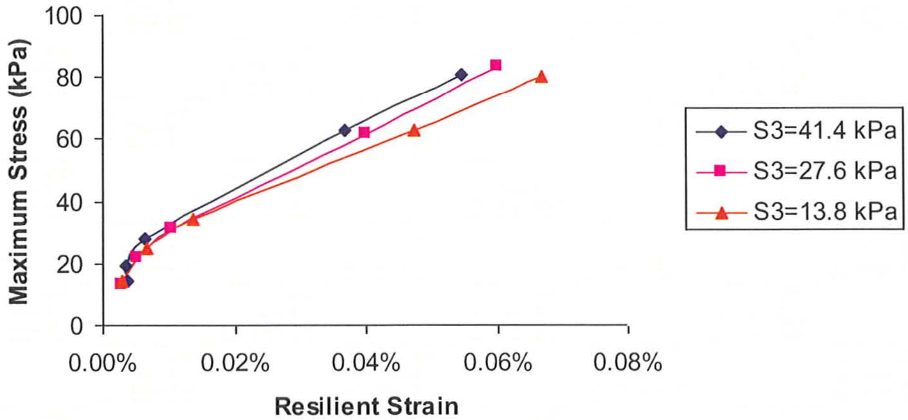


Figure 58 Stress vs. Resilient Strain *w* =5% (Frozen)

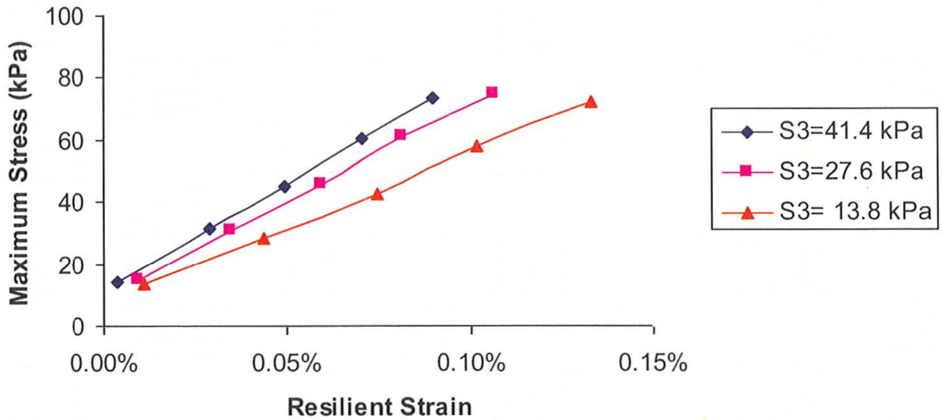


Figure 59 Stress vs. Resilient Strain *w* =8%, (Frozen)

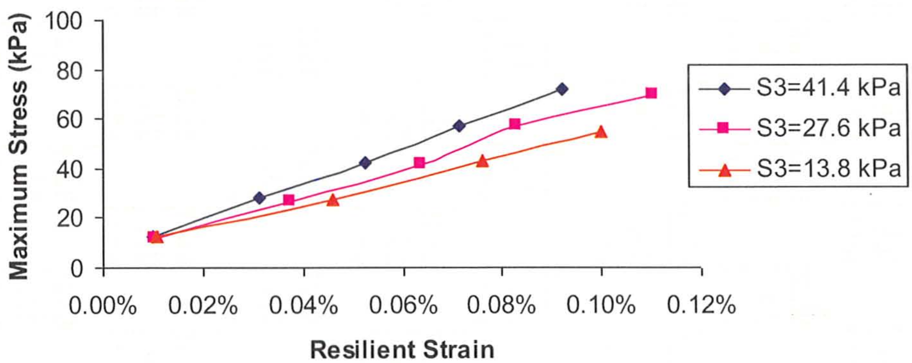


Figure 60 Stress vs. Resilient Strain, *w* =10% (Frozen)

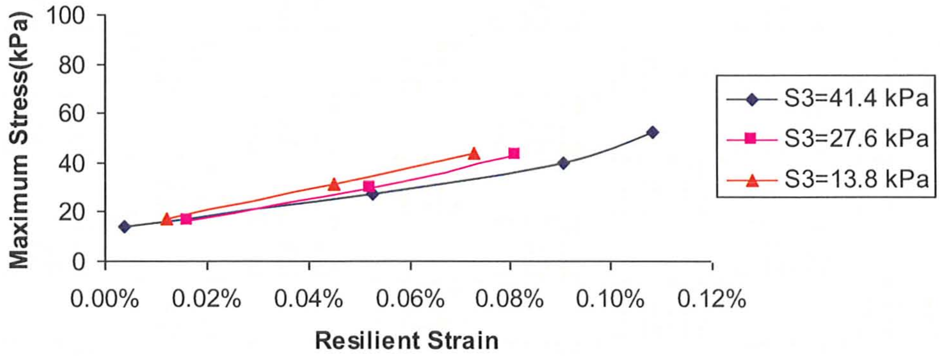


Figure 61 Stress vs. Resilient Strain *w* =12% (Frozen)

As per Figures 62, 63, 64 and 65, under the constant water content, the strain increases as the stress ratio (deviator stress/bulk stress) increases. The stress ratio under different water content with the same cell pressure tends to approach a constant limit. For example, the stress ratio under 13.8 kPa (2 psi) varies between 0.7 to 0.9 regardless of the water content. Also, the stress ratio under 41.4 kPa (6 psi) changes from 0.4 to 0.6 regardless of the water content.

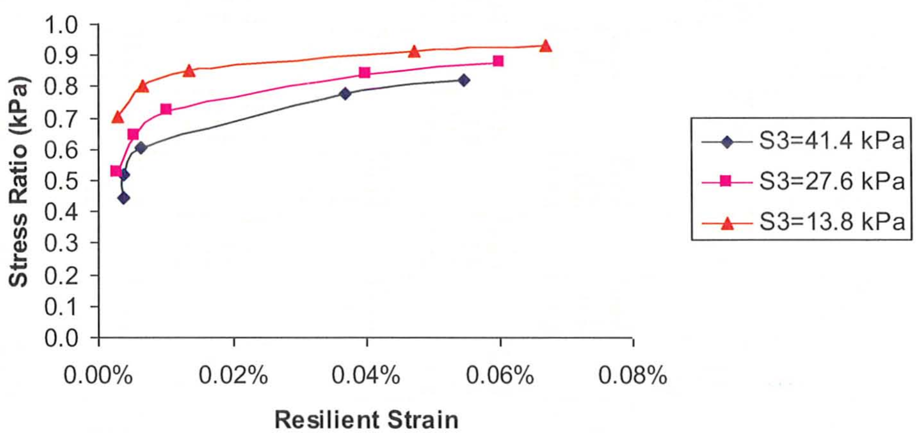


Figure 62 Stress Ratio vs. Resilient Strain *w*=5% (Frozen)

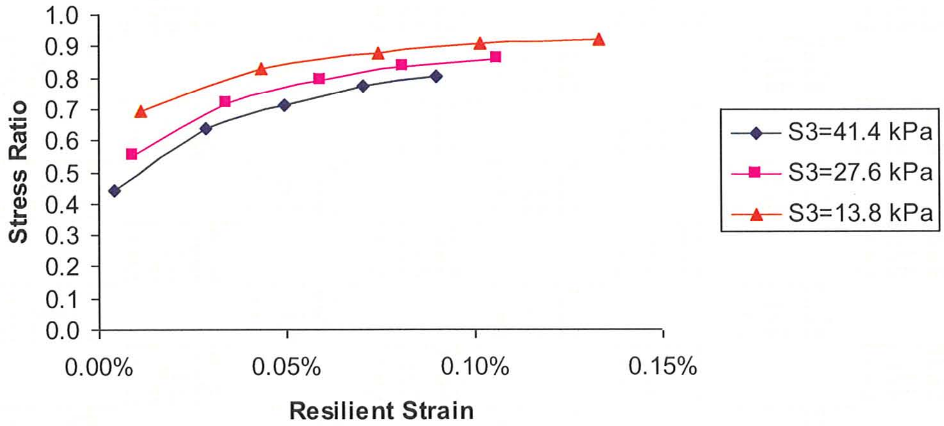


Figure 63 Stress Ratio vs. Resilient Strain *w* =8% (Frozen)

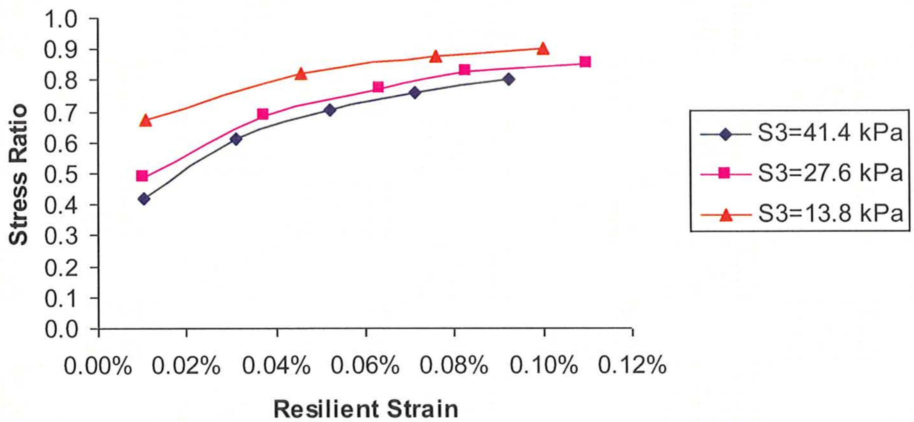


Figure 64 Stress Ratio vs. Resilient Strain *w* = 10% (Frozen)

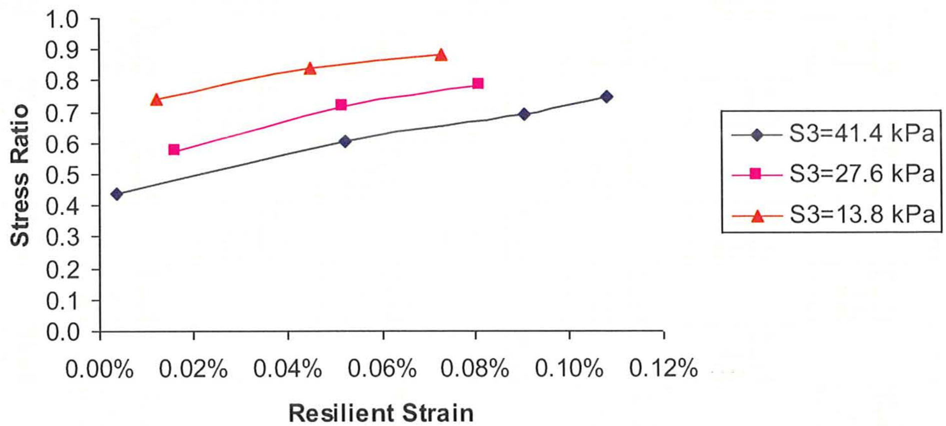


Figure 65 Stress Ratio vs. Resilient Strain *w*=12% (Frozen)

Figure 66 presents the relationship between resilient modulus and confining pressure. As it can be seen, the resilient modulus increases as confining pressure increases. Figure 67 shows that as water content increases the resilient modulus decreases. This could be the result of increase of pore water pressure during the testing.

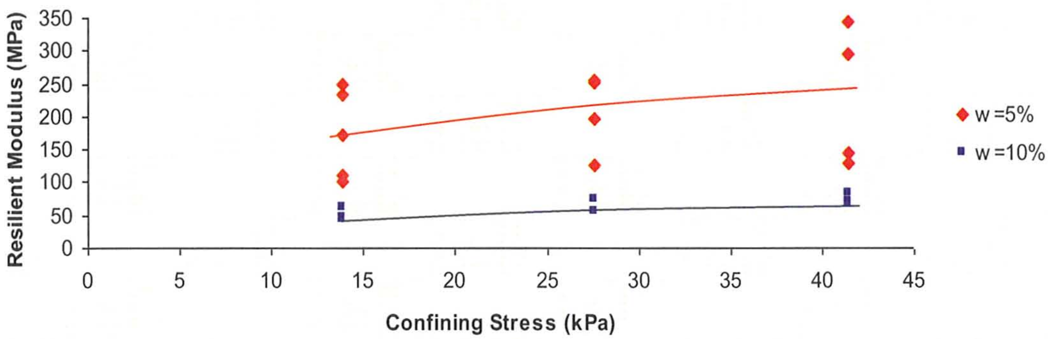


Figure 66 Resilient Modulus vs. Confining Pressure (Frozen)

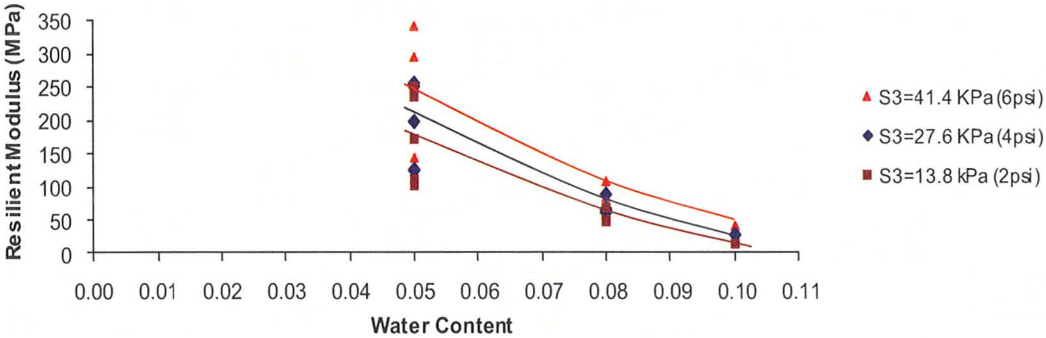


Figure 67 Resilient Modulus vs. Water Content (Frozen)

4.2.2 Accumulative Displacement under 6000 Repeated Load

In this section, the accumulated deformation after 6000 cycles repeated loading is discussed for unfrozen soil in Section 4.2.2.1 and the soil specimens after one freeze-thaw cycle in Section 4.2.2.2.

4.2.2.1 Accumulative Displacement under 6000 Repeated Load: Unfrozen Soil

Unfrozen soil samples under a cell pressure of 13.8 kPa (2 psi) were tested with cyclic load of 6000 repetitions. More specifically, cyclic deviator stresses with the amplitudes of 13.8 kPa, 27.6 kPa and 41.4 kPa are repeated 2000 times for each stages (total 3 stages), respectively. Since only the accumulated displacement is of the interest, 20 readings per 10 seconds were captured during the test. Afterwards, the average of the readings from two LVDTs was taken as the measured deformation for analysis and the results are discussed as follows.

It can be seen that the accumulated displacements increase as the water content increases, as shown by comparing Figures 68, 69, 70 and 71.

It can be observed that the displacement of samples with small water content accumulated gradually. For samples with high water content, the displacement occurred mostly after 4000 load repetitions. In addition, there is a significant difference in the displacement after every 2000 load repetitions. It seems that as the applied cyclic stress increases the displacement significantly increases correspondingly. In the first stage of loading with the cyclic deviator stress amplitude of 13.8 kPa (2 psi), the accumulative displacements of all specimens within 2000 loading cycles tend to approach a certain limit and the deformation becomes stable. Under increased amplitudes of cyclic stress in stages 2 and 3, the rate of accumulative displacement tends to increase substantially; as shown in Figures 68, 69, 70 and 71.

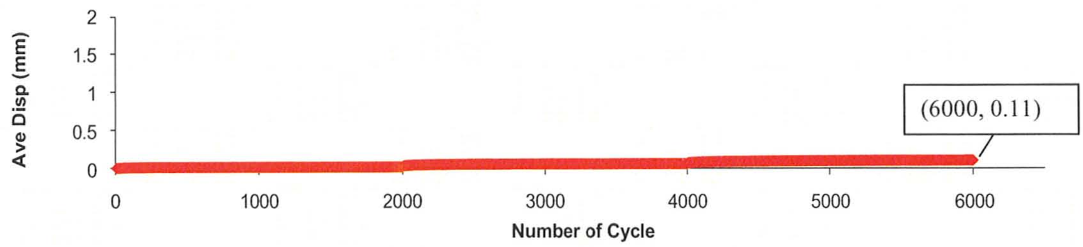


Figure 68 Average Accumulative Displacement (Unfrozen), *w* =5%

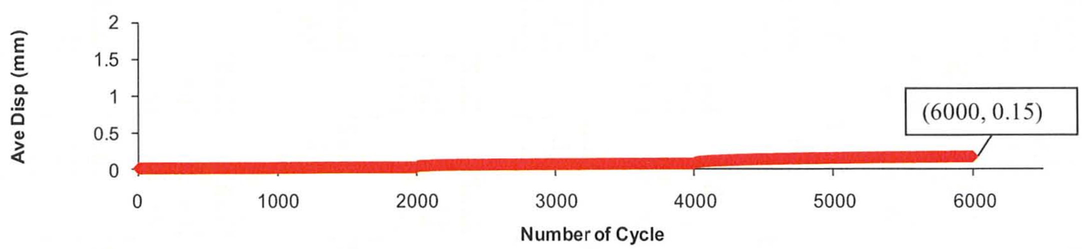


Figure 69 Average Accumulative Displacement (Unfrozen), *w* =8%

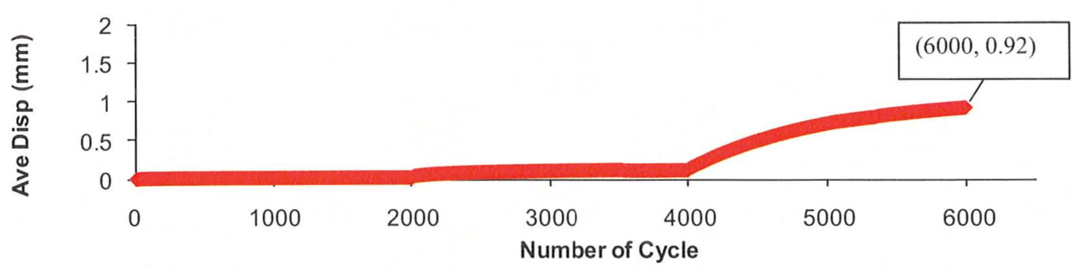


Figure 70 Average Accumulative Displacement (Unfrozen), *w* =10%

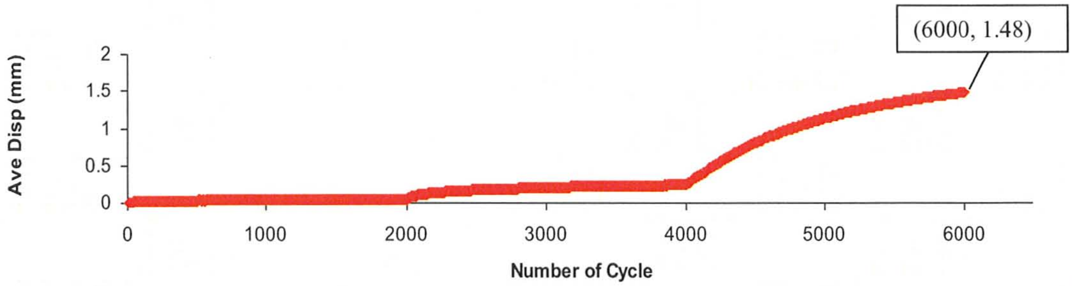


Figure 71 Average Accumulative Displacement (Unfrozen), w =12%

4.2.2.2 Accumulative Displacement of Soil after One Freeze-Thaw Cycle

The frozen soil samples (after one freeze-thaw cycle) under 13.8 kPa (2 psi) cell pressure were tested with cyclic load of 6000 repetitions. More specifically, cyclic stresses with the amplitudes of 13.8 kPa, 27.6 kPa and 41.4 kPa are repeated 2000 times each.

The experimental data presented in Figures 72, 73 and 74 show how the displacements increase as the water content varies between 5% and 10% for specimens subjected to one freezing-thaw cycle. The specimen with 12% water content failed in this test and hence no results are presented.

In general, the accumulative axial displacement increases with the number of load repetition for selected water content. Moreover, when the cyclic stress amplitude is changed at the end of each 2000 cycles, a quick increase in the accumulative settlement is observed.

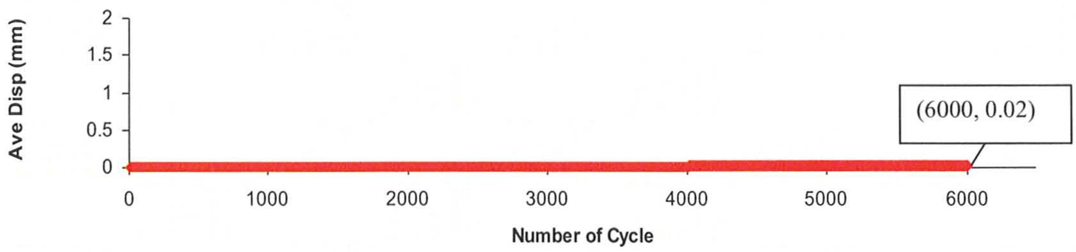


Figure 72 Average Accumulative Displacement (Frozen), *w*=5%

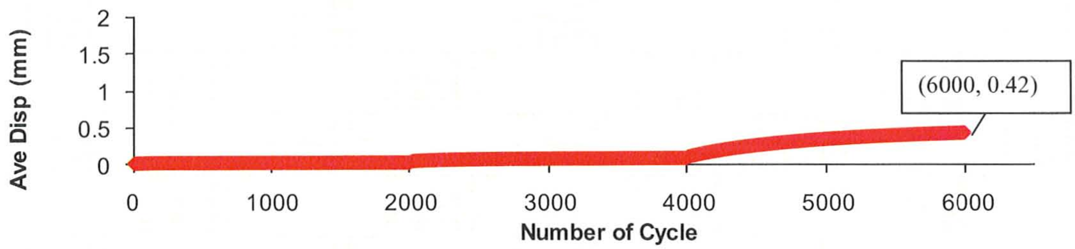


Figure 73 Average Accumulative Displacement (Frozen), *w*=8%

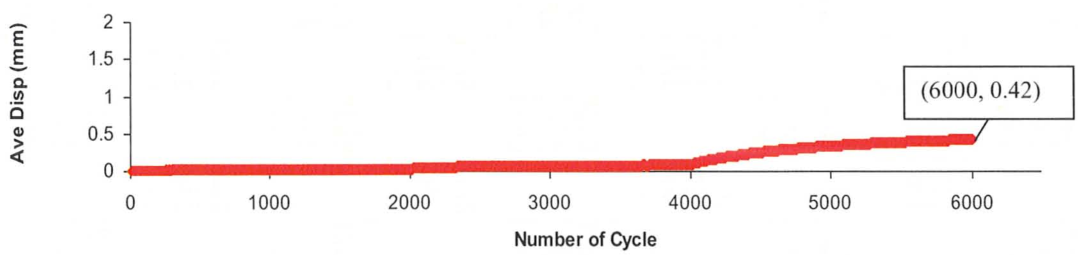


Figure 74 Average Accumulative Displacement (Frozen), *w* =10%

4.2.3 Comparison of Unfrozen Soil and Soil after first freeze-thaw cycle

This section compares the behavior of specimens under unfrozen and frozen (first freeze-thaw cycle) conditions at different water contents.

4.2.3.1 Comparison of Unfrozen Soil and Soil after One Freeze-Thaw Cycle Containing 5% Water Content

Dependency of Resilient Modulus on Bulk Stresses: For specimens with the water content of 5%, under a selected cell pressure (13.8 kPa, 27.6 kPa and 41.4 kPa) the resilient modulus for unfrozen specimens significantly decreases after the first 100 load repetitions (applied stress amplitude of 13.8 kPa) as the bulk stress increases (Figures 75, 76 and 77). However the resilient modulus for specimens subject to the first freeze-thaw cycle gradually decreases as the bulk stress increases. Also in Figures 75, 76 and 77, when S_3= 41.4 kPa (6 psi), at the bulk stress of 80 kPa, Mr (Unfrozen)= 95 MPa and Mr (Frozen)=145 MPa; when S_3= 27.6 kPa (4 psi) at bulk stress= 80 kPa, Mr (Unfrozen)= 105 MPa and Mr (Frozen)=130 MPa; when S_3= 13.8 kPa (2 kPa) at bulk stress= 80 kPa Mr (Unfrozen)= 98 MPa and Mr (Frozen)=105 MPa. Thus, it can be seen that resilient modulus of the sample after one frozen-thaw cycle tends to increases as the cell pressure increases at the same bulk stress after 400 load repetitions. However, unfrozen samples do not follow the same trend. Actually, the resilient modulus of unfrozen soil (at the same bulk stress) increases when cell pressure increases from 13.8 kPa (2 psi) to 27.6 kPa (4 psi) but decreases when the cell pressure increases from 27.6 kPa (4 psi) to 41.4 kPa (6 psi).

Stress against Strain Relation: In Figures 78, 79 and 80, for a given cell pressure (13.8 kPa, 27.6 kPa, 41.4 kPa) the variation of stress with strain for frozen and unfrozen specimens follows the same pattern. It should be noted that the samples after one frozen-thaw cycle under 41.4 kPa (6 psi) cell pressure has smaller strain than that of unfrozen specimens. In other words, as cell pressure decreases, the resilient strain of soil after the first frozen-thaw cycle increases more than that of unfrozen soil specimens of the same water content. In these Figures, it is also seen that as the stress increases, there is a significant increase in the strain of the frozen samples (after first frozen-thaw cycle) after 300 load repetitions regardless of the confining pressure. However, the strain of the unfrozen samples gradually increases as the stress increases.

Stress Ratio against Strain: In Figures 81, 82 and 83, for both unfrozen samples and samples after the first frozen-thaw cycle, as the cell pressure increases for the same resilient strain, the stress ratio increases.

Accumulative Strain: In Figure 84**,** it can be observed that the accumulative displacement of unfrozen soil is greater than that of soil specimens after one frozen-thaw cycle for the water content of 5%. This implies that for specimens with low water content, a freeze-thaw cyclic tends increase the resilient modulus and reduces accumulative deformation under cyclic loading.

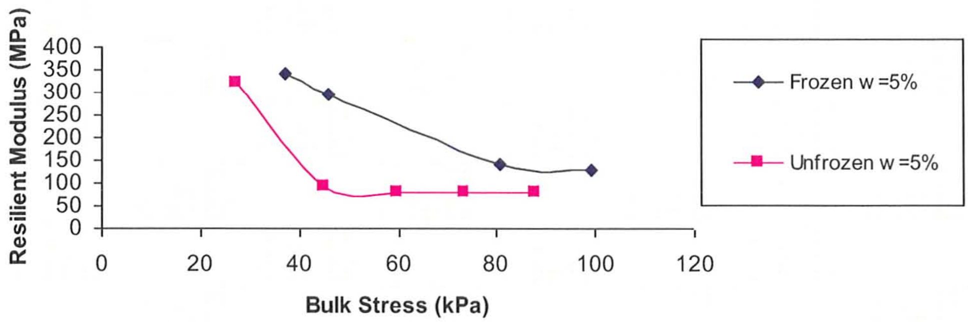


Figure 75 Resilient Modulus vs. Bulk Stress for S_3= 41.4 kPa (6 psi) *w* =5% (Comparison)

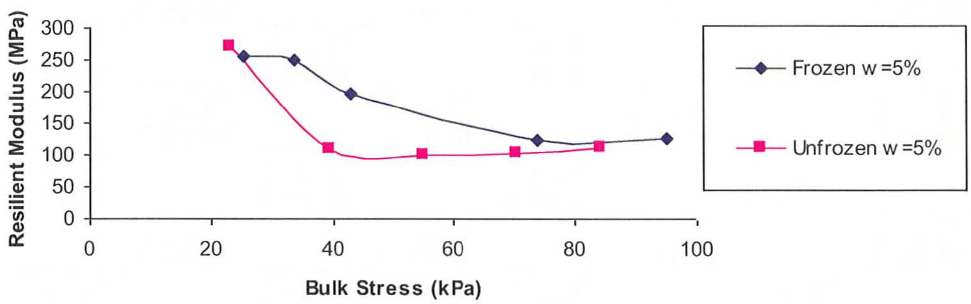


Figure 76 Resilient Modulus vs. Bulk Stress for S_3= 27.6 kPa (4 psi), *w*=5% (Comparison)

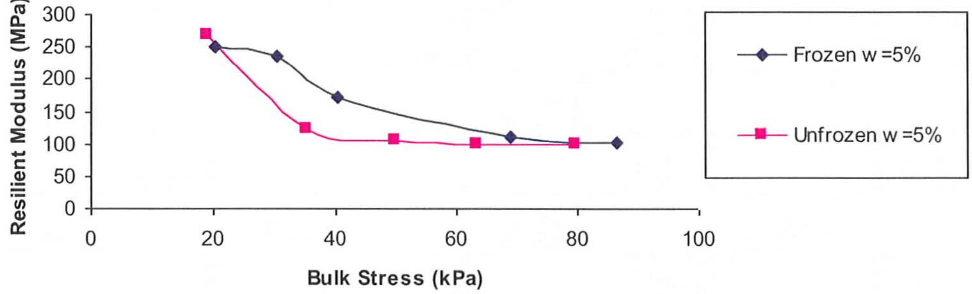


Figure 77 Resilient Modulus vs. Bulk Stress for S_3= 13.8 kPa (2psi), *w* =5% (Comparison)

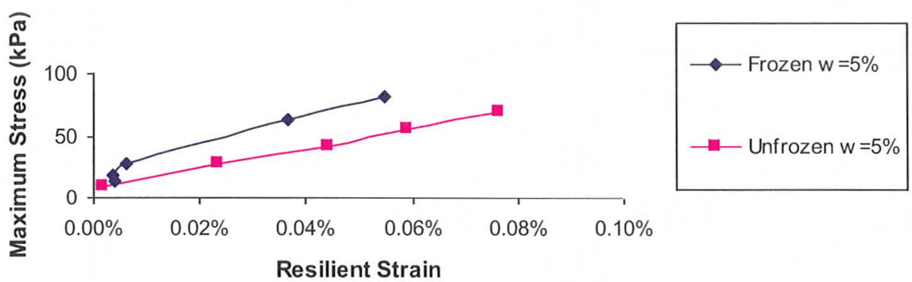


Figure 78 Stress vs. Resilient Strain for S_3= 41.4 kPa (6psi), *w* =5% (Comparison)

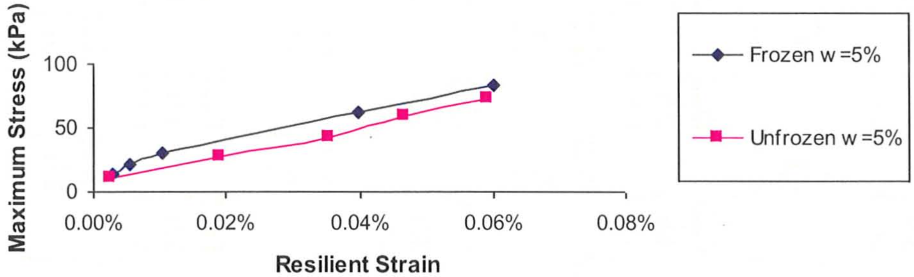


Figure 79 Stress vs. Resilient Strain for S_3= 27.6 kPa (4 psi) *w* =5% (Comparison)

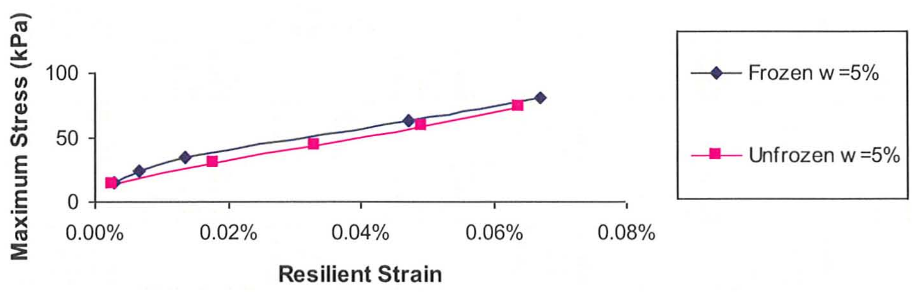


Figure 80 Stress vs. Resilient Strain for S_3= 13.8 kPa (2psi), *w*=5% (Comparison)

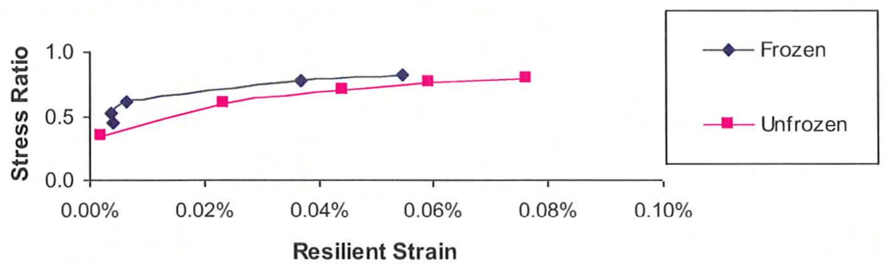


Figure 81 Stress Ratio vs. Resilient Strain, S_3= 41.4 kPa (6 psi), *w*=5% (Comparison)

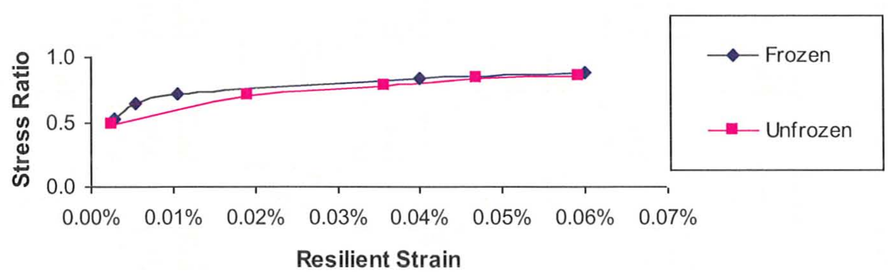


Figure 82 Stress Ratio vs. Resilient Strain, S_3= 27.6 kPa (4 psi), *w* = 5% (Comparison)

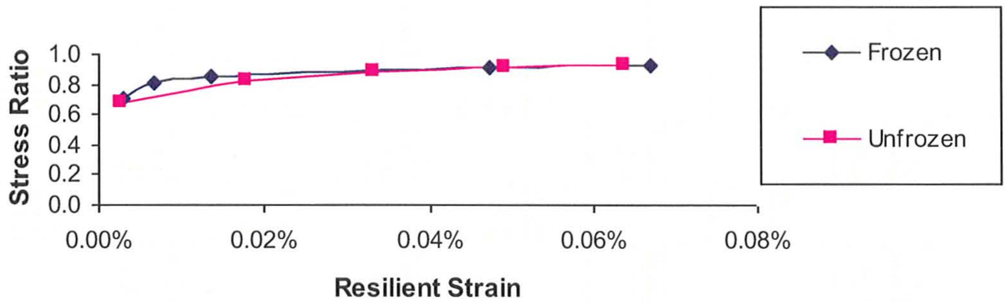


Figure 83 Stress Ratio vs. Resilient Strain, S_3= 13.8 kPa (2 psi), *w* = 5% (Comparison)

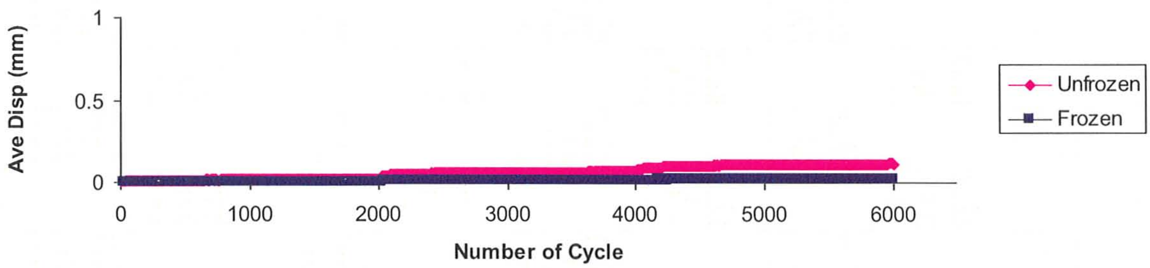


Figure 84 Average Accumulative Displacement, *w* =5% (Comparison)

4.2.3.2 Comparison of Unfrozen Soil and Soil after One Frozen-Thaw Cycle with 8% Water Content

The behavior of unfrozen samples with 8% water content is compared with the behavior of samples having the same water content after first frozen-thaw cycles and the results are outlined as following:

Dependency of Resilient Modulus on Bulk Stresses: For specimens with the water content of 8%, under a selected cell pressure (13.8, 27.6, 41.4 kPa) the resilient modulus for unfrozen specimens significantly decreases as bulk stress increases (Figures 85, 86 and 87). However the resilient modulus for specimens after the first freeze-thaw cycle only have a minor decrease as the bulk stress increases. When comparing with the results at 5% water content (Figures 75, 76 and 77) and those at 8% water content (Figures 85, 86 and 87), it is observed that the resilient modulus at 5% water content is larger than the resilient modulus at 8% water content regardless of the sample type (unfrozen or after first freeze-thaw cycle) and the confining pressure.

Stress against Strain: In Figures 88, 89 and 90, it can be seen that the samples after one freeze-thaw cycle have greater resilient stain at the same stress level regardless of confining pressure. Also, as the cell pressure increases the resilient stain decreases for both types of samples. However, this decrease is more noticeable in the samples after the first freeze-thaw cycle when comparing with unfrozen samples. In comparison of Figures 78, 79 and 80 with Figures 88, 89 and 90, it is observed that all samples have increased strain under the same applied cyclic stress when the water content increases from 5% to 8%.

Stress Ratio against Strain: In Figures 91, 92 and 93, for both unfrozen samples and samples after one freeze-thaw cycle (frozen) at the same resilient strain, the stress ratio increases as the cell pressure is increased. There is no significant difference between stress ratios of unfrozen samples and samples after the first frozen-thaw cycle. However, there is a significant difference in the resilient strain of these two types of samples. More specifically, the resilient strain of samples after the first frozen-thaw cycle is greater than the resilient strain of unfrozen samples.

Accumulative strain: It can be observed from Figure 94 that the accumulative displacement of after first freeze-thaw cycle silty clay when the water content is 8% is greater than that sample when it is unfrozen.

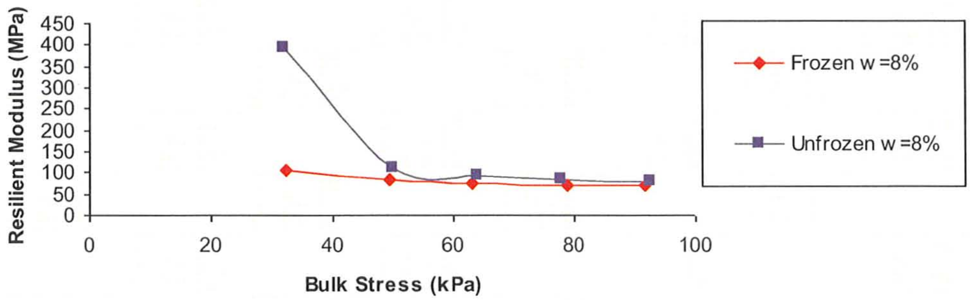


Figure 85 Resilient Modulus vs. Bulk Stress for S_3= 41.4 kPa (6 psi), *w* =8 % (Comparison)

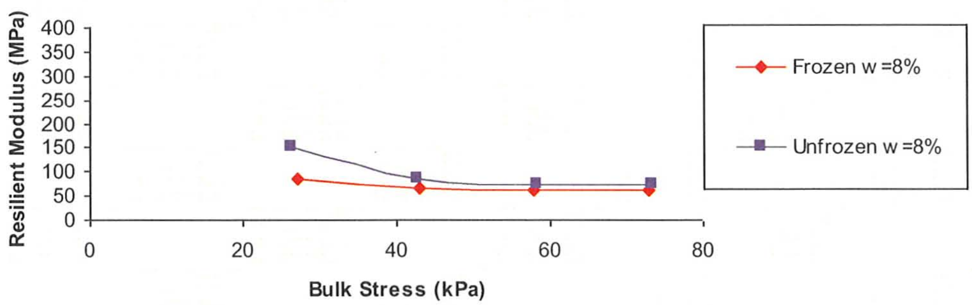


Figure 86 Resilient Modulus vs. Bulk Stress for S_3= 27.6 kPa (4 psi) *w* =8% (Comparison)

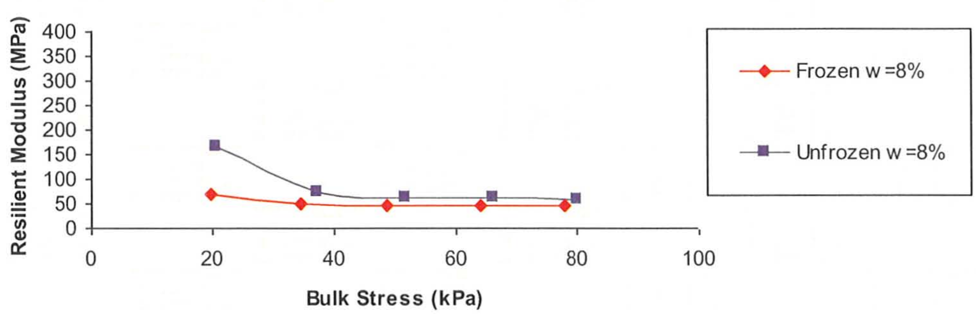


Figure 87 Resilient Modulus vs. Bulk Stress for S_3= 13.8 kPa (2 psi), *w* =8 % (Comparison)

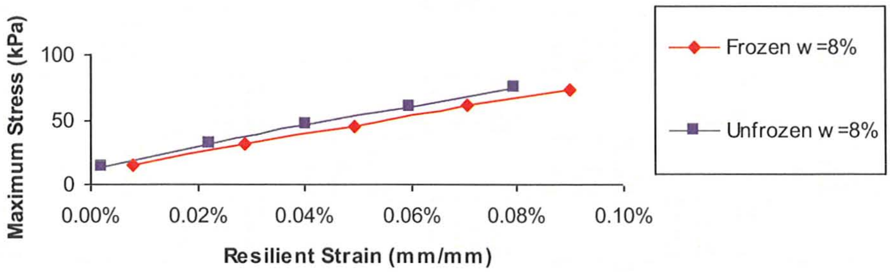


Figure 88 Stress vs. Resilient Strain for S_3= 41.4 kPa (6 psi), *w* =8 % (Comparison)

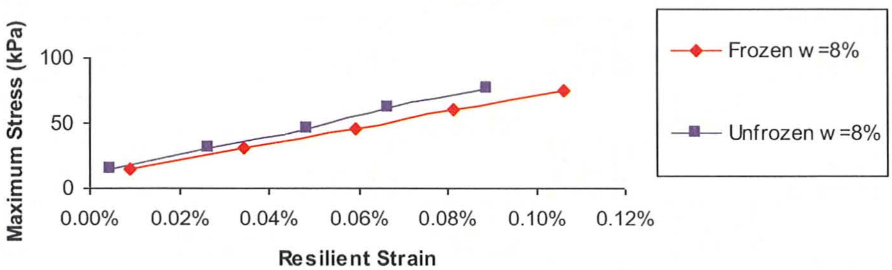


Figure 89 Stress vs. Resilient Strain for S_3= 27.6 kPa (4 psi), *w* =8 % (Comparison)

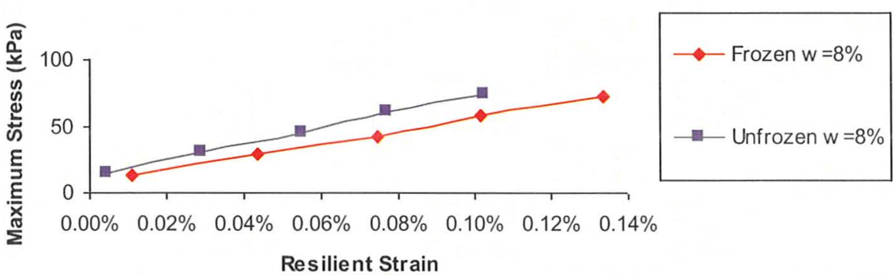


Figure 90 Stress vs. Resilient Strain for S_3= 13.8 kPa (2 psi), *w* =8 % (Comparison)

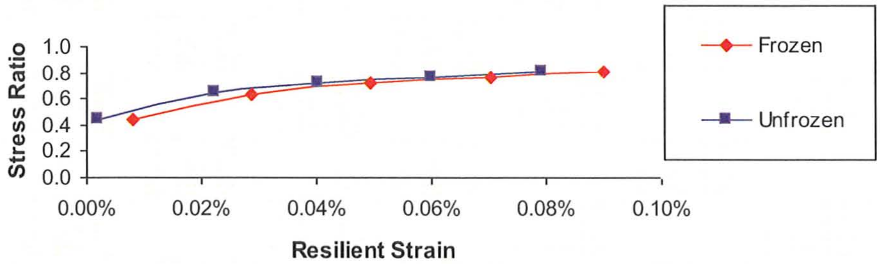


Figure 91 Stress Ratio vs. Resilient Strain, S_3= 41.4 kPa (6 psi), *w*= 8% (Comparison)

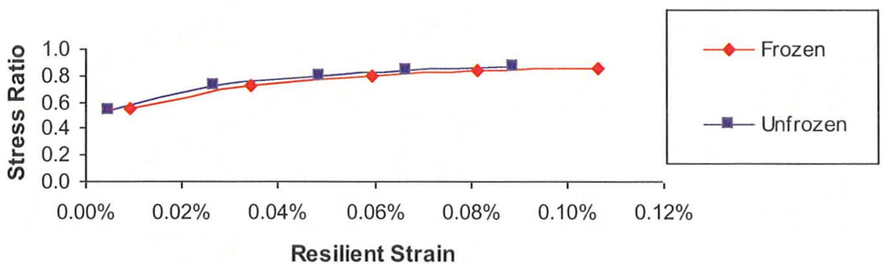


Figure 92 Stress Ratio vs. Resilient Strain, S_3= 27.6 kPa (4 psi), *w*=8% (Comparison)

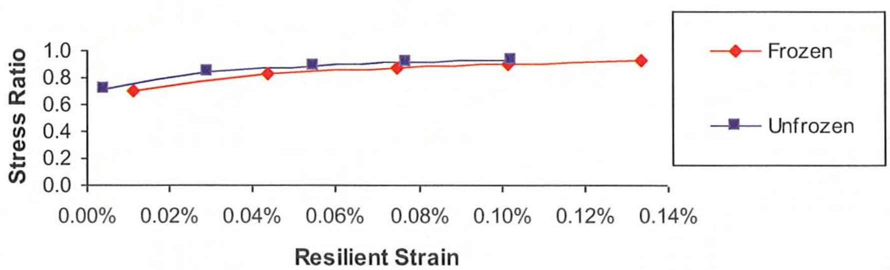


Figure 93 Stress Ratio vs. Resilient Strain, S_3= 13.8 kPa (2 psi), *w* =8% (Comparison)

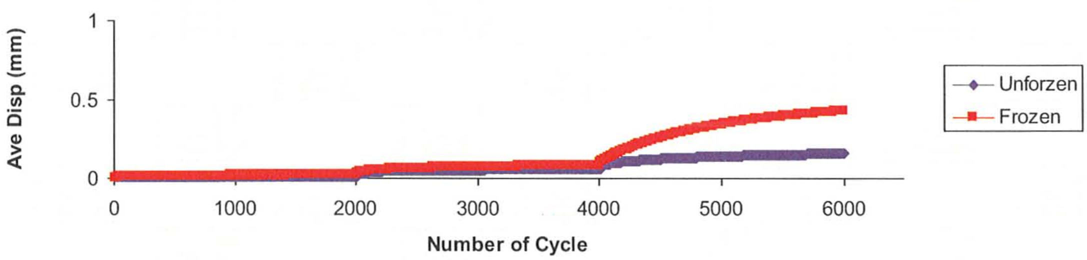


Figure 94 Average Accumulative Displacement, *w*=8% (Comparison)

4.2.3.3 Comparison of Unfrozen Soil and Soil after One Frozen-Thaw Cycle at 10% Water Content

The comparison of the behavior of samples with 10% water content can be observed as per following discussion:

Dependency of Resilient Modulus on Bulk Stresses: According to Figures 95, 96 and 97, the resilient modulus of both types of samples under 13.8 kPa (2 psi) or under 27.6 kPa (4 psi) cell pressure decreases as the bulk stress increases and approaches a constant. It should be recalled that the increase in bulk stress at a constant cell pressure is the result of increasing deviator stress. Regardless of cell pressure, the samples after the first frozen-thaw cycle have a lower resilient modulus than that of unfrozen samples at the same bulk stress. In comparison of specimens with water content 8% (Figures 85, 86 and 87) and 10%, it can be observed that the resilient modulus under the same cell pressure decreases as the water content increases from 8% to 10%. It should be noted that this observation is corrected for both types of the samples.

Stress against Strain: In Figures 98, 99 and 100, the trend of stress-strain relationship of unfrozen sample is almost similar to that of specimens subjected to one frozen-thaw cycle. However, the Strain of the samples after first freeze-thaw cycle is greater than unfrozen at constant cell pressure. As the cell pressure decreases, the resilient strain of the samples (after the first frozen-thaw cycle and unfrozen samples) increases. In comparison of the figures at 8% water content (Figures 88, 89 and 90) to the Figures in 10% water content (Figures 98, 99 and 100), it can be observed that, under the same stress state, the water content has influence on the resilient strain for the unfrozen samples and frozen samples. The resilient strain increases as the water content increases.

Stress Ratio against Resilient Strain: It is observed from Figures 101, 102 and 103 that the variation of deviator stress/bulk stress ratio against resilient strain for both type samples is almost similar. As the stress ratio increases, the resilient strain increases. However, it can be seen that the resilient strain after the first freeze-thaw cycle is greater than that under unfrozen condition.

Accumulative Strain: As per Figure 104, the accumulative deformation of both type samples is almost similar for the first two stages of cyclic loading (up to 4000 load repetitions). However, in the last stage of loading (after 4000 load repetitions), the accumulative deformation of unfrozen sample becomes greater than that of the specimen subjected to one frozen-thaw cycle.

The accumulative displacement of the samples with high water content increases after first freeze-thaw cycle, however the accumulative displacement of samples with low water content (5%) decreases after first freeze-thaw cycle. The difference in accumulative displacement of samples with high water content is significant compare with low water content. This can be seen clearly in Figure 105 which demonstrates the difference of accumulative displacement of Frozen (after first freeze-thaw cycle) and unfrozen with water content of 5%, 8% and 10%.

Resilient Modulus against Confining Pressure: As per Figure 106 and 107, the water content influences on the relation between resilient modulus and confining pressure. For samples with 5% water content, the trend of frozen sample is above the trend of unfrozen sample (as per Figure 106). However, for the samples with 10% water content, the unfrozen sample is above the frozen sample (as per 107). This because the resilient strain of sample with 10% water content increases after first freeze-thaw cycle

But, the resilient strain of sample with 5% water content sample decreases after first freeze-thaw cycle.

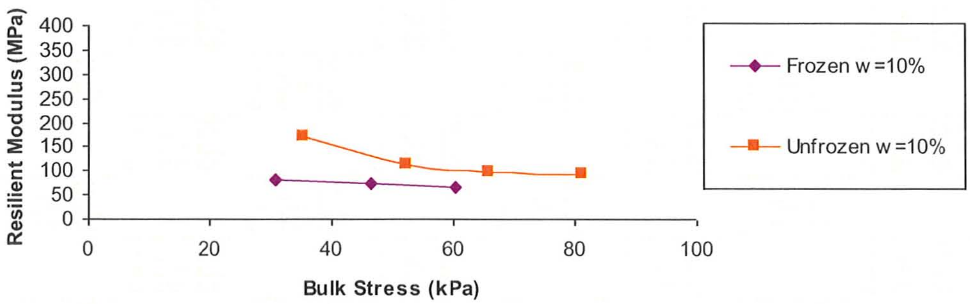


Figure 95 Resilient Modulus vs. Bulk Stress for S_3= 41.4 kPa (6 psi), *w*=10% (Comparison)

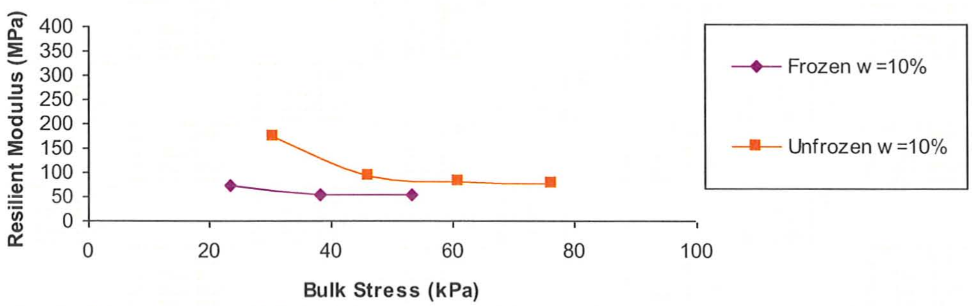


Figure 96 Resilient Modulus vs. Bulk Stress for S_3= 27.6 kPa (4psi), *w*=10% (Comparison)

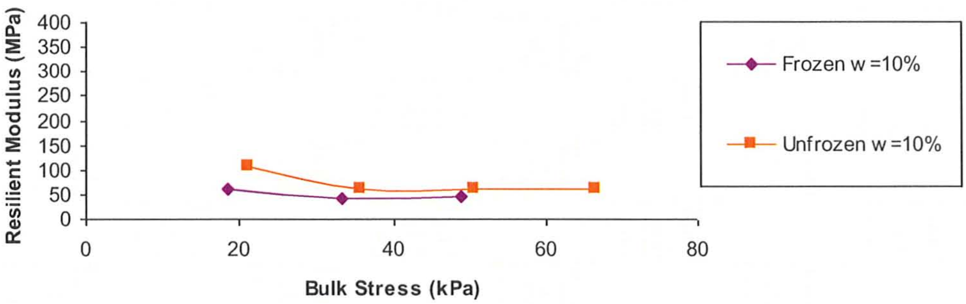


Figure 97 Resilient Modulus vs. Bulk Stress for S_3= 13.8 kPa (2psi), *w*=10% (Comparison)

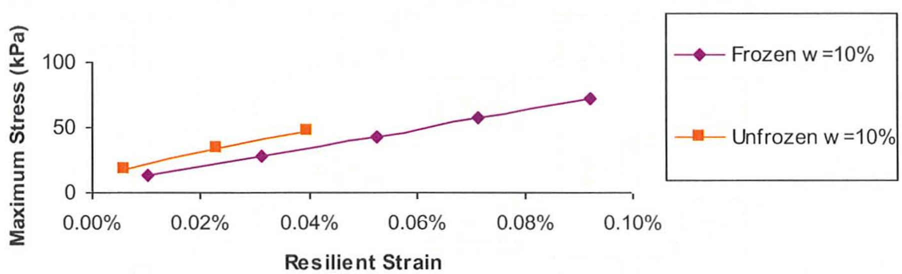


Figure 98 Stress vs. Resilient Strain S_3= 41.4 kPa (6 psi), *w*=10% (Comparison)

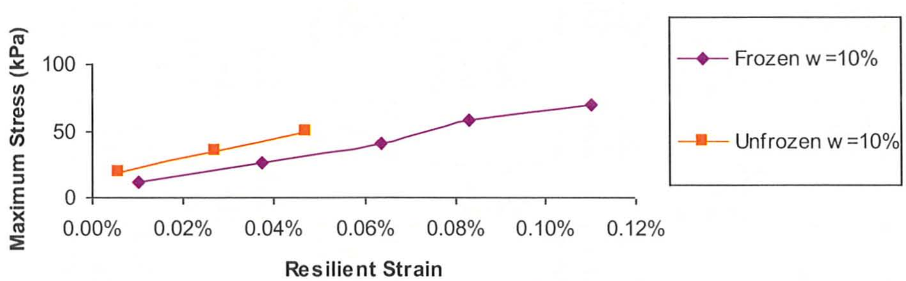


Figure 99 Stress vs. Resilient Strain for S_3= 27.6 kPa (4 psi), *w*=10% (Comparison)

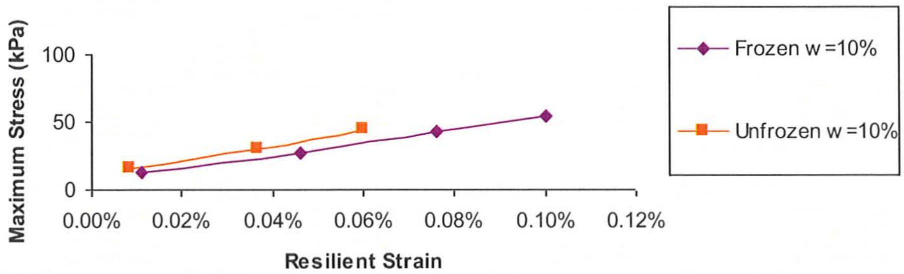


Figure 100 Stress vs. Resilient Strain for S_3= 13.8 kPa (2 psi), *w*=10% (Comparison)

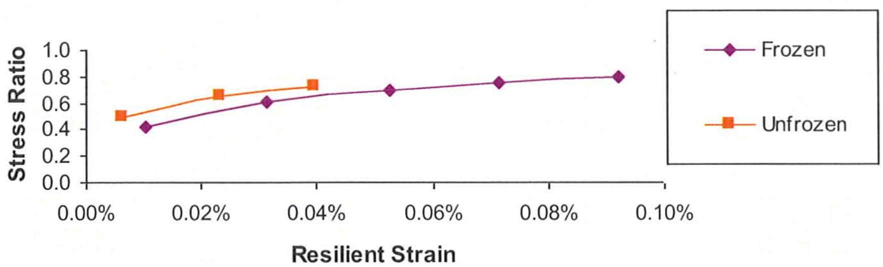


Figure 101 Stress Ratio vs. Resilient Strain, S_3= 41.4 kPa (6psi), *w*=10% (Comparison)

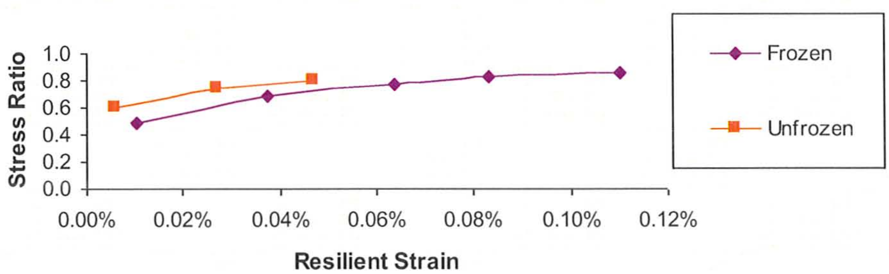


Figure 102 Stress Ratio vs. Resilient Strain, S_3= 27.6 kPa (4 psi), *w*=10% (Comparison)

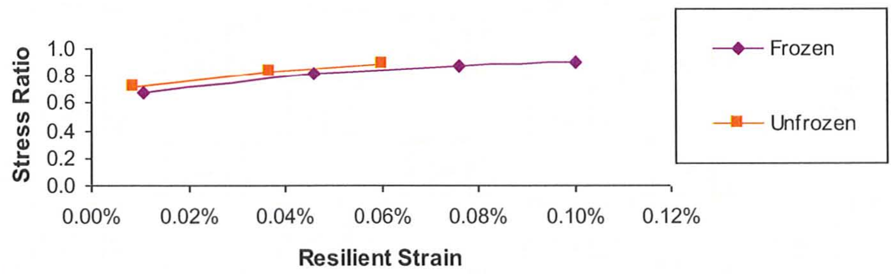


Figure 103 Stress Ratio vs. Resilient Strain, *w*=10%, S_3=13.8 kPa (2 psi) (Comparison)

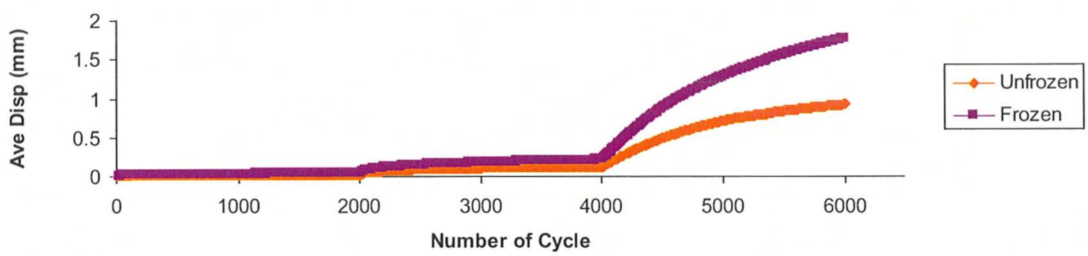


Figure 104 Average Accumulative Displacement, *w*=10% (Comparison)

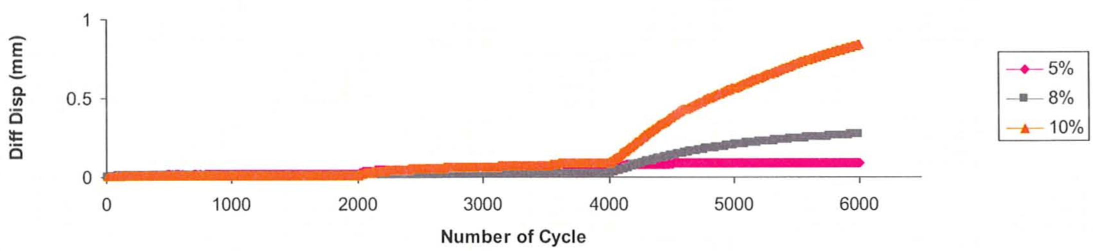


Figure 105 Difference of Average Accumulative Displacement, *w*= 5% & 8% & 10%

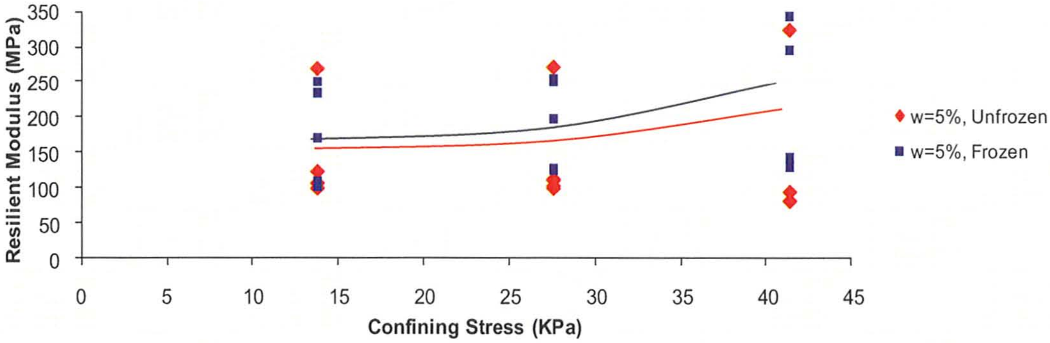


Figure 106 Resilient Modulus vs. Confining Pressure (Comparison), *w*=5%

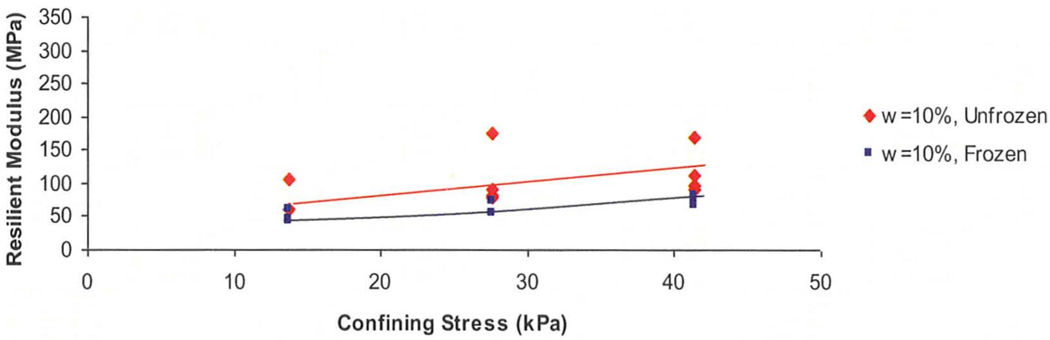


Figure 107 Resilient Modulus vs. Confining Pressure (Comparison), *w*=10%

4.2.3.4 Comparison of Unfrozen Soil and Soil after One Frozen-Thaw Cycle at 12% Water Content

The behavior of unfrozen samples with 12% water content is compared with the behavior of samples after the first frozen-thaw cycles with the same water content and results are outlined as per following:

Dependency of Resilient Modulus on Bulk Stresses: For specimens with the water content of 12%, under a selected cell pressure (27.6 kPa and 41.4 kPa) and at same bulk stress the resilient modulus for unfrozen specimens is greater than the resilient of modulus for the samples after first frozen-thaw cycle but for 13.8 kPa (2 psi) the Mr values of these two types of specimens are practically the same. This can be seen in Figure 108, 109 and 110. It should be noted that the effect of frozen-thaw cycle becomes more significant when the water content is increased. For example, the resilient modulus values of 8% or 10% or 12% specimens after the frozen-thaw cycle are much lower than the resilient modulus values of the unfrozen specimens under the same stress state.

Stress against Strain: In Figures 111, 112 and 113, it can be seen that as the cell pressure decrease, the effect of frozen-thaw cycle on the resilient strain decreases under the same applied cyclic stress. For example, For 300 load repetitions under 41.4 kPa (6 psi), the resilient strain of unfrozen soil is much smaller than the resilient strain of frozen samples. However, for 300 load repetitions under 13.8 kPa (2 psi) cell pressures, there is a insignificant difference between resilient strain of specimens. This is because of pore water pressure in high water content samples.

Stress Ratio against Strain: In Figures 114, 115 and 116, it can be seen that for both type sample as the stress ratio increases the resilient strain increases. In comparison of Figure 103 with Figure 116, it can be obtained that under smaller cell pressure, after frozen-thaw cycle, the water content may not have significant effect on neither the resilient strain nor the corresponding stress ratio, at least for the variation of water content from 10% to 12%. The values were gained from the mentioned Figure and listed in following tables.

13.8 kPa (after first frozen-thaw cycle)			
Water Content	Smax (kPa)	ε_r	$\Delta\sigma/\theta$
10%	12.49	0.011%	0.68
10%	27.19	0.046%	0.82
10%	42.92	0.076%	0.88
10%	54.95	0.100%	0.90

13.8 kPa (after first froze-thaw cycle)			
Water Content	Smax (kPa)	ε_r	$\Delta\sigma/\theta$
12%	17.24	0.012%	0.74
12%	31.58	0.045%	0.84
12%	43.92	0.073%	0.88

Accumulative Strain: The result regarding accumulative deformation could not be obtained since the sample failed during resilient modulus testing.

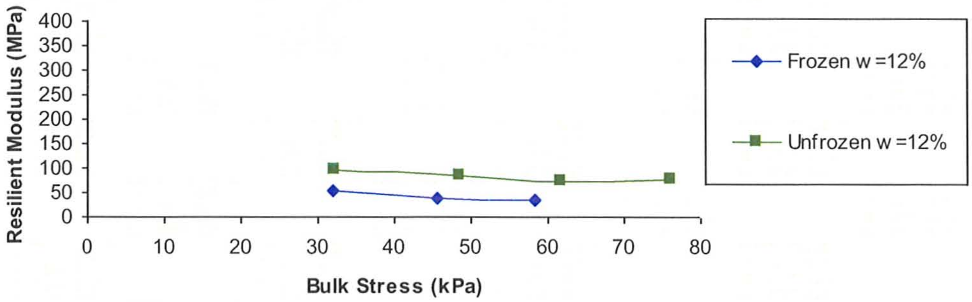


Figure 108 Resilient Modulus vs. Bulk Stress for S_3= 41.4 kPa (6 psi), *w*=12% (Comparison)

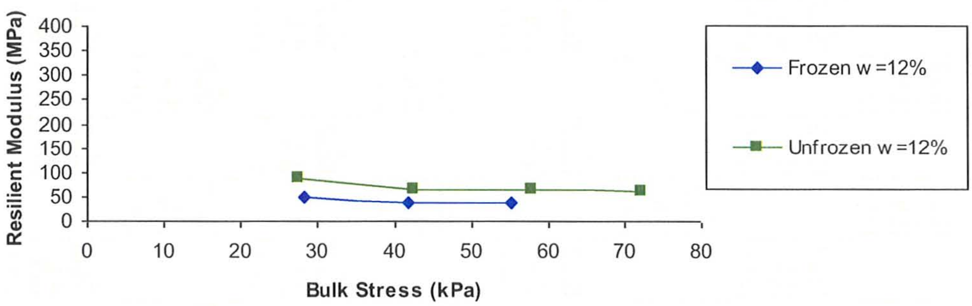


Figure 109 Resilient Modulus vs. Bulk Stress for S_3= 27.6 kPa (4 psi), *w*=12% (Comparison)

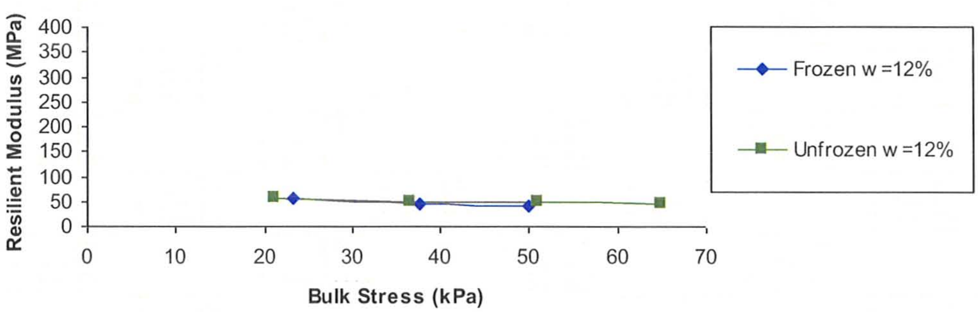


Figure 110 Resilient Modulus vs. Bulk Stress for S_3= 13.8 kPa (2 psi), *w*=12% (Comparison)

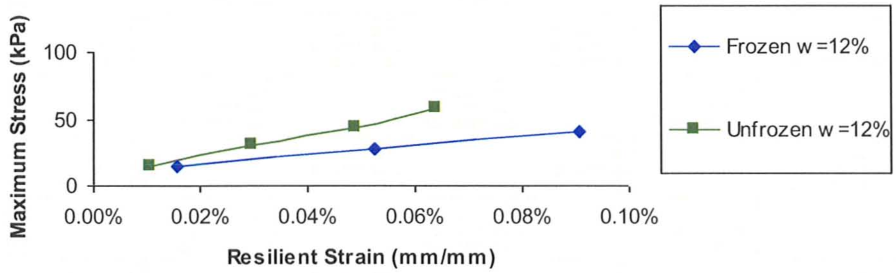


Figure 111 Stress vs. Resilient Strain for S_3= 41.4 kPa (6 psi), *w*=12% (Comparison)

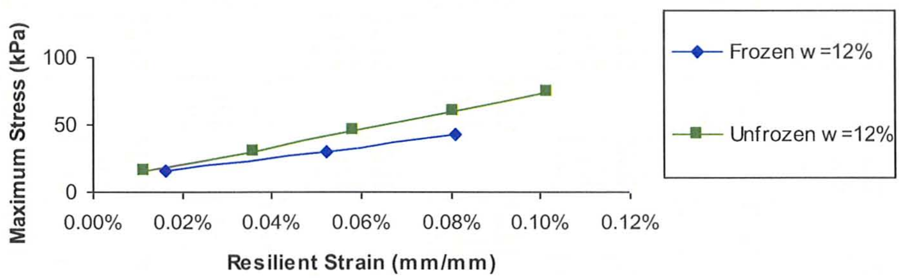


Figure 112 Stress vs. Resilient Strain for S_3= 27.6 kPa (4 psi), *w* =12% (Comparison)

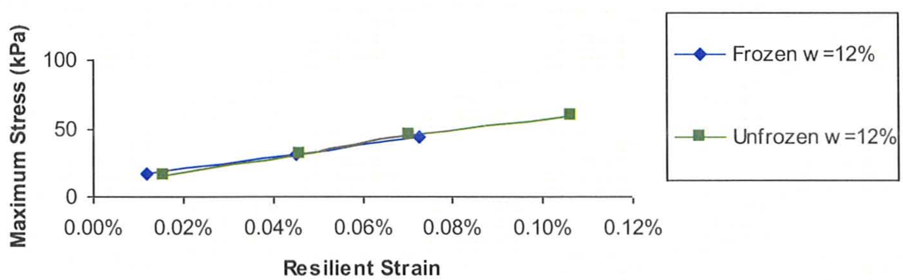


Figure 113 Stress vs. Resilient Strain for S_3= 13.8 kPa (2 psi), *w*=12% (Comparison)

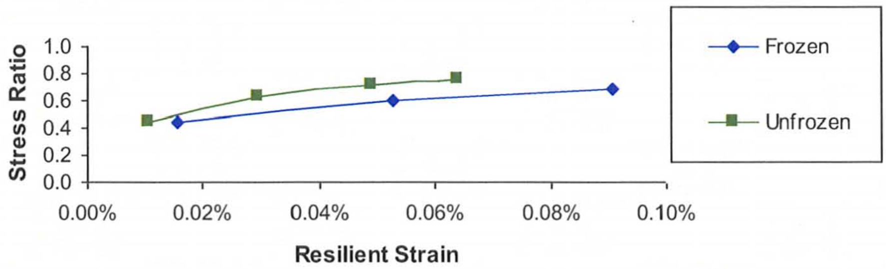


Figure 114 Stress Ratio vs. Resilient Strain, S_3= 41.4 kPa (6psi), *w*=12% (Comparison)

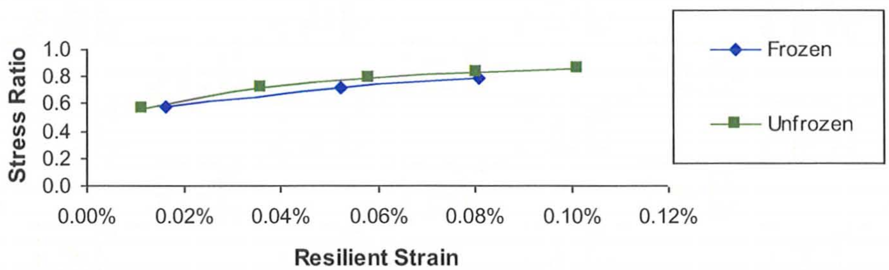


Figure 115 Stress Ratio vs. Resilient Strain, S_3= 27.6 kPa (4psi), *w*=12% (Comparison)

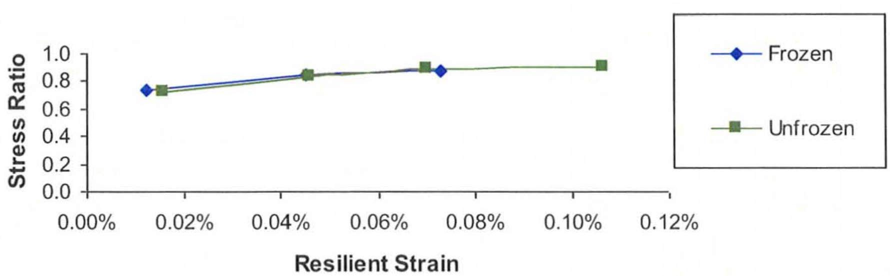


Figure 116 Stress Ratio vs. Resilient Strain, S_3= 13.8 kPa (2psi), *w*=12% (Comparison)

4.2.4 Failure Patterns of Soil Specimens

Figure 117 shows the photos of samples taken after the specimens were removed from the triaxial cell after accumulative displacement tests. Horizontal and vertical cracks, which can be considered as precursor or indicators of failure, are found on some specimens, as marked in Figure 118. In general, the horizontal cracks were found on the interface between soil layers associated with static compaction, and specimens with low water content is more fragile to horizontal cracks. For example, the specimen with 8% water content had a horizontal failure through the entire specimen which divided the specimen in to two pieces. However the sample with 12 % water content was deformed in different way. As it can be seen, this sample was deformed around the vertical axis and it moved to the side in the horizontal direction.

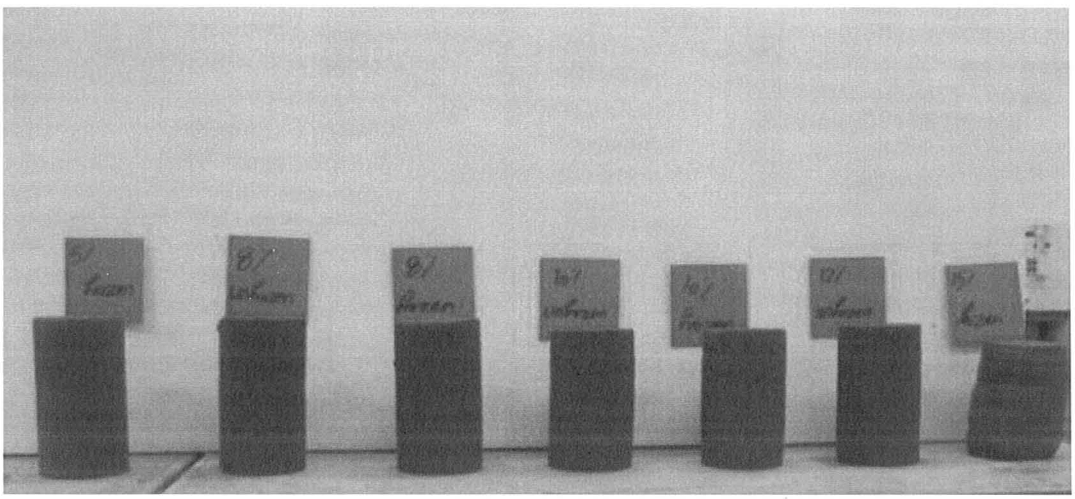


Figure 117 The Samples after Accumulative Displacement Test

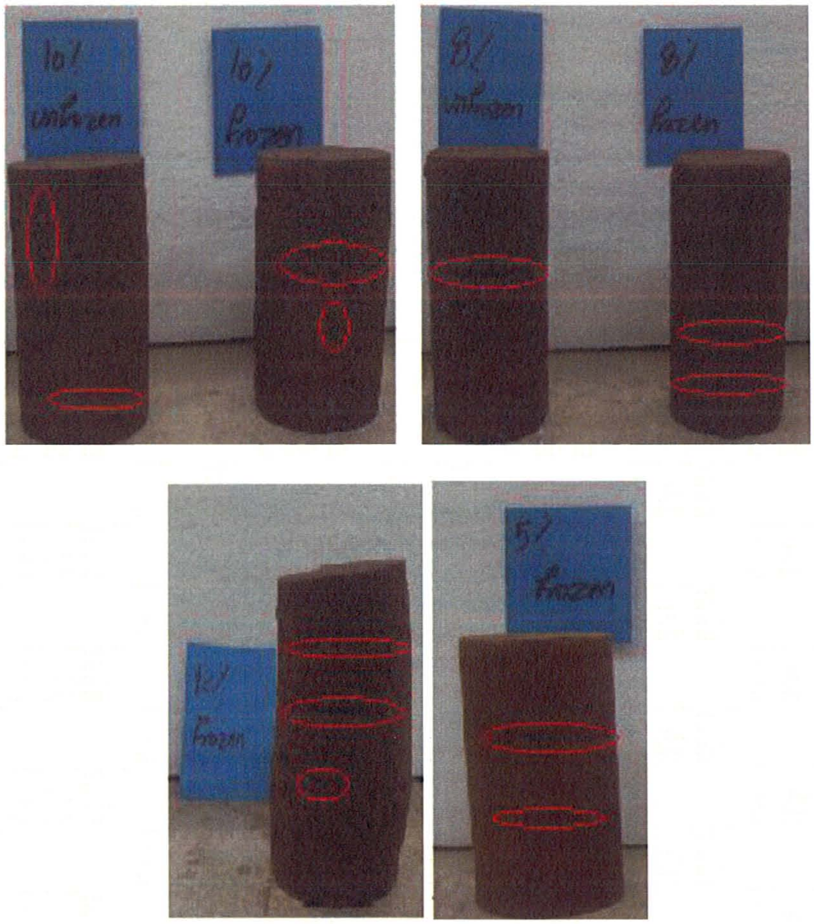


Figure 118 The Comparison of Samples after Accumulative Displacement Test

CHAPTER 5: SUMMARY, CONCLUSION, RECOMMENDATION

5.1 Summary

The behavior of soil with different water contents subject to frozen-thaw cycles has significant effect on the performance of pavement in the springs. Appropriate control of subgrade deflection under repeated traffic load can assist geotechnical engineers for extending the service life of pavements. .

In this report, the behavior of silty-clay soil under unfrozen and after one frozen-thaw cycle were investigated. Focus was placed on the effect of frozen-thaw cycle on the resilient modulus and accumulative permanent deformation under repeated loading at different water contents. The test results under frozen (after first freeze-thaw cycle) and unfrozen conditions were compared for future consideration which may help for upcoming studies in this field.

The resilient modulus test was performed as per ASSHTO T307-99-2003. After completion of this test, the accumulative displacement of the samples was recorded corresponding to 2000 load repetitions at different deviator stress levels though three stages. The results were plotted and compared which can be found in Section 4.

5.2 Conclusions

1. Unfrozen Condition:

- As the water content increases, the resilient modulus decreases when the other conditions are the same.

- Under constant cell pressure, the resilient modulus decreases as the bulk stress increases.
- Under constant cell pressure and constant water content, as the deviator stress increases the resilient modulus decreases.
- The resilient strain increases as the cyclic stress amplitude increases under the same and constant confining pressure.
- As the confining pressure increases the resilient modulus increases.
- The resilient modulus decrease as the deviator stress increases for the same confining pressure. This trend is more obvious when the water content is low.
- As the water content increases the accumulative deformation increases because of pore water pressure. The effective stress decreases as the pore water pressure increases.

2. Specimens after One Frozen-Thaw Cycle:

- As the bulk stress increases the resilient modulus decreases. The samples with higher water content have less resilient modulus. The sample with low water content 5% has higher resilient modulus.
- The resilient modulus decreases as the deviator stress increases.
- Under constant cell pressure and constant water content, as the bulk stress increases the resilient modulus decreases, which in fact reflects the effect of stress deviator.
- As the cell pressure decreases the stain increases and the cyclic stress decreases.
- Under constant cell pressure, as the strain increases the stress ratio increases.

- Similar to unfrozen specimens, as the water content increases the accumulative deformation increases because of pore water pressure. The effective stress decreases as the pore water pressure increases

3. Comparison of Unfrozen and Frozen (after First Freeze-Thaw Cycle) Silty Clay

- For the same cell pressure, unfrozen samples with low water content have lower resilient modulus than frozen samples with the same water content.
- Unfrozen samples with high water content have higher resilient modulus than frozen samples. However, the difference in resilient modulus of the samples with high water content is not as significant as the difference in resilient modulus of the samples with low water content samples.
- The resilient strain increases significantly when the cyclic stress increases for both type of specimens. The samples after first frozen-thaw cycle have a significant increase in their resilient strain when the water contents increases. However, unfrozen samples only have a slight increase in their resilient stain when their water content increases.
- For both unfrozen and frozen specimens, as the cyclic deviator stress increases, the resilient strain increases.
- The samples after first frozen-thaw cycle with high water content have larger accumulative resilient strain under cyclic load comparing with unfrozen samples.

- For both type of specimen, as the confining pressure increases the resilient modulus increases.
- For both type of specimen, as the water content increases the resilient modulus decreases.
- For both unfrozen and frozen specimens, for a given confining pressure, the resilient modulus decreases as the cyclic deviator stress is increased, this also appears as a decrease of resilient modulus with bulk stress.
- As the water content increases, the resilient modulus of the samples after first frozen-thaw cycle tends to decreases more significantly than unfrozen samples.
- In general, at the same stress state and same water content, the resilient strain of the samples after first frozen-thaw cycle is greater than that of unfrozen samples.
- For the samples having low water contents (5%), the accumulative displacement of unfrozen samples is greater than the samples after first frozen-thaw cycle. However, the samples after first frozen-thaw cycle with high water content (8%, 10% and 12%) could have greater accumulative deformation compare to the unfrozen samples with the same water content.

5.3 Recommendation

The following recommendation could be given after completion this report:

- This report was obtained via fabricating only 10 samples. One samples of each water content (5%,8%,10%,12%,15%) under two different conditions, unfrozen and frozen (after first freeze-thaw cycle). This test could be done by fabricating three samples with each water contents under these two different conditions.

However instead of 15% water content, it should be 13% or 14% for silty clay since 15% is too high and it is difficult to fabricate the sample.

- This test should be repeated for second freeze-thaw cycle in order to understand the soil behavior. There is no significant difference between unfrozen samples and samples after fist freeze-thaw cycle.
- The 12% sample under frozen condition (after first freeze-thaw cycle) failed under accumulative deflection test. This test needs to be repeated for this sample in order to obtain the deformation under 12% water content.

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