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Financial Impact of Fines in the Unbound Pavement Layers

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This study continued the research effort on evaluating the resilient behavior of D-1 base course materials when there is limited water access during freezing. D-1 material from the Northern region of Alaska was used, and a closed system was adopted for the specimen preparation process to represent an extreme natural freezing process condition in which no water intake occurs during freezing. Resilient moduli (M_R) of soil specimens were measured and influencing factors investigated included four fines contents ranging from 6% to 12%, three moisture contents ranging from 3.3% to 6%, three temperature gradients (low, medium, and high) during the freezing process, and a series of temperatures ranging from -5°C to 20°C.

The study confirmed several findings from previous study (Li et al. 2010). In addition, it was found that temperature gradient and stress state are important influencing factors. In a closed system, for D-1 materials with different fines contents, soils tended to increase in M_R after a freeze-thaw cycle, in some cases significantly, due to soil structure change during the freezing process. M_R models were then calibrated to predict the resilient behavior of D-1 material under different temperature, moisture, and fines contents and under both non-frozen and frozen conditions.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

Impact of Fines in the Unbound Pavement Layers

Final Project Report

by

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EXECUTIVE SUMMARY

The resilient modulus (M_R) of unbound granular base course material is an important input for pavement design. In Alaska, due to distinctiveness of local climate, material source, fines content and groundwater level, the resilient properties of D-1 granular base course materials are significantly affected by seasonal changes. The presence of fines (P_{200}) affects the frost susceptibility of base materials and controls the ability of aggregate to support vehicular load, especially during the spring-thaw period. In a previous study, Li et al. (2010) systematically evaluated the impact of fines content on the resilient properties of D-1 base course materials with varied fines content, gradation, moisture content, and temperature during thawing, providing regression coefficients k_i, which are required for flexible pavement design. A laboratory investigation was conducted on three D-1 material from the Northern, Central, and Southeast regions of the Alaska Department of Transportation and Public Facilities at different temperatures, moisture, and fines content. An open system frost heave cell, in which free water uptake was allowed during freezing, was fabricated for specimen preparation to simulate the natural freezing process. The open system represented one extreme water access condition (free water intake) in nature.

In the present study, a similar investigation was performed to evaluate the impact of fines content on the resilient behavior of D-1 base course materials. However, unlike the study by Li et al. (2010), a closed system was adopted for the specimen preparation process to represent the other extreme natural freezing process condition in which no water intake occurs during freezing. Only D-1 material from the Northern region was used in the present investigation. Also, three temperature gradients instead of one were applied during the freezing process. Influencing factors investigated included four fines contents ranging from 6% to 12%, three moisture contents ranging from 3.3% to 6%, three temperature gradients (low, medium, and high), and a series of temperatures ranging from -5°C to 20°C.

Preliminary tests were conducted first to determine physical properties such as gradation, optimum moisture content (OMC), and maximum dry density (MDD). 4-inch by 8-inch soil specimens were fabricated according to the designed moisture and fines contents. For repeated load triaxial tests on D-1 material under subfreezing conditions, soil specimens were conditioned in the closed system frost heave cell to simulate the freezing process without water intake. For different batches of specimens, three temperature gradients were applied during the freezing

process. Frost heave values during freezing were recorded by the linear variable differential transformers (LVDT) mounted on the tops of the specimens. Also, temperature changes at the sides of the specimens were captured by the attached thermocouples.

Because a closed system was used for specimen conditioning, frost heave values during specimen preparation were relatively small when compared with those from the previous study (Li et al., 2010). Also, test results showed that frost heaving of the tested D-1 material could be influenced by applied temperature gradients. At high freezing gradients, specimens experienced slight shrinkage during freezing, rather than expansion. At medium freezing gradients, specimens expanded slightly, by about 0.1–1.5% of total height. At low freezing gradients, specimens expanded more noticeably, by approximately 0.5–2.0% of total height.

Under the low temperature gradient, freezing progressed at a relatively constant rate down through the specimen. This slowly moving freezing front allowed moisture to accumulate and freeze in situ in the pore spaces, which led to full expansion of moisture without redistribution. Thus, the frozen soil volume increased as the volume of the moisture increased. However, a rapidly moving freezing front in the D-1 material caused particles of moisture to freeze quickly, which resulted in a loss of moisture from the area being frozen and hence a reduction in volume as part of the moisture escaped into the unfrozen pore spaces beneath. After the freezing process, soil specimens were further conditioned in the environmental chamber to reach the target testing temperature for the repeated triaxial test. After temperature equilibrium in the specimens, repeated load triaxial tests at subfreezing temperatures were conducted. After testing at subfreezing temperatures, repeated load triaxial tests at room temperature were conducted on soil specimens after the freeze-thaw cycle. Also, repeated load triaxial tests at room temperature were conducted on soil specimens without a freeze-thaw cycle.

Similar to the findings in the study by Li et al. (2010), this study found that for unfrozen D-1 materials with fines contents of 8%, the M_R decreased as moisture increased, but for D-1 material with 6% fines, no significant loss of M_R was identified with increased moisture. At low moisture content, M_R increased significantly with fines content, while at optimum moisture content, the M_R increase was much less. At moisture contents of 3.3% and 5.3%, it was found that 8% fines content generally produced the highest M_R values for unfrozen specimens at room temperature, which was consistent with the conclusion from the previous study. Furthermore, the M_R of specimens containing 10% and 12% fines generally decreased relative to that of 6% fines with increasing deviator stress and confining pressure. Resilient modulus values of D-1 material decreased with an increase of temperature for specimens prepared under low and medium temperature gradients. However, for D-1 material specimens prepared under high temperature gradient, from -5°C to -3°C, mean M_R values increased with increased temperature. Stress state is another important factor that can influence resilient behavior of D-1 material. At -5°C, a nearly linear relationship was found between M_R and deviatoric stress. However, at -1°C, this linear relationship only existed when the applied deviatoric stress was low. After reaching the peak M_R value, M_R value decreased with an increase of deviatoric stress. In other words, the effect of deviatoric stress on resilient behavior of D-1 material was temperature-dependent, which was consistent with the previous study (Li et al., 2010). At room temperature (20°C), for D-1 materials with different fines content, it was found that the M_R value slightly increased with an increase of deviatoric stress.

As presented in the previous study (Li et al., 2010), when an open system during freezing was used, D-1 materials tended to experience a decrease in M_R at room temperature after a freeze-thaw cycle due to the increase of moisture content. However, in a closed system, for D-1 materials with fines contents of 6%, 10%, and 12%, without water uptake, it was found that soils tended to increase in M_R after a freeze-thaw cycle, in some cases significantly, due to soil structure change during the freezing process.

In this study, it was found that temperature gradient had no clear influence on the resilient behavior of most of the tested D-1 material at subfreezing temperatures. However, for specimens prepared under different temperature gradients, medium temperature gradient caused the highest M_R values. Low and high temperature gradients generally produced lower M_R values.

Resilient modulus models were calibrated to predict the resilient behavior of D-1 material under different temperature, moisture, and fines contents and under both non-frozen and frozen conditions. Similar to the previous study (Li et al., 2010), for the prediction of M_R under unfrozen conditions, the fines content and moisture content and the interaction between them were introduced into the model specified in the Mechanistic-Empirical Pavement Design Guide (MEPDG) to correlate with coefficients k_i, which are required for flexible pavement design by the MEPDG software. The modified model developed for M_R prediction of D-1 materials at subfreezing temperatures (Li et al., 2011) was used in this study. To incorporate the influence of ice content on resilient behavior of the tested D-1 material, a new model was developed for M_R

prediction of the tested D-1 material at subfreezing temperatures. A higher coefficient of determination (R^2) was obtained when the new model was used to predict the resilient behavior of D-1 material under subfreezing temperatures.

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CHAPTER 1. INTRODUCTION

This study is complementary to a previous investigation (Li et al., 2010) on the impact of fines content on the resilient behavior of roadway base course materials during and after freezing and thawing. The previous study determined resilient behavior of D-1 aggregates that were allowed to absorb moisture during the freezing process with a single freezing temperature gradient. The resilient behavior of D-1 aggregates were further investigated with a closed system freezing process, various freezing temperature gradients, and higher fines content in aggregates.

Problem Statement

Base course saturation and weakening because of partial thawing are typical springtime conditions in most northern regions and normally are reflected by reductions in the resilient properties of the affected materials. The presence of fines (P_{200}) affects frost susceptibility of base materials and controls the aggregates' ability to support vehicular load, especially during the spring-thaw period.

The resilient behavior of typical Alaska base course materials with different fines contents and moisture conditions from different material sources was investigated under different temperatures in a completed project by Li et al. (2010). Basic findings included (1) a two to three order of magnitude increase in the strength of all materials at subfreezing temperatures, and (2) significant loss of stiffness upon thawing of most soils tested. Fines content and moisture content co-affect the resilient moduli of D-1 materials before and after the freeze-thaw cycle. Especially under high initial moisture content, the difference in resilient moduli before and after the freeze-thaw cycle is not big with an increase of fines content. These findings were obtained using an open system in which the material has free access to water during the freezing process. As the open system of water access represents the worst-case scenario for a road structure, it is necessary to investigate the behavior of base course materials under other conditions to complement the existing research and gain an improved understanding of the combined effect of fines content and moisture content on the resilient behavior of D-1 materials.

In the previous study, D-1 materials from three regions with a fines content of 10% were all slightly frost-susceptible according to Casagrande's criteria. However, the previous study did not show significant frost heave for those materials with high fines. Since temperature gradient is another possible factor that affects frost heave behavior of D-1 materials, the present study used different temperature gradients for specimen preparation to better correlate the effect of fines content, frost heave, and the resilient behavior of Alaska granular materials.

Research Objectives

The following objectives were undertaken:

- To further investigate the resilient behavior of Alaska base course materials under the condition that materials have limited access to water during the freezing process,
- To compare and correlate the resilient behavior of Alaska base course materials under different water-access conditions, with various moisture and fines contents, and
- To evaluate the financial impact of allowable fines in the unbound pavement layers.

Research Methodology

To meet the objectives of this study, the following major tasks were accomplished:

- Task 1: Literature Survey
- Task 2: Material Properties, Mixture Design and Specimen Preparation
- Task 3: Laboratory Performance Tests
- Task 4: Data Processing and Analyses
- Task 5: Draft of Final Report and Summary of Findings

Task 1: Literature Survey

Task 1 involved a comprehensive literature search of published materials and ongoing research projects to obtain the latest information related to evaluation of the impact of fines content on the resilient modulus and performance of base course materials during thawing. Databases of TRB, TRIS, COMPENDIX, and UMI THESIS AND DISSERTATIONS were searched. Information and data from previous work conducted by ADOT&PF on this topic were also gathered, reviewed, and documented. The literature findings are summarized in Chapter 2.

Task 2: Material Properties, Mixture Design, and Specimen Preparation

Task 2 was performed mainly in the laboratory. The D-1 materials used were collected from the Northern region of Alaska and were the same Northern region aggregate used in the previous study. Aggregate properties were evaluated first. These tests included particle-size distribution (sieve analysis and hydrometer tests according to AASHTO T 27 (AASHTO, 2002) and ASTM D422-63 (ASTM, 2007), and moisture content. The aggregate properties information was used to finalize the experimental design factors, which included freezing temperature gradient, fines content, moisture content, and testing temperature. These results are summarized in Chapter 3.

Table 1.1 lists the design factors and different levels that were considered in Task 2. The four fines contents selected were 6%, 8%, 10%, and 12% (passing No. 200 sieve), and the three moisture contents selected were optimum moisture content (OMC), 2% below OMC, and 0.7% above OMC. Compaction tests were performed to obtain the OMC and maximum dry density (MDD). All levels for different design factors were finalized according to the aggregate test results proposed above, and project length and budget permission. The D-1 materials used in this research were compacted to specimens 4 inches in diameter by 8 inches in height using the impact compaction method, following AASHTO T-180 (AASHTO, 2002). A closed system with no water access was introduced for the process of preparing frozen specimens. Three different temperature gradients were used to generate different frost heaves for the laboratory performance tests in Task 3.

Table 1.1 Experimental design factors

Factors	Levels
Fines type	Silt
Freezing temperature gradient (preparation)	Low, medium, and high
Fines content	6%, 8%, 10%, and 12% (passing No. 200 sieve)
Testing temperature	-5, -3, -1, 20°C without freeze-thaw cycle, and 20°C after a freeze-thaw cycle
Moisture content	OMC, OMC – 2%, OMC + 0.7%

Task 3: Laboratory Performance Tests

Under Task 3, frost heaving susceptibility and the resilient property of specimens prepared in the previous task were evaluated according to test protocols described in the ASTM or AASHTO Standard Test Method. Specimens to be tested under subfreezing temperatures (i.e., -5°C, -3°C, and -1°C) were frozen in the frost heave cell with three different temperature gradients (low, medium, and high levels). Water was kept from flowing into the soil specimens during freezing. The frost heaving susceptibilities of the soil specimens were measured. The soil specimens were then taken out of the frost heave cell and put into the environmental chamber to freeze to different temperatures. Five temperature levels (i.e., -5°C, -3°C, -1°C, 20°C without a freeze-thaw cycle, and 20°C after a freeze-thaw cycle) were selected to simulate the full freeze-thaw cycling, where -5°C, -3°C, and -1°C represent the soil under frozen conditions and 20°C is used to represent the soil under thawed conditions.

Repeated load triaxial tests based on AASHTO T 307-99 (AASHTO, 2002) were conducted to determine the resilient moduli of specimens during one full freeze-thaw cycle. For thawed conditions, the resilient moduli of the soil specimens were determined by testing specimens in an undrained condition directly after thawing. For each test, three replicates were used. The testing procedures are detailed in Chapter 3.

Task 4: Data Processing and Analyses

Laboratory test data were statistically analyzed in Task 4. The effects of moisture content and fines content on the M_R values of base course materials with limited water access were evaluated. The results were further compared with results of base course materials with an open system from the previous project. These results and comparisons are presented in Chapter 4. In addition, all testing data are available in the Appendices.

Task 5: Draft of Final Report and Summary of Findings

In Task 5, a final report was drafted upon the completion of data analyses as a complementary study of the previous project. The research findings from this study and a comparison with findings from the previous study are summarized in Chapter 5.

CHAPTER 2. LITERATURE REVIEW

The unbound granular layer in pavement serves as a major structural component in flexible pavement performance. A considerable amount of research has been devoted to measuring the resilient properties of base course materials since the introduction of the concept of resilient modulus (M_R) in the mid-1950s.

Other Studies on M_R of Granular Materials

Experimental results on the M_R of granular materials using different aggregate sources, testing procedures, or numerical models have been reported (Uzan, 1999; Cheung and Dawson, 2002; Davich et al., 2004; Werkmeister et al., 2004; Abushoglin and Khogali, 2006). Rada and Witczak (1981) evaluated 271 test results obtained from ten research agencies and indicated that the primary variables that influence the M_R response of granular materials are stress state, degree of saturation, and degree of compaction. Moisture content is known to have great impact on the M_R of granular materials (Hicks and Monismith, 1971; Tian et al., 1998; Li and Qubain, 2003; Toros and Hiltunen, 2008; Attia and Abdelrahman, 2010). The effect of fines content on resilient behavior of granular materials was also investigated; however, controversial conclusions have been drawn from different studies (Hicks, 1970; Gandara et al., 2005; Liang, 2007). Other physical properties, such as aggregate type, gradation, and shape and texture, are also important factors that affect the resilient behavior of base materials (Janoo et al., 1997; Eggen and Brittnacher, 2004; Bennert and Maher, 2005; Mayrberger and Hodek, 2007). Generally, the M_R of rough, angular crushed materials was higher than that of rounded gravel (Barksdale and Itani, 1989; Thom and Brown, 1988), and triaxial strength increases as the coarse fraction increases (Bennert and Maher, 2005). In addition, a considerable amount of research has been devoted to describing the stress dependence of M_R, such as the K-θ model (Hicks and Monismith, 1971; Kalcheff and Hicks, 1973) and octahedral stress model (Witczak and Uzan, 1988). Previous studies have developed relationships between base material properties and regressed *k*-coefficients and exponents of constitutive models (Mohammad et al., 1999; Dai and Zollars, 2002; Kim and Kim, 2007; Hopkins et al., 2007; Malla and Joshi, 2008; Li et al., 2010), though the physical properties correlated to resilient modulus varied between different materials and locations.

In 1993, the American Association of State Highway and Transportation Officials (AASHTO, 1993) proposed a new pavement design procedure that incorporates the M_R concept, to properly describe the behavior of pavement materials subjected to moving traffic. Resilient modulus has become an essential input for pavement design/analysis procedures and a critical parameter in evaluating the engineering behavior of pavement materials, such as stiffness and water susceptibility.

Since 1993, many research efforts have been directed at understanding the effects of materials, moisture, and stress conditions on resilient properties of unbound granular aggregates and further recommending associated specifications and practices for state agencies. Mayrberger and Hodek (2007) evaluated the M_R of Michigan materials at the limits of gradation and varying degrees of saturation for the Michigan Department of Transportation (DOT). Petry et al. (2008) determined the resilient moduli for common Missouri subgrade soils and unbound granular base materials at their optimum water content and at an elevated water content (a worse-case scenario during the life of a pavement) for the Missouri DOT. Another study on graded aggregate base courses (Baus and Li, 2006) in South Carolina recommended that the South Carolina DOT consider the feasibility of relaxing the current gradation specification limit and re-evaluating layer thickness restrictions. An ongoing project led by North Carolina State University is intended to develop performance-related criteria that can be incorporated into the current North Carolina DOT standard specifications that are used for acceptance of aggregate base course for pavement structure. Another study conducted by Gandara et al. (2005) evaluated aggregate gradation, especially the fines content on base material performance in Texas, and found that increases in the amount of fines have a large impact on the engineering properties of base materials. The study results also showed, however, that the percentage of fines used in the base material mixtures had a limit (approximately 10%). In the range of 5% to 10% fines, the base is less moisture-susceptible and has higher compressive strength and a higher M_R value. It is not uncommon to find Texas bases with fines content between 20% and 25%. The study by Gandara et al. would suggest the Texas DOT determine if the low fines bases lead to improved field performance, as the Texas DOT is the only DOT in the United States that does not control the P_{200} fraction of its flexible bases.

Previous Studies in Cold Regions

The resilient behavior of unbound granular material is more complicated when subjected to freeze-thaw cycles (which are typical in cold regions). In all these factors, fines content plays an important role in frost heave and subsequent thaw weakening. In the early 1930s, Casagrande (1932) proposed a widely known rule of thumb for identifying potentially frost-susceptible soils which are non-uniform soils containing more than 3% of grains smaller than 0.02 mm, or very uniform soils containing more than 10 percent smaller than 0.02 mm under natural freezing conditions and with sufficient water supply. No ice segregation was observed in soils containing less than 1 percent of grains smaller than 0.02 mm, even if the groundwater level is as high as the frost line.

Application of the Casagrande criterion requires a hydrometer test of soil suspension to determine the distribution of particles passing the 0.075 mm sieve and to compute the percentage of particles finer than 0.02 mm. Significant loss of strength is often associated with frost heave. Johnson et al. (1978) and Cole et al. (1986) investigated the resilient properties of granular materials from frozen to thawed conditions. Basic findings from these investigations include (1) the occurrence of significant loss of strength upon thawing of most soils tested, (2) a gradual regaining of strength as moisture drains from the soil during the recovery period, and (3) a two to three order of magnitude increase in the strength of all materials at subfreezing temperatures. Associated with a reduction in M_R was a significant reduction in matric suction after freeze-thaw cycling, based on the findings of Fredlund et al. (1975). The reduction in matric suction was substantial below the optimum water content, diminishing above optimum. Simonsen et al. (2002) carried extensive resilient modulus laboratory tests during a full freeze-thaw cycle on various coarse and fine-grained subgrade soils, in which a closed system and omni-directional freezing and thawing were used. A closed system is the most conservative test method in terms of stiffness reduction during thawing, which cannot necessarily represent the real field conditions.

An intensive performance study in 1980 of 120 flexible pavement sections in Alaska (McHattie, 2004) indicated that the percentage of fines (weight-based percentage of particles finer than the #200 sieve, also known as P_{200} content) usually controls the aggregate's ability to support vehicular load, especially during the springtime thaw period. The general relationship is low P_{200} content = good support, and high P_{200} content = poor support. Excess P_{200} will cause springtime softening in subsurface base/subbase layers and subsequent deterioration of the surface layer, explained by a correlation between the amounts of frozen moisture to the P_{200} content in granular layers. Additional research led to the development of the excess fines method for Alaska flexible pavement design based on the establishment of an empirical relationship between the P_{200} content and the deflection of springtime pavement surfaces corresponding to a thaw-weakened state. As a useful indicator of frost susceptibility for pavement design purposes, the critical excess fines content varies with different aggregate sources, gradations, moisture contents, etc. The Casagrande (1932) criterion was used to determine the frost susceptibility of unbounded granular material. In order to simplify the application of the Casagrande criterion and eliminate the hydrometer test, it was implicitly assumed that 50% of the grains were smaller than 0.02 mm in the fines passing the No. 200 sieve. This is the reason why, in the Standard Specifications for Highway Construction (Green, 2004), it is stipulated that D-1 material shall have a fines content of less than 6%.

Recently Completed Study in Alaska

In a recently completed project (Li et al., 2010), a laboratory investigation was conducted on three D-1 materials from Northern, Central, and Southeast regions of ADOT&PF using different temperatures and moisture and fines contents. The objectives of the study were to systematically evaluate the impact of fines content on the resilient properties of D-1 base course materials with varied fines content, gradation, moisture content, and temperature during thawing and provide regression coefficients k_i, which are required for flexible pavement design. Resilient modulus data were determined by conducting repeated triaxial tests on D-1 materials with non-plastic fines content ranging from 3.15% to 10% and moisture content ranging from 3.3% (OMC-2%) to 6% (OMC+0.7%). Permanent deformation data on aggregate specimens were collected from M_R tests as well.

For the M_R tests at subfreezing temperatures, a frost heave cell was designed and fabricated for specimen preparation. To simulate the natural frost heave in winter, aggregate specimens underwent a freezing process in the frost heave cell. The designed frost heave cell is an open system that allows free water intake during the freezing process. Frost heave data and change of moisture contents after the freezing process were obtained from frost heave tests. Resilient modulus tests were also conducted on aggregate specimens after the freeze-thaw cycle.

However, most specimens collapsed during testing, which indicates significant loss of M_R after the freeze-thaw cycle.

Resilient behavior of D-1 materials were affected by temperature and deviator stress. At room temperature, the M_R of D-1 materials from three regions increased with an increase of confining pressure when moisture contents ranged from 3.3% to 6%. However, at low moisture content, the M_R decreased as the applied deviator stress increased. When moisture content was at the OMC or higher, the M_R increased with the increase of deviator stress. However, the effect of confining pressure became insignificant for D-1 materials at high moisture content. At subfreezing temperatures, the confining pressure did not exhibit a significant effect on M_R values. However, temperature was found to be another important influencing factor on M_R of D-1 materials, especially when temperature ranged from -5°C to 0°C. As temperature decreased, M_R increased. However, when temperature was decreased to -5°C, M_R values seemed to be stable, and further change of temperature did not result in any significant change of M_R.

The reduction of M_R after the freeze-thaw cycle was inevitable and significant, especially for aggregate specimens with high fines content. The permanent strain of D-1 materials was significantly affected by moisture content. The higher the moisture content, the higher the permanent strain. The effect of fines content on permanent strain of D-1 materials was insignificant, and this could be due to other factor such as moisture content, aggregate shape, and material source. At subfreezing temperatures, permanent deformation increased with an increase of temperature, especially when the temperature was close to 0°C.

Regression equations were developed to correlate M_R values with the physical properties (moisture and fines contents), stress states, and temperature conditions of D-1 materials. For D-1 materials tested at room temperature, M_R was found to be a function of stress state, moisture, and fines contents. At subfreezing temperatures, M_R was a function of deviator stress, temperature, and aggregate type. The equations were compared with those based on the Long Term Pavement Performance (LTPP) data (Li et al., 2011). Data results and analysis indicated that, for Alaska granular D-1 materials, the M_R model developed was more practical than the LTPP model.

These findings were obtained using an open system in which the material has free access to water during the freezing process. As the open system of water access represents the worst-case scenario for a road structure, it is necessary to investigate the behavior of base course materials under other conditions to complement the existing research and gain an improved understanding of the combined effect of fines content and moisture content on the resilient behavior of D-1 materials.

CHAPTER 3. LABORATORY STUDY

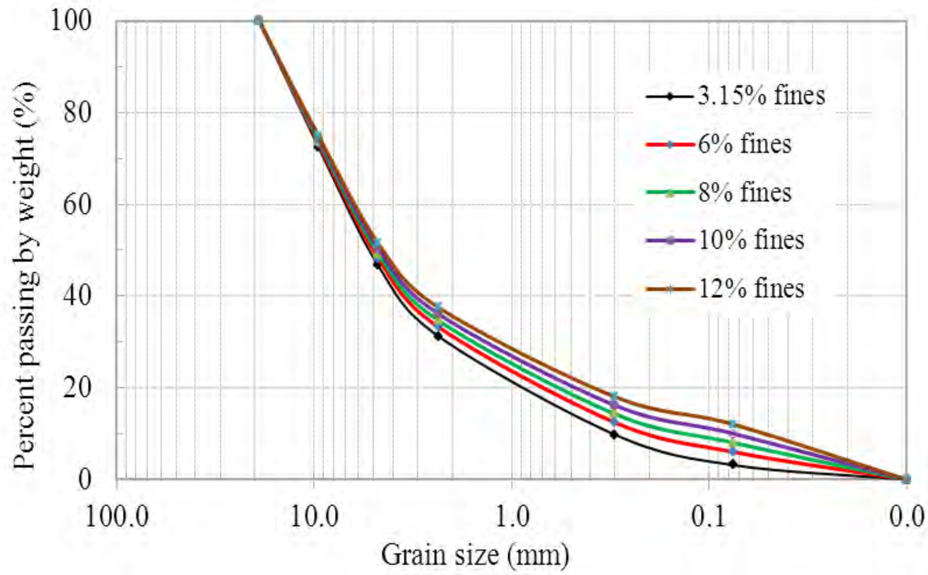
Chapter 3 consists of a description of experimental details related to this study including materials, specimen preparation, and testing program. General aggregate properties such as aggregate gradations, optimal moisture content (OMC), and maximum dry density (MDD) are presented. Preparation of testing equipment and specimens is described, along with the repeated load triaxial tests. These triaxial tests, which comprised the bulk of the test data, were used for calculating and evaluating the seasonal variation of the resilient properties and permanent deformation of D-1 granular base course materials with different fines and moisture contents, temperatures, and freezing temperature gradients.

Materials

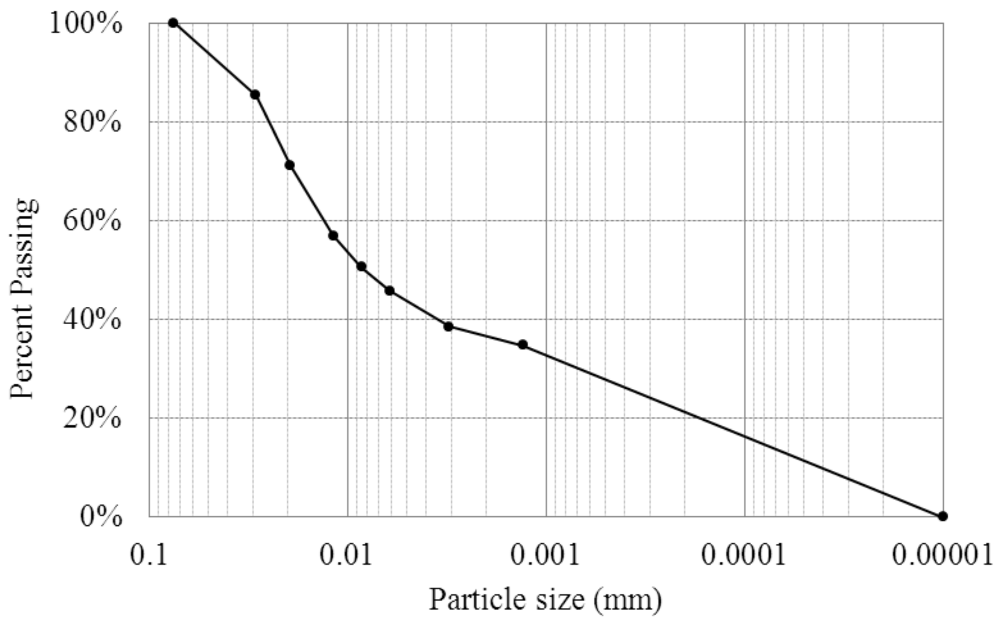
The previous study considered three material types (Northern, Central, and Southeast) during the evaluation of resilient modulus. This study, however, considered one material type: D-1 materials collected exclusively from Alaska's Northern region, as classified by ADOT&PF, and specifically from the same aggregate source used in the previous study.

Gradation

The gradation curves of D-1 materials are presented in Figure 3.1. The reference fines content was 3.15%. However, the minimum fines content used was 6%. This content corresponds to the 6% maximum fines content specified in Alaska's Standard Specifications for Highway Construction (Green, 2004). Higher fines contents of 8%, 10%, and 12% were used to determine resilient properties, with increasing fines content up to twice the specified maximum. This choice was made in accordance with the study objective of evaluating the possibility of increasing the allowable fines content in aggregate design. The gradations as shown in Figure 3.1a for aggregates with 6%, 8%, 10%, and 12% fines contents were obtained by increasing the fines (<0.075 mm) contents in the reference gradation from 3.15% to the target percentages while maintaining proportions of particles with a size greater than 0.075 mm unchanged. The particle-size distribution for D-1 materials less than 0.075 mm (No. 200 sieve) was determined using a hydrometer test (ASTM D422-63) (see Figure 3.1b). For the used D-1 materials with different fines contents, their percentages of particles less than 20 um and 2 um are summarized in Table 3.1.



(a) Gradation curves of D-1 materials



(b) Hydrometer test results on particles less than 0.075 mm

Figure 3.1 Gradation curves of D-1 materials

Table 3.1. Contents of particles less than 0.02 and 0.002 mm in D-1 materials

Fines(<0.075mm)	% less than 20 μm (0.02 mm)	% less than 2 μm (0.002 mm)
3.15%	2.27%	1.14%
6 %	4.33%	2.18%
8 %	5.77%	2.90%
10 %	7.21%	3.63%
12 %	8.66%	4.35%

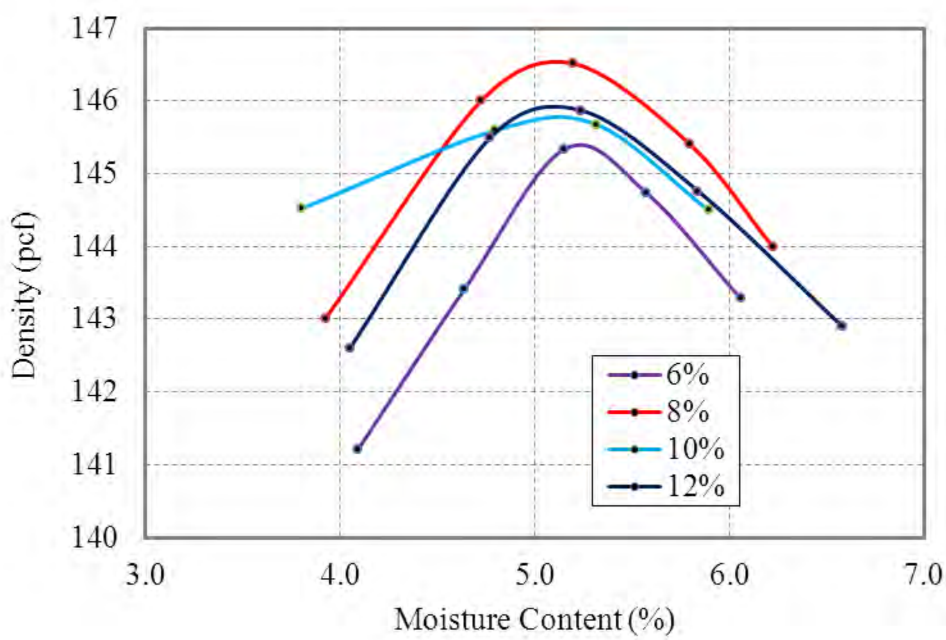
OMC and MDD

To determine the OMC and MDD of D-1 materials, compaction tests were conducted according to ASTM D 1557 Method C (2007). Aggregate specimens were compacted in 5 layers, and each layer was subjected to 56 blows with a 10-pound hammer drop at 18 inches (457 mm). The specimens used were 8 inches in height and 4 inches in diameter according to the M_R test procedure in T307 (AASHTO, 2002). The mechanical compactor used is shown in Figure 3.2.

Figure 3.2 Automatic compactor

The results from compaction testing are presented in Figure 3.3. These results were generally consistent with the results of the previous study, which determined that the MDD for Northern region aggregates ranged from 145 to 150 pcf (depending on fines content). The previous study suggested that MDD increases slightly for increasing fines content. The results from this study showed a similar trend, although current data show a slight decline in MDD for an increase in fines of 8% to 12%. Note that some error in compaction testing resulted from water bleeding off the soil during compaction, especially at lower fines content tested with higher moisture content.

Optimum moisture content as measured from these results is approximately 5.2%. However, in the interest of maintaining consistency with the previous study, and because the difference is within the testing margin of error, this study used an OMC of 5.3%.



Fines content (%)	OMC (%)	MDD (pcf)
6	5.2	145.4
8	5.2	146.6
10	5.2	145.8
12	5.1	145.9

Figure 3.3 Compaction results for D-1 materials

Specimen Preparation

Factors considered to affect the M_R of D-1 materials in Alaska pavements include fines content, temperature, freezing temperature gradient, and moisture content. The laboratory test factorials are summarized in Table 1.1. Four fines contents were used: 6%, 8%, 10%, and 12%. Five different temperatures were used: -5°C, -3°C, -1°C, 20°C, and 20°C after one freeze-thaw cycle. Three different freezing gradients were used: 0.15°C/cm (low), 0.30°C/cm (medium), and

0.45°C/cm (high). The three moisture contents used—3.3% (OMC-2%), 5.3% (OMC), and 6% (OMC+0.7%)—were identical to the moisture contents used in the previous study. The moisture content here was the design moisture content when aggregate blended with water. Moisture content of 6%, which is 0.7% above OMC, was found to be the maximum moisture content that aggregate can hold during compaction.

The design factors used are presented in Table 1.1. Each combination of factors was tested with three replicates. The aggregates with specified gradations were first mixed with water to a specified moisture content, and then compacted using the compactor. For the M_R test at room temperature, the aggregate specimen was covered by a rubber membrane. After covering with a membrane, the aggregate specimen was immediately used for the M_R tests under unfrozen conditions. For M_R tests at subfreezing temperatures, a frost heave cell was designed for the specimen preparation. Aggregate specimens were put into the frost heave cell to perform the frost heave test first. A cylindrical plastic mold was used to hold the specimen during the frost heave test and to provide a barrier between the water bath and the specimen (see Figure 3.4).

Aluminum plates were used to cover the top of specimen molds, and five holes were predrilled along one side of the mold to allow the installation of thermocouples for the duration of frost heave testing, as shown in Figure 3.4. The thermocouples were fixed to the plastic mold using tape, and used to monitor temperatures at different points on the specimen during the freezing process. After installation of the thermocouples, the specimen was ready to be placed into the frost heave cell for the one-dimension frost heave test.

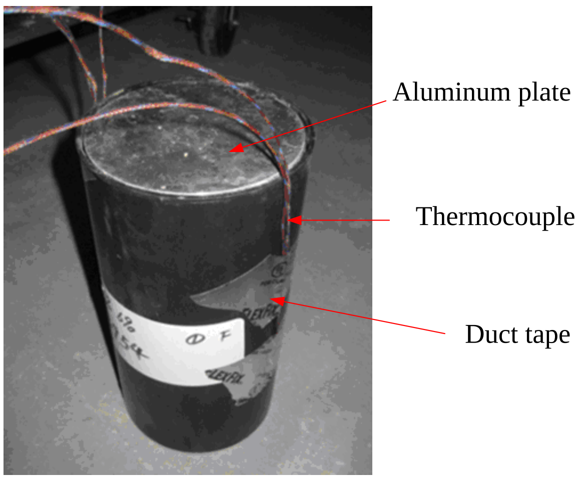


Figure 3.4 Specimen before frost heave test

Testing Program (Setup and Methods)

Frost Heave Test

A frost heave cell was designed and constructed to simulate the natural freezing process. The setup allowed up to eight aggregate specimens to undergo freezing and frost heave testing simultaneously. The testing device allowed specimens to freeze uniaxially. The frost heave tests were performed to generate frozen aggregate specimens for the M_R tests under subfreezing temperatures.

Most of the apparatus and procedures used to freeze the specimens and run the frost heave tests were conducted in a manner identical to the previous study, but two major changes were required because of the difference in this study's design factors.

The first major change was that it was necessary to impose a closed rather than an open system during frost heave testing. In the procedure used for the previous study, the bottom surfaces of the cylindrical molds were opened to the water by removing approximately 50% of the area. Then, to maintain a realistic open system, a porous stone and filter paper were placed at the bottom of the soil specimen to ensure free water intake. In the present study, however, the focus was exclusively on a closed system. To maintain this, a different specimen mold was used. The mold needed to be sealed as much as possible to prevent water from rising into the specimen. Consequently, the porous stone and filter paper elements were discarded, and a solid plastic cylinder with no holes in the bottom was used to hold each specimen during freezing (see Figure 3.5). Once the specimen was placed in the mold and the thermocouples were installed, the entire cylinder was wrapped with tape to ensure a good barrier against water entry from the water bath. In this way, the initial moisture content at compaction remained essentially unchanged throughout the entire freezing process of the specimen.

Figure 3.5 Specimen freezing mold

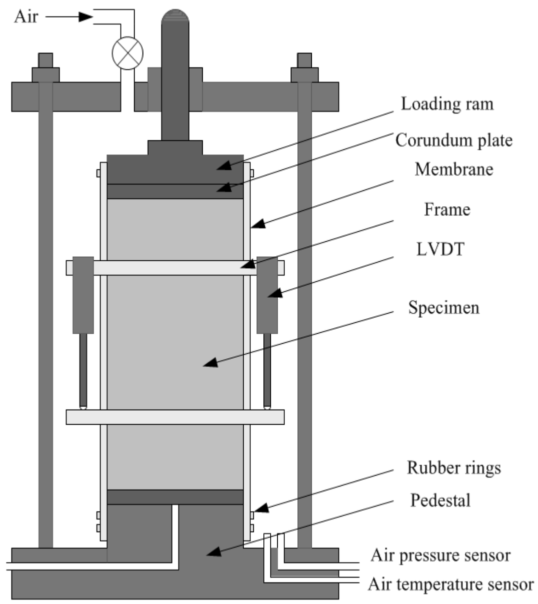
After removal from the water bath and subsequent thorough freezing, the specimens were removed from the molds and wrapped loosely in thin plastic, then covered with a rubber membrane. This procedure guaranteed consistent moisture content throughout testing. Final moisture content after all frost heave and resilient modulus testing was within 0.5% of the original compaction mixture.

The second major change involved varying the freezing temperature gradients. These gradients consisted of “low” (indicating less gradient than that used in the previous study), “medium” (indicating a similar gradient), and “high” (indicating a higher gradient). The water bath temperature was maintained at approximately 1°C for all temperature gradients. Therefore, to achieve different temperature gradients in the specimens, the gradient was adjusted by altering the chamber temperature. The exact gradients used were 0.15°C/cm (low), 0.30°C/cm (medium), and 0.45°C/cm (high), corresponding to chamber temperatures of -2°C, -5°C, and -8°C, respectively. The medium gradient used was similar to the basic gradient of 0.25°C/cm of the previous study.

The frost heave process was complete for each specimen set when the chamber temperature and the temperature of the top of the specimen reached equilibrium. This process took 1 to 3 days, depending on the temperature gradient. Due to the temperature of the water bath (1^{o}C), the bottoms of the specimens in the plastic molds were still unfrozen, and the specimens, therefore, were prone to breakage. To prevent breakage, the specimens were allowed to freeze solid after the gradient was achieved. Freezing was accomplished by placing the specimens into the main chamber for 4 to 8 hours before removing the molds.

M_R Test

As in the previous study, resilient properties were evaluated by using the repeated triaxial test. Figure 3.6 (a) schematically shows the setup for the M_R tests used, and Figure 3.6 (b) shows a photo of the test setup.



(a) Schematic plot

(b) Test setup

Figure 3.6 Repeated loading triaxial test setup

To determine resilient moduli at different subfreezing temperatures, aggregate specimens, after the frost heave test, were conditioned in the environmental chamber to the lowest testing temperature of -5°C. At least 12 hours were spent on this conditioning process to ensure sufficient time for aggregate specimens to reach thermal equilibrium everywhere. After the temperature of aggregate specimens stabilized, specimens were subjected to repeated loading sequences according to AASHTO T307 (2002).

A repeated dynamic haversine loading waveform with a loading duration of 0.1 sec and a rest period of 0.9 sec was used in the M_R test to simulate the passing of one axle over a pavement followed by a period of rest before the next axle in the field, as shown in Figure 3.7. The maximum load is 10 times as much as the constant contact stress, and the difference between them is the deviator stress. Contact stress is defined as the vertical load placed on the specimen to maintain positive contact between the specimen cap and the specimen.

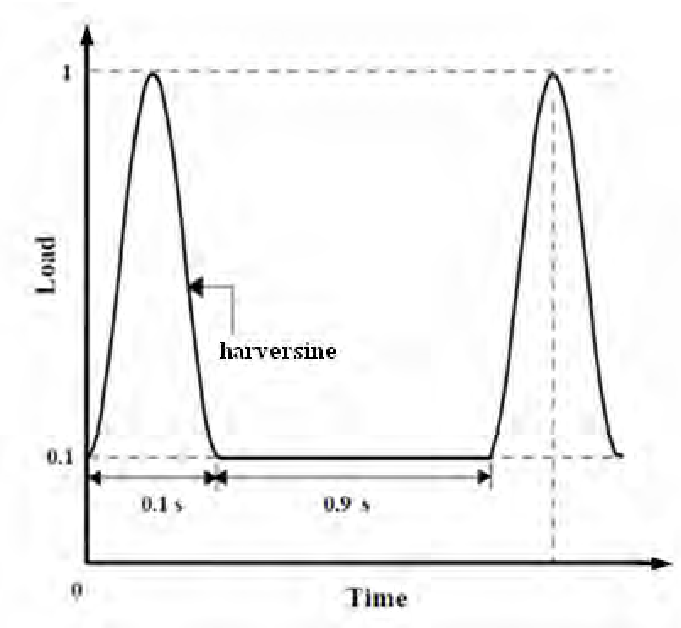


Figure 3.7 Applied load form in M_R test

Preloading was used to reduce disturbances caused by the specimen preparation procedure and to minimize the effects of imperfect contact between end platens and specimen (conditioning sequence in Table 3.2). After conditioning, every loading sequence was repeated 100 times, as long as the permanent strain was within a 5% limit (AASHTO, 2002). The criterion was used for the entire loading history, with confining pressure ranging from 3 psi to 20 psi and deviator stress ranging from 2.7 psi to 36 psi. Table 3.2 shows the loading sequences used. Note that the command values for the deviator stress (listed in Column 3) represent the intended loading programmed into the MTS apparatus. However, because of apparatus limitations, the actual loading measured by the load sensors was normally slightly different from the command load. See an example of loading sequence for deviator stress in column 4 of Table 3.2. To account for this difference, all M_R calculations were computed using the actual deviator stress values rather than the command values.

Table 3.2 Loading sequences used in M_R tests

1	2	3	4	5	6	7
Sequence Number	**Confining Pressure**	**DS (command load)**	**DS (sample actual load)**	**Bulk Stress**	**Contact Stress**	**Loading Applications**
	$\sigma_2 = \sigma_3$ (psi)	**σ_d (psi)**	**σ_d (psi)**	**(psi)**	**(psi)**	
Conditioning	15	13.5	13.71	58.5	1.5	500
1	3	2.7	2.97	11.7	0.3	100
2		5.4	5.85	14.4	0.6	100
3		8.1	8.70	17.1	0.9	100
4	5	4.5	4.97	19.5	0.5	100
5		9	10.78	24	1	100
6		13.5	14.12	28.5	1.5	100
7	10	9	8.53	39	1	100
8		18	19.01	48	2	100
9		27	29.58	57	3	100
10	15	9	8.14	54	1	100
11		13.5	12.93	58.5	1.5	100
12		27	29.82	72	3	100
13	20	13.5	13.52	73.5	1.5	100
14		18	18.10	78	2	100
15		36	35.62	96	4	100

*σ_2, σ_3 = *principal stresses, psi; and* σ_d = *deviator stress, psi.*

To avoid possible leakage and disturbances of the specimens, air temperature was monitored by a thermometer located in the environmental chamber, as well as a thermocouple located inside the triaxial cell. The readings from these devices were then used to determine if the temperature had stabilized at the target temperature. Vertical deformation was monitored by using two linear variable differential transformers (LVDTs), which were mounted on circumferential rings clamped on the specimen. The load was monitored with a miniature load cell located on the loading ram outside the triaxial cell.

The M_R tests were conducted at four temperatures for each of the frozen specimens: -5°C, -3°C, -1°C, and 20°C. This final test determined the resilient modulus after one freeze-thaw cycle. Based on information found in the previous study, the specimens were left to reach thermal equilibrium for 8 to 12 hours between temperature changes before testing was done. This period of thermal equilibrium included the temperature change from -1°C to 20°C. Specimens were kept from losing moisture during the equilibration time. Measurement of specimen weight between cycles, as well as measurement of specimen moisture content when all testing was complete, indicated an average loss of about 0.2% overall moisture content with every temperature cycle, which was considered acceptable.

To obtain resilient modulus data at room temperature without the intrusion of a freeze-thaw cycle, unfrozen specimens were tested in the same way as frozen and thawed specimens.

CHAPTER 4. TEST RESULTS AND ANALYSIS

Chapter 4 presents a summary of this study's results, focusing on frost heave and resilient behavior of tested soils. Test results for resilient modulus behavior for various aggregate combinations were analyzed with respect to a number of influencing factors. Each analysis included both a description of the observed behaviors and a statement of the correlation of general trends for each influencing factor. This analysis determined the overall patterns of aggregate behavior that emerged during testing.

Frost Heave Behavior

The frost heave behavior of D-1 materials from Alaska's Northern region was the subject of study by researchers at Brigham Young University (BYU), in conjunction with project investigators for this study (Homewood and Guthrie, 2012). In the study, the effects of both freezing gradient and aggregate fines content were thoroughly detailed. An investigation of the resilient modulus of soils for different regions provided more data on the frost heave characteristics of aggregate specimens (Li et al., 2010).

In the interest of continuity, an objective of the present study was to gather frost heave data for aggegate specimens before resilient modulus testing in order to compare the data with the results of the previous studies. This section summarizes the data and results found during specimen preparation.

Figures 4.1–4.3 show frost heave curves, in millimeters on the left axis, and the corresponding minimum temperature curve on the right axis. All curves represent the change in frost heave or temperature with respect to time, with initial time representing the positioning of specimens in the freeze chamber. Frost heave curves are given in each case for one specimen, each containing 6%, 8%, 10%, and 12% fines. The minimum temperature curve represents the temperature near the upper surface of each specimen, nearest the air chamber.

Figure 4.1 shows the frost heave of one batch of specimens at 5.3% moisture content (MC) that was subjected to a high freezing gradient. Observe that the temperature at the top reached equilibrium at about -12°C, indicating that in this particular test, the final gradient stabilized at approximately 0.64°C/cm, which was well over the target gradient of 0.45°C/cm and was one of the largest gradients achieved in the frost chamber.

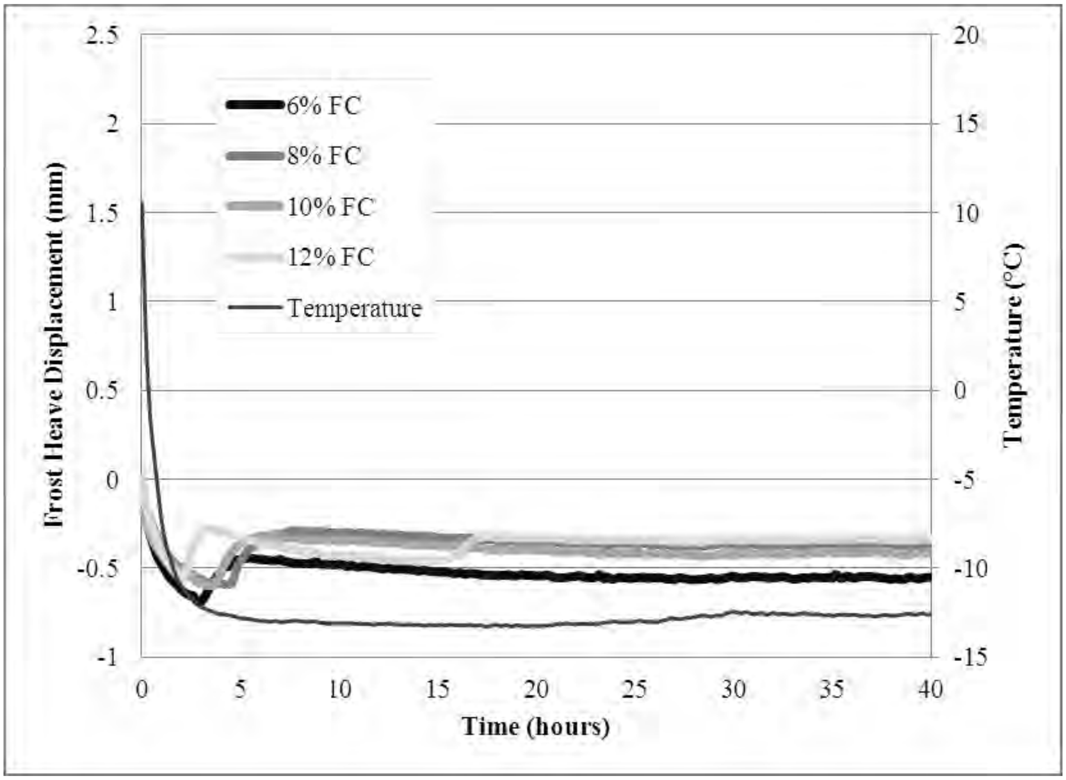


Figure 4.1 Frost heave curves (high gradient, MC = 5.3%)

Figure 4.1 indicates that specimens had a general tendency to decrease in volume over time when exposed to a high freezing gradient. The consequent shrinkage was about 0.2% for all fines contents. Initial freezing of the top layer of soil was very rapid, with this layer reaching equilibrium with the air temperature after approximately 5 hours. The initial decrease in height ($t < 3$ hours) was followed by a slight but abrupt recovery in height. This recovery began more quickly for specimens with higher fines contents. After this spike in height, all specimens reverted to a slow but continuous decrease in height until thermal equilibrium was reached throughout the specimens.

Figure 4.2 shows the frost heave of one batch of specimens at 3.3% moisture content that was subjected to a medium freezing gradient. In this case, the equilibrium temperature was about -5°C, indicating a final gradient of 0.29°C/cm that essentially matched the target gradient of 0.30°C/cm for a medium gradient.

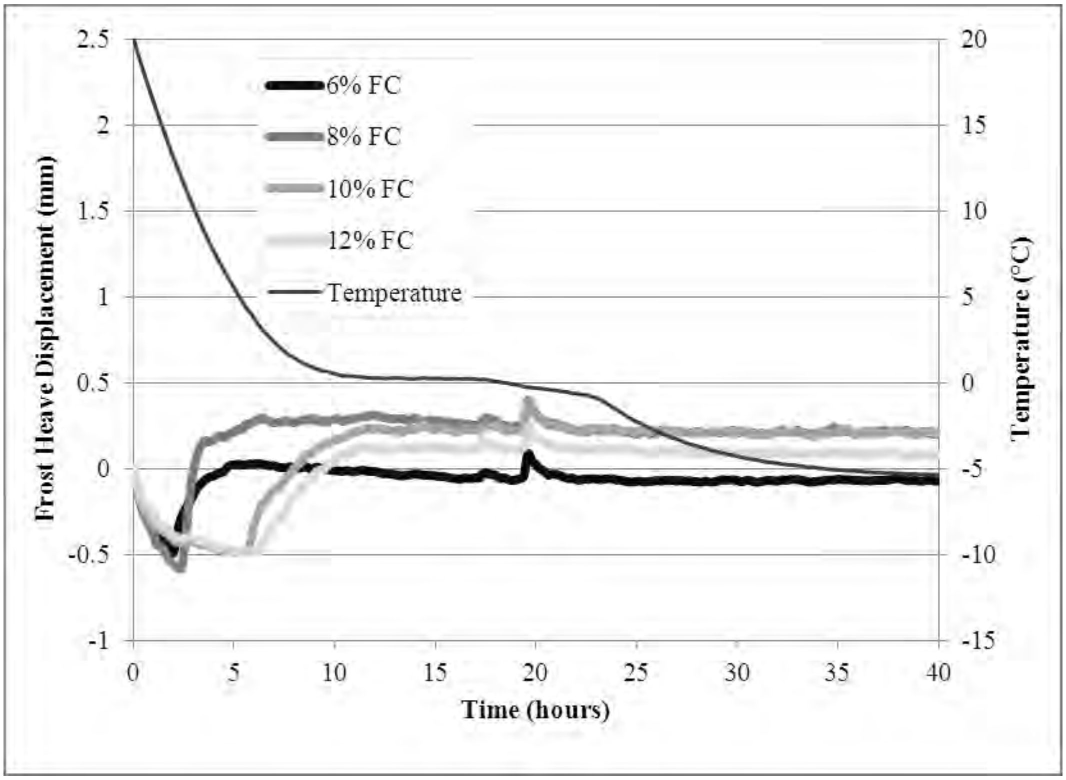


Figure 4.2 Frost heave curves (medium gradient, MC = 3.3%)

Figure 4.2 shows an overall trend towards increased volume at a medium freezing gradient, and thus positive frost heave. However, note that the specimen containing 6% fines decreases very slightly in height, as opposed to the other three specimens, all of which showed some increase. In general, the frost heave ranged from 0 to 0.15%, indicating relatively insignificant frost heave at this gradient for specimens at low moisture content.

Figure 4.3 shows the frost heave of one batch of specimens at 3.3% moisture content that was subjected to a low freezing gradient. The equilibrium temperature of -2.5°C indicates a freezing gradient of about 0.17°C/cm, which once again was very close to the target gradient of 0.15°C/cm for a low gradient.

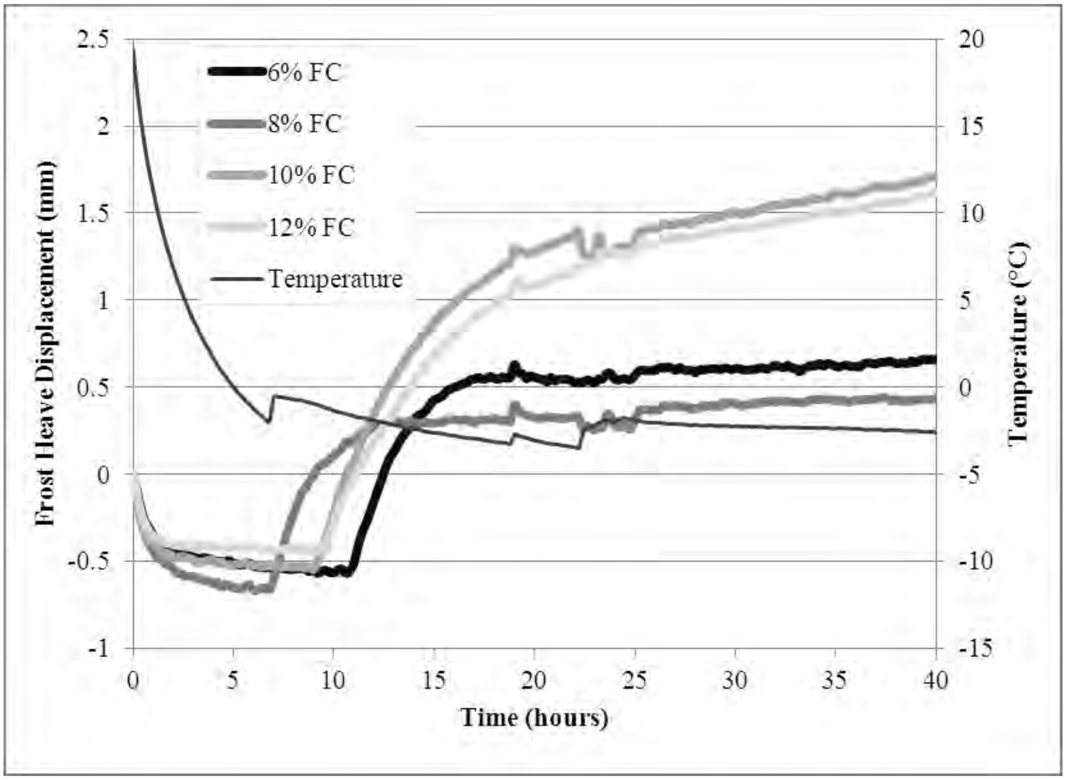


Figure 4.3 Frost heave curves (low gradient, MC = 3.3%)

Note that Figure 4.3 shows specimen volume increasing much more than that of specimens in the previous two figures. Here, there is an increase in height of about 0.2% for 6% and 8% fines, and about 0.8% for 10% and 12% fines. While very small, these increases show that there was a definite tendency for soil volume to increase when frozen slowly in this manner. Indeed, even after 40 hours, some soil particles remained unfrozen, causing a continuing heave as moisture in the pore spaces froze and increased in volume. This effect was greater at higher fines contents.

In the graphs above, data for the curves are obtained from a single freezing cycle for each graph, and hence are not adjusted for variation during different cycles. Some data for other gradient and moisture content combinations were collected during testing, but because of errors in the testing apparatus, this data proved difficult to reconstruct and are not presented here.

Figures 4.1–4.3, taken together, indicate that frost heave increased with decreasing freezing gradient. At high freezing gradients, specimens experienced slight shrinkage during freezing, rather than expansion. At medium freezing gradients, specimens expanded slightly, about 0.1–1.5% of total height. At low freezing gradients, specimens expanded more noticeably, by approximately 0.5–2.0% of total height. Despite the increase in expansion, no increase greater than 3% was observed in the data collected, indicating that frost heave was relatively insignificant in all cases.

Nevertheless, freezing gradient was a major factor in the magnitude of frost heave that was observed. Since freezing was conducted in a closed system, both fines content and moisture content remained constant throughout the freezing process. Analysis of the frost heave data indicated that in many cases, the differences in frost heave between specimens of identical fines and moisture contents were equal to or greater in magnitude than the differences among specimens of varying fines and moisture contents. Thus, the isolated effect of temperature gradient on frost heave was usually more significant than the effects of fines content and moisture content.

To determine the progression of the freezing front within the specimens, temperature data were collected by thermocouples attached at each of 5 points from top to bottom of each specimen. Thermocouples are numbered from 1 at the bottom to 5 at the top. Figures 4.4–4.5 illustrate typical continuous temperature data collected in this manner during the freezing process. Temperatures are displayed for each of the 5 thermocouple points on a single specimen, from bottom to top. Observe that the temperature curves are upside down with respect to specimen orientation, since the top of the specimen is the coldest zone.

Note that in Figure 4.4, the top thermocouple (number 5) reaches approximately -3.5°C, while the bottom thermocouple (number 1) reaches a point just below freezing. The difference between these readings indicates a low freezing gradient. By contrast, as shown in Figure 4.5, the high freezing gradient caused the entire sample to freeze by the end of the 40-hour testing period. To determine the actual value of the gradient, it is necessary to observe the temperature differential between thermocouples 1 and 5 at the point where 1 crosses the 0°C point, for this represents the point at which the bottom surface is just beginning to freeze. In this case, the gradient is approximately 12° over the length of the specimen, placing it at the upper end of the high gradient range (0.4–0.6°C/cm). The low and high gradients shown here represent the outer boundaries of testing, since the previous study focused entirely on medium gradients.

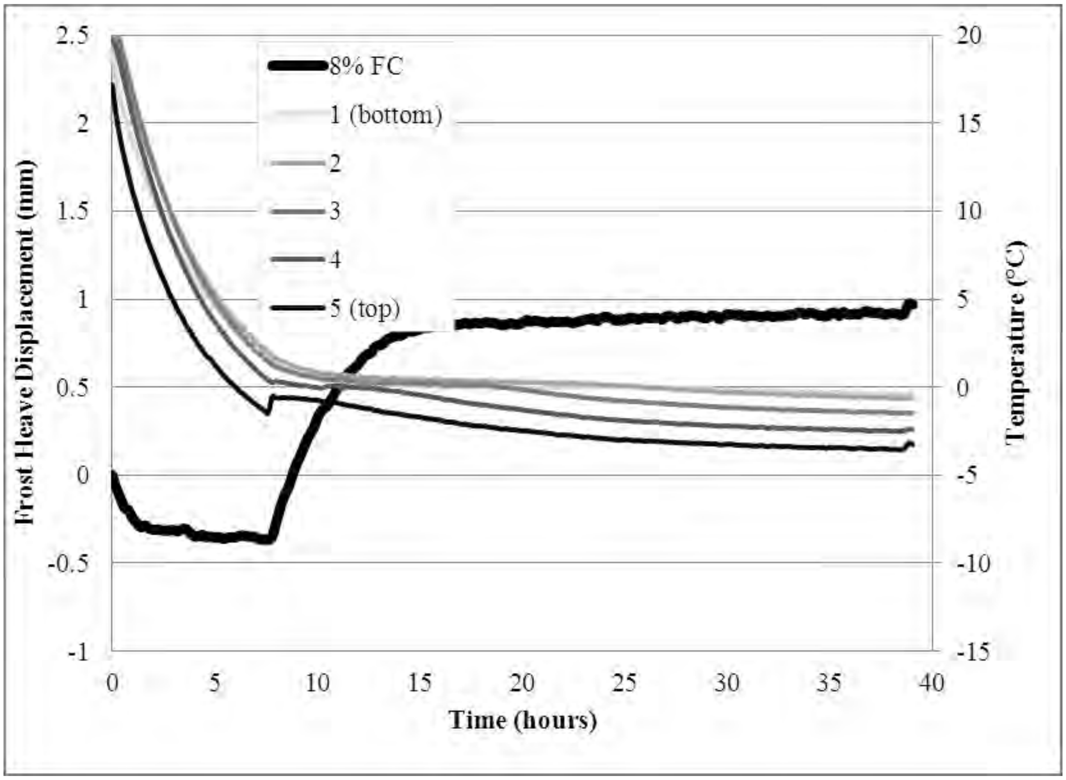


Figure 4.4 Temperature curves for single specimen (low gradient, MC = 5.3%)

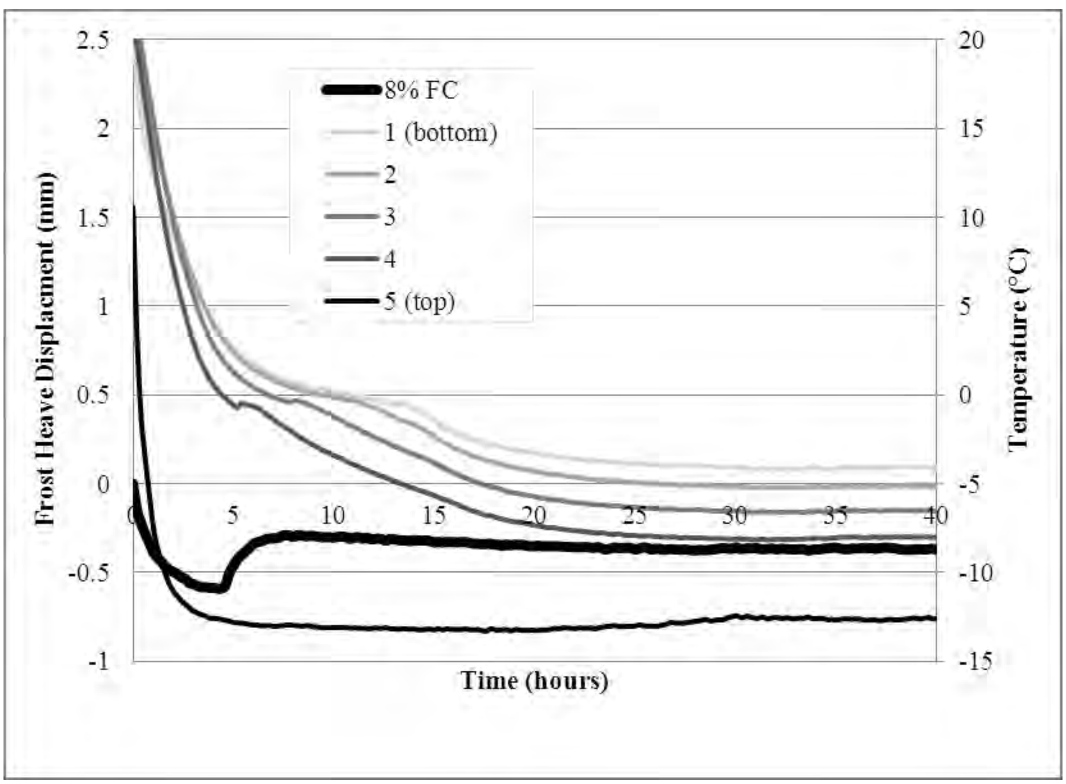


Figure 4.5 Temperature curves for single specimen (high gradient, MC = 3.3%)

As shown in Figure 4.4, for specimens subjected to a low freezing gradient, freezing progressed at a relatively constant rate down through the specimen; this allowed for maximum development of frost heave, since the pore spaces froze evenly and expanded continuously. The high freezing gradient, on the other hand, caused the upper surface of the specimen to freeze rapidly. This finding agrees with the findings of the BYU study (Homewood and Guthrie, 2012, pp. 32–35), that higher freezing gradients tend to impede the formation of ice lenses and thus result in less frost heave.

To understand the behavior of soil during the freezing process, a brief investigation of the characteristics of freezing soil is necessary. Figure 4.6 conceptualizes a soil specimen, seen in cutaway view from the side. It is exposed to freezing temperatures at the top but not the bottom, similarly to the actual specimens frozen in the frost heave chamber.

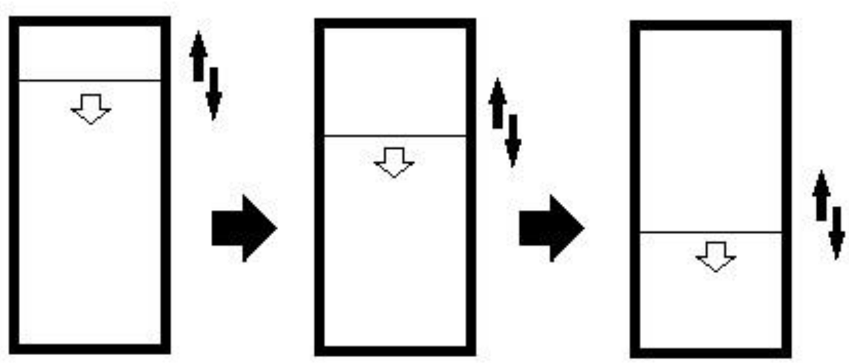


Figure 4.6 Downward progression of freezing front in soil specimen

As the freezing front progresses downward in unsaturated soil, water changes from the liquid state to the solid state, thereby increasing in volume by about 9%. However, this volume increase in moisture is not immediately reflected in the soil particles. The effect of this freezing on the soil particles depends on a number of factors.

Most importantly, the speed with which the frost front moves in the soil has a noticeable effect on the soil particles through which it is moving. This speed is directly related to the freezing gradient, since a higher freezing gradient creates a freezing front that moves more rapidly through the soil. Therefore, the speed of this movement directly impacts the frost heave, as seen in Figure 4.6.

A rapidly moving freezing front in unsaturated soil causes particles of moisture to freeze in situ quickly, which, in turn, forces the unfrozen moisture directly at the freezing boundary away from the freezing front. These conditions result in a loss of moisture from the area being frozen and, hence, a reduction in volume as part of the moisture escapes into the unfrozen pore spaces beneath. This moisture redistribution can be considerable, depending on the speed of the freezing front, and is responsible for the overall reduction in soil height seen for specimens frozen at a high freezing gradient, as shown in Figure 4.1. Furthermore, observe from the initial soil shrinkage in all specimens in Figures 4.1–4.3 that this shrinking process occurs during initial freezing for any freezing gradient, because the temperature of the specimen top drops drastically with respect to the rest of the specimen when the specimen is placed in the frost heave chamber.

A slowly moving freezing front, on the other hand, allows moisture to accumulate and freeze in the pore spaces, which allows the moisture to reach its full expansion. Thus, the frozen soil volume increases as the volume of the moisture increases. Note in Figure 4.3 that specimens frozen at a low freezing gradient expanded by the largest amount after their recovery from initial shrinkage.

In general, as the freezing front continues to move downward through the soil specimen, various behaviors will be observed, depending on the speed of the freezing front, the soil porosity, and the amount of free moisture in the soil. If the moisture redistribution during freezing is considerable, local expansion may occur in a specimen that experiences overall shrinkage, or vice versa. If the soil is saturated, or nearly saturated, more moisture redistribution will take place and the soil will experience greater frost heave than if it is drier. Increasing fines contents decrease the porosity of the soil, increase the ability of soil to absorb water, and cause soil expansion to be larger for a given amount of moisture expansion in a particular soil zone.

In summary, this study found that the behavior of aggregate specimens in a closed system when subjected to freezing was influenced chiefly by freezing gradient. Fines content played a secondary role. However, because moisture was not allowed to enter the specimens during freezing, the heaving values observed during this study were much smaller than the heaving values observed in the open system of the previous study (Li et al., 2010) and the BYU study (Homewood and Guthrie, 2012). Indeed, the frost heave became relatively insignificant for the moisture contents used. In a closed system, therefore, the aggregates only became frost-susceptible when subjected to low freezing temperature gradients, which allowed the slowest movement of the frost front and consequently the greatest expansion.

Resilient Behavior

A number of material and freezing characteristics influence the resilient behavior of aggregates. This report considers the major factors found to significantly affect resilient behavior: moisture content (MC), fines content (FC), temperature, stress state, freeze-thaw cycles, and freezing temperature gradient. With the exception of temperature gradient, each of these factors was considered in Li et al. (2010, p. 45). This study further investigates the behavior and interrelationships of these factors.

Moisture Content

Moisture content was found to be the factor that most affects the resilient modulus of soils. This finding is consistent with the results of the previous study (Li et al., 2010, p. 45).

As discussed in Li et al. (2010), specimens were tested at three different moisture contents: 3.3%, 5.3%, and 6%. Specimens tested at a moisture content of 6% failed during every testing attempt, regardless of whether they had undergone a freeze-thaw cycle and regardless of fines content. As a result, data for resilient moduli at 20°C for moisture content above 6% are unavailable.This limitation underscores the importance of low moisture content to the resilient modulus of a soil.

Figures 4.7–4.10 illustrate the resilient moduli of unfrozen soils containing 6%, 8%, 10%, and 12% fines content by comparing low (3.3%) and optimum (5.3%) moisture contents, repectively. Note that each deviator stress was associated with a certain confining pressure. The five levels of confining pressure are shown across the upper axis, while the corresponding levels of deviator stress are shown on the lower axis.

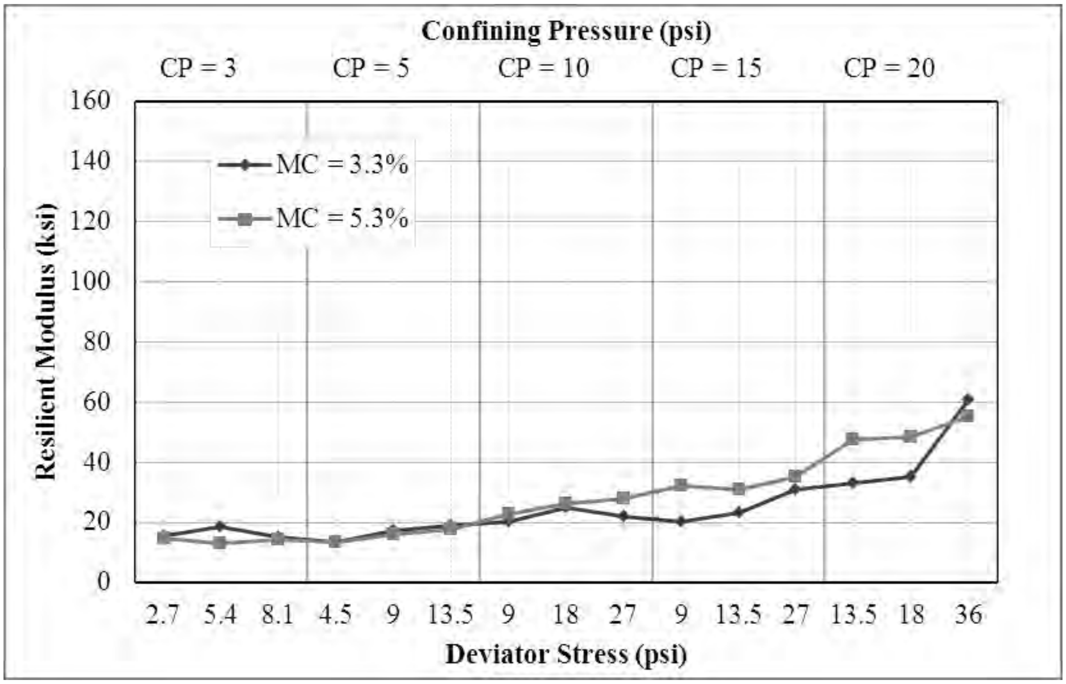


Figure 4.7 M_R at varying moisture contents (FC = 6%, 20°C)

Figure 4.7 shows typical test results for soil specimens containing 6% fines. At both moisture contents, the resilient modulus of the soils increased with confining stress. Under most conditions, resilient modulus increased with the increase of deviator stress. Under a few cases, resilient modulus either first increased (hardening) and then decreased (softening) or first decreased and then increased, with an increase in deviator stress. However, the changes were very small and could be related to experimental errors.

It is difficult to isolate significant differences in the resilient moduli of the two moisture contents. The change in resilient modulus as moisture content increases from 3.3% to 5.3% is relatively small. At low deviator stresses and confining pressures, the resilient moduli at two moisture contents are essentially identical. At higher deviator stresses, corresponding to confining pressures of 10–15 psi, the specimens with higher moisture content developed a slightly higher modulus than did the drier specimens. Only at high stresses is there a decrease in resilient modulus with increasing moisture, which is less than 15% of the resilient modulus of the drier specimens.

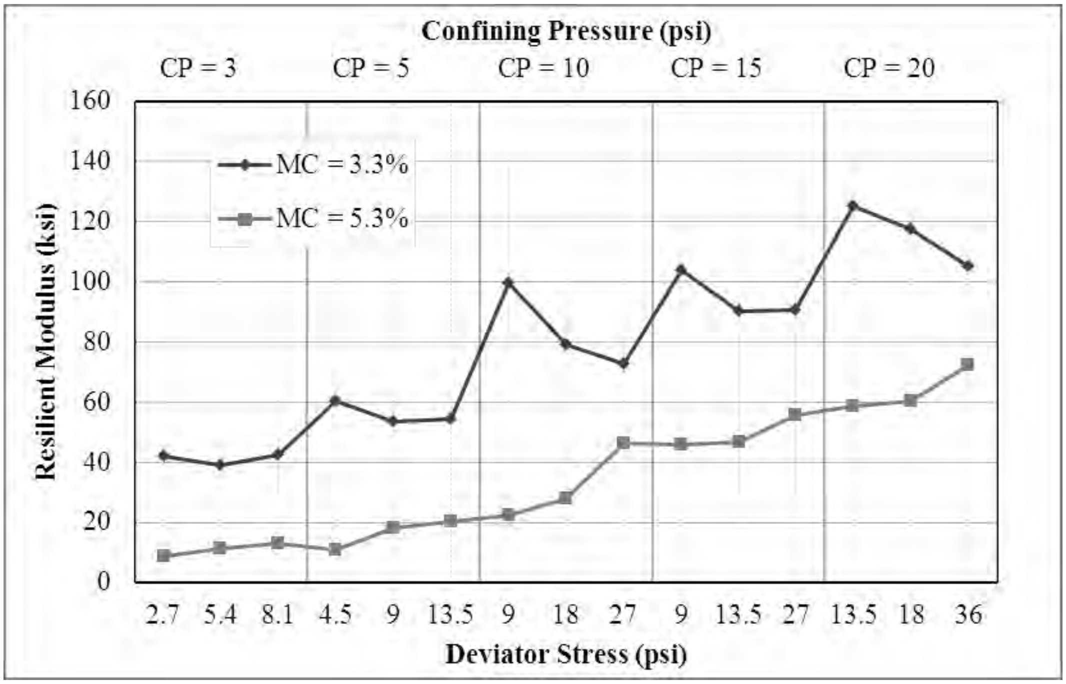


Figure 4.8 M_R at varying moisture contents (FC = 8%, 20°C)

Figure 4.8 shows typical test results for soil specimens containing 8% fines at different moisture contents. It is clear that the drier soil specimens had a higher resilient modulus than the wetter specimens did. At both moisture contents, the resilient modulus of the soils increased with confining stress. For soil specimens with 3.3% moisture content, resilient modulus decreased with an increase in deviator stress at a constant confining pressure. However, for soil specimens with 5.3% moisture content, resilient modulus increased with an increase in deviator stress at a constant confining pressure. There is a marked decrease in resilient modulus when moisture content is higher. In every case, the decrease is approximately 30 ksi, representing a 30–75% loss in modulus, depending on the level of deviator stress.

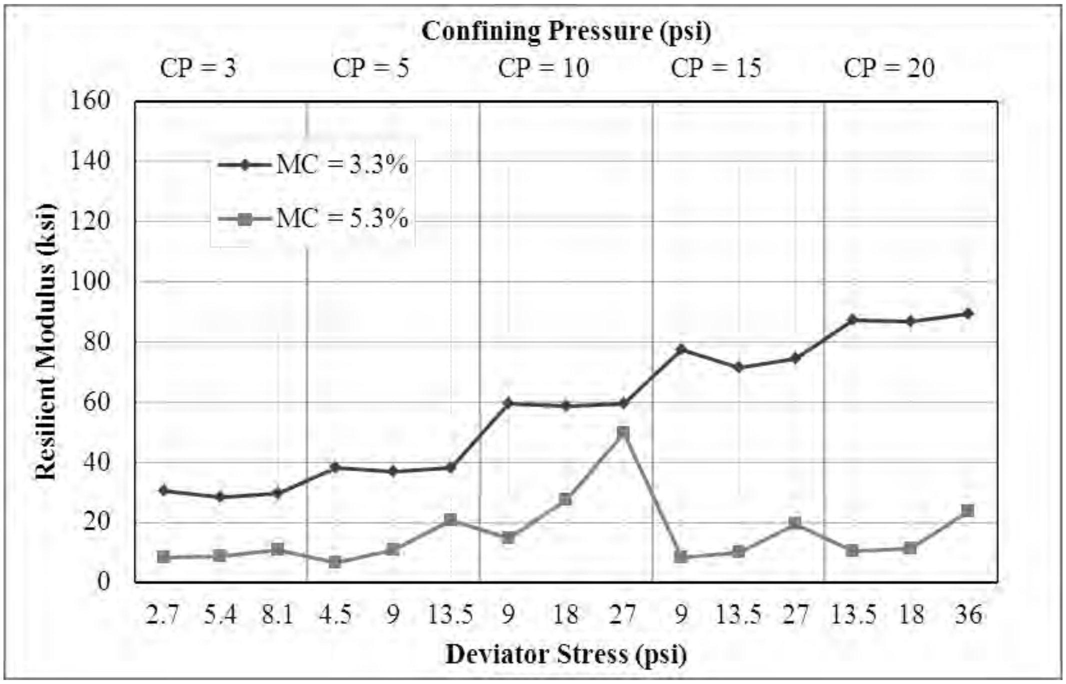


Figure 4.9 M_R at varying moisture contents (FC = 10%, 20°C)

Figure 4.9 shows typical test results for soil specimens containing 10% fines at 3.3% and 5.3% moisture contents. Similar to the previous two figures, the drier soil specimens (3.3% moisture content) always had higher resilient modulus than wetter specimens did. At both moisture contents, the resilient modulus of the soils generally increased with confining stress. However, for soil specimens with 5.3% moisture content, there was a significant decrease in resilient modulus when the confining pressure increased from 10 to 15 psi. This is not reasonable since soils are frictional materials and an increase in confining pressure should have caused a hardening effect, which means an increase in resilient modulus with increase in confining pressure. The unexpected decrease in resilient modulus at confining pressure of 15 psi seems to imply a localized failure or defects in the soil specimen.

For soil specimens with 3.3% moisture content, the resilient modulus first decreased and then increased with an increase in the deviator stress at a constant confining pressure. The variations, however, were very small or negligible. For soil specimens with 5.3% moisture content, the resilient modulus increased with an increase in deviator stress at a constant confining pressure.

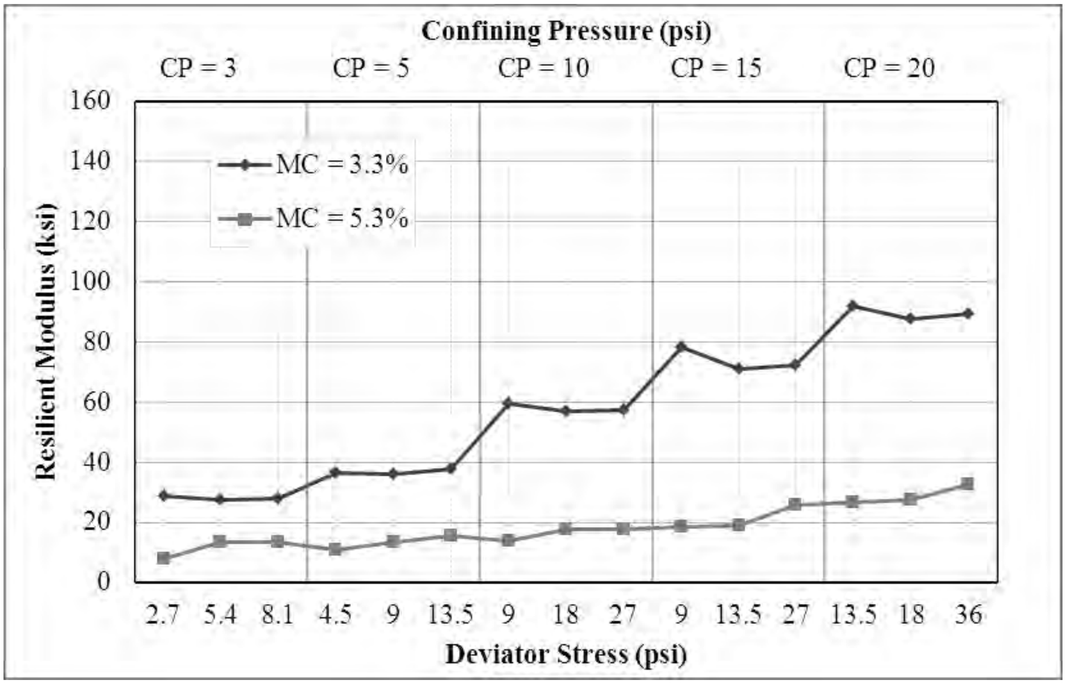


Figure 4.10 M_R at varying moisture contents (FC = 12%, 20°C)

Figure 4.10 shows typical test results for soil specimens containing 12% fines at 3.3% and 5.3% moisture contents. Resilient moduli of the drier soil specimens (3.3% moisture content) were always 200–300% higher than were soil specimens with 5.3% moisture content. At both moisture contents, the resilient modulus of the soils increased with confining stress. For soil specimens with 3.3% moisture content, the resilient modulus slightly decreased with an increase in deviator stress at a constant confining pressure. However, for soil specimens with 5.3% moisture content, the resilient modulus increased with an increase in deviator stress at a constant confining pressure.

Based on these observations, this study finds that for unfrozen soils with fines content of 8% and above, the resilient modulus decreases as moisture increases. As moisture content increases from 3.3% to 5.3%, the resilient modulus decreases to 75%. Higher losses accompanied the application of higher deviator stresses. This finding agrees with the findings of the previous study. For 6% fines, however, this study found no significant loss of resilient modulus with increased moisture, which can be explained by the effective stress in unsaturated soils, using Bishop's equations: $\sigma' = \sigma + \chi s$. For the same soil, the drier the soil is, the higher the suction. Consequently, the effective stress in the soil is higher, which caused a higher resilient modulus. The χ factor is usually small for granular materials with less fines than those with more fines. Consequently, if the fines content of the soil is small, the effect due to soil suction is not as significant.

Fines Content

Determining the impact of fines content was one of the priorities of this study. A different range of fines was used, in which the 3.15% fines used as the reference in the previous study was removed and 12% fines was substituted, fully doubling the current maximum fines content of 6% specified by ADOT&PF. Figures 4.11 and 4.12 show the resilient modulus of unfrozen specimens with various fines contents at moisture contents of 3.3% and 5.3%, respectively. As mentioned above, values for soil specimens with 6% moisture content are unavailable at this temperature.

Figure 4.11 indicates that at all confining pressures and deviator stress levels, resilient moduli were the smallest when the fines content was 6%. Resilient modulus peaked when the fines content was 8% and then decreased when fines content decreased to 10%. There was no visible difference in resilient modulus between soils with 10% and 12% fines contents. Figure 4.11 also indicates that for soil specimens with 3.3% moisture content, the resilient modulus increased with the increase of confining pressure.

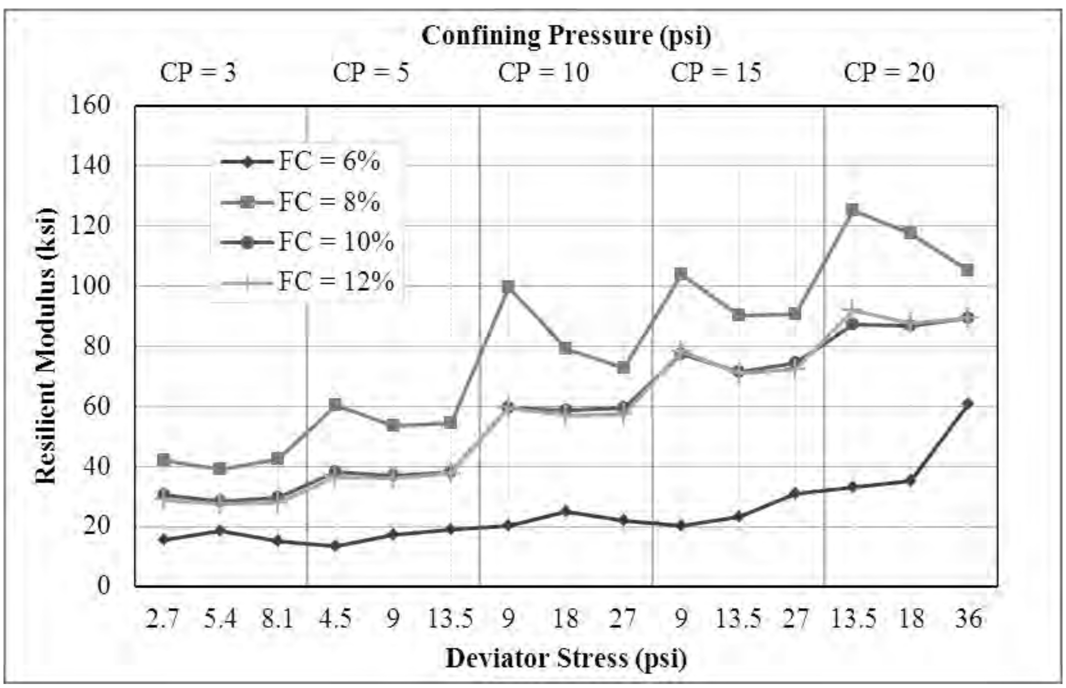


Figure 4.11 M_R at varying fines contents (MC = 3.3%, 20°C)

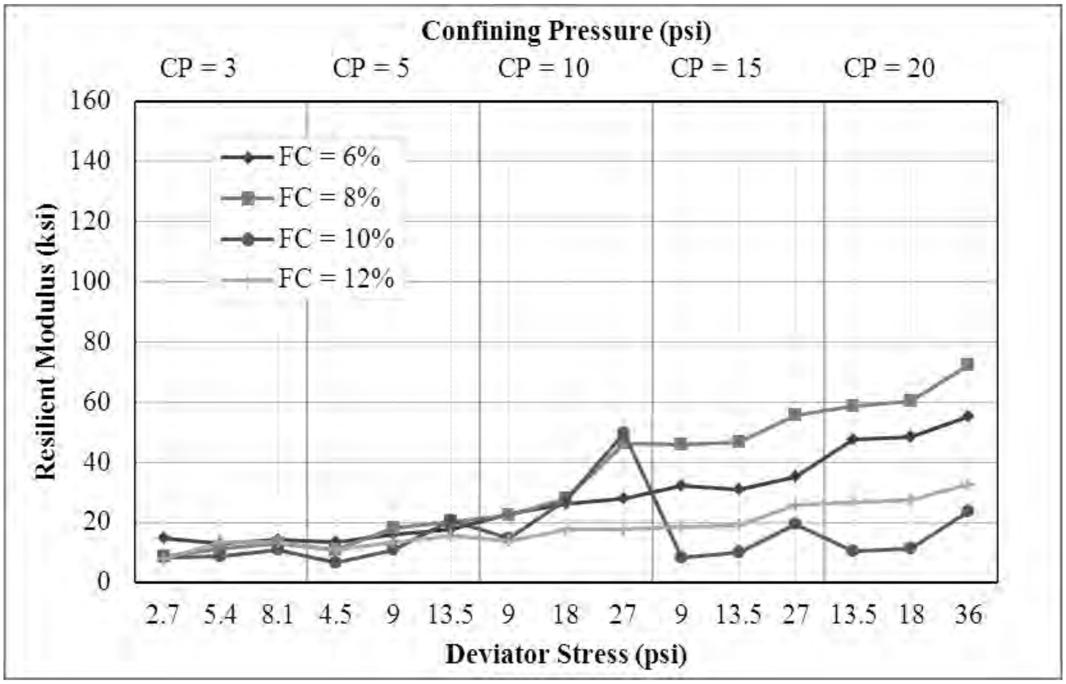


Figure 4.12 M_R at varying fines contents (MC = 5.3%, 20°C)

As observed in the previous study, it was found that the impact of fines content varied somewhat depending on moisture content. Specifically, for low moisture content, resilient modulus increases significantly with fines content, but for optimum moisture content, this increase is much less.

For both moisture contents, this study found that 8% fines content generally produces the highest resilient moduli for unfrozen specimens at room temperature, which further agrees with the conclusion of the previous study. Additionally, the resilient modulus of specimens containing 10% and 12% fines generally decreased relative to the resilient modulus of specimens containing 6% fines with increasing deviator stress and confining pressure. Based on this information, a slightly higher fines content than 6% may be optimum.

Temperature

The resilient modulus of aggregate materials containing moisture is heavily influenced by temperature. As presented in the previous section, moisture has a detrimental effect on resilient modulus at temperatures above freezing. This effect is largely due to the lubricating action of water interacting with soil particles. Conversely, at sub-freezing temperatures, soil moisture becomes ice and contributes to the resilient modulus of the aggregate. With sufficient moisture and cold, aggregates can behave essentially as solids because of the network of ice crystals interlocking the particles.

Figures 4.13–4.15 contain the entire distribution of data at various moisture and fines contents and the mean value of the distribution at each temperature (-5, -3, -1, and 20°C). The distributed values are shown in gray, and the mean values, which represent the overall trend, are shown as black diamonds.

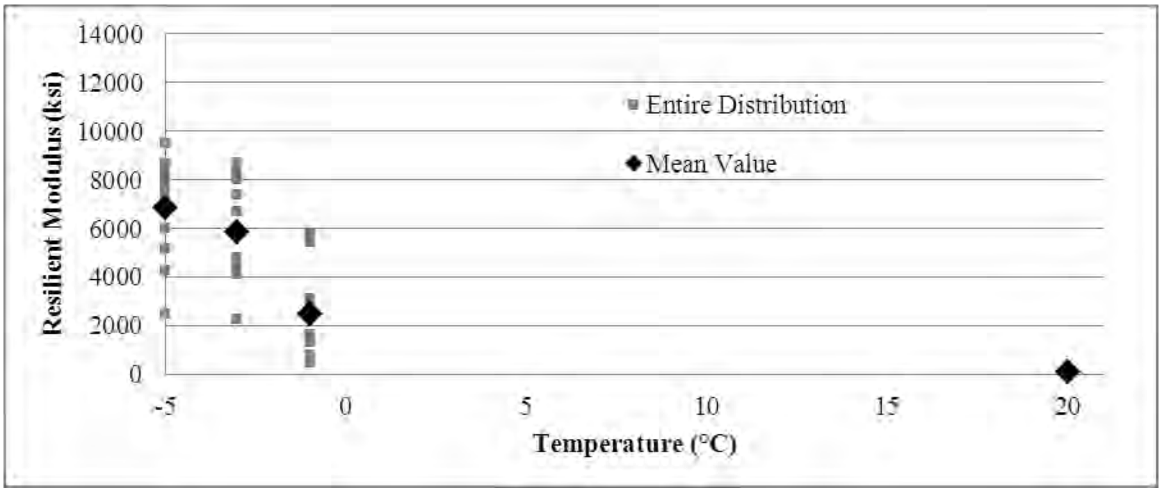


Figure 4.13 M_R vs. temperature distribution (low gradient)

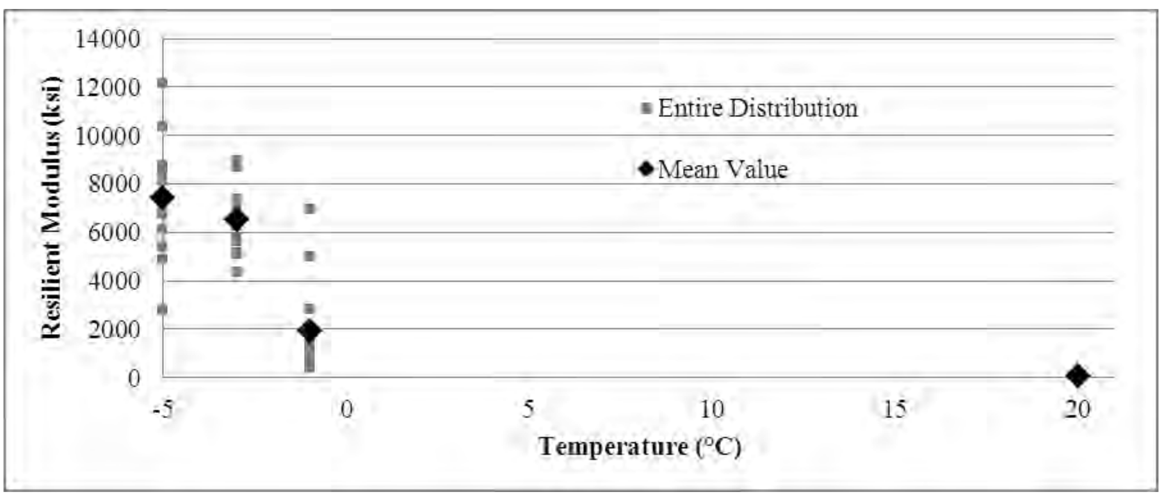


Figure 4.14 M_R vs. temperature distribution (medium gradient)

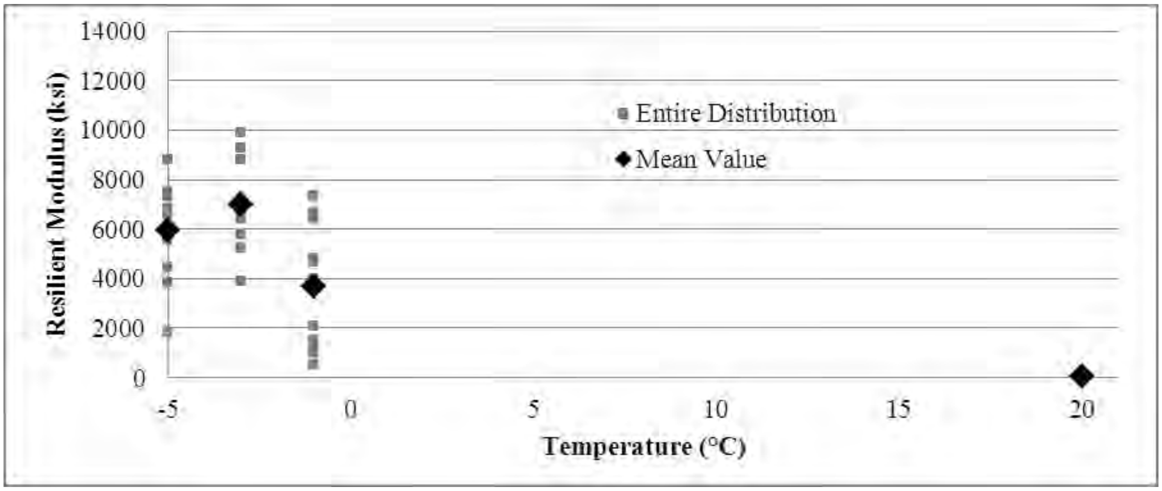


Figure 4.15 M_R vs. temperature distribution (high gradient)

In all three figures, the mean resilient modulus is relatively small for specimens tested at 20°C. As shown in the section on moisture content, no value at that temperature exceeded 120 ksi. By contrast, the mean values for specimens tested well below freezing are much higher. Observe that the mean values at -5°C and -3°C range from 6000–8000 ksi, and no values at those temperatures are below 2000 ksi. Since -1°C is a transition temperature for aggregates, where they contain both liquid water and ice crystals, resilient modulus values for this temperature dropped considerably, with mean values ranging from 2000–4000 ksi. Furthermore, some of the individual data points for high moisture content at this temperature approach the 100–500 ksi range.

For low and medium freezing gradients, specimens had the highest resilient modulus at -5°C, with subsequent increasing temperatures reducing the resilient modulus in a curvilinear manner. The mean value decrease in resilient modulus was in the range of 15% for a temperature increase of -5° to -3°C, and in the range of 60% for a temperature increase of -3° to -1°C. These ranges correlate with the findings of the previous study. For high gradients, a mean value increase in resilient modulus of about 15% was seen with a temperature increase of -5° to -3°C, followed by a decrease of about 45% with a temperature increase of -3° to -1°C. A possible reason for this change in behavior for high freezing gradient will be discussed in the section on Temperature Gradient.

Stress State

Stress state is another important factor known to affect the resilient properties of aggregate. The effect of stress state on the specimens was influenced by all the factors previously discussed, but depended particularly on temperature. As described earlier, soil behaves essentially as a solid at cold temperatures, but as soil temperature rises, approaching the freezing point and thus warmer temperatures, soil regains its aggregate properties.

For soils with higher fines content at low temperatures, the resilient modulus was found to be linearly related to deviator stress on the soil, as shown in Figure 4.16. The effects of freezing gradient and moisture content were minimal.

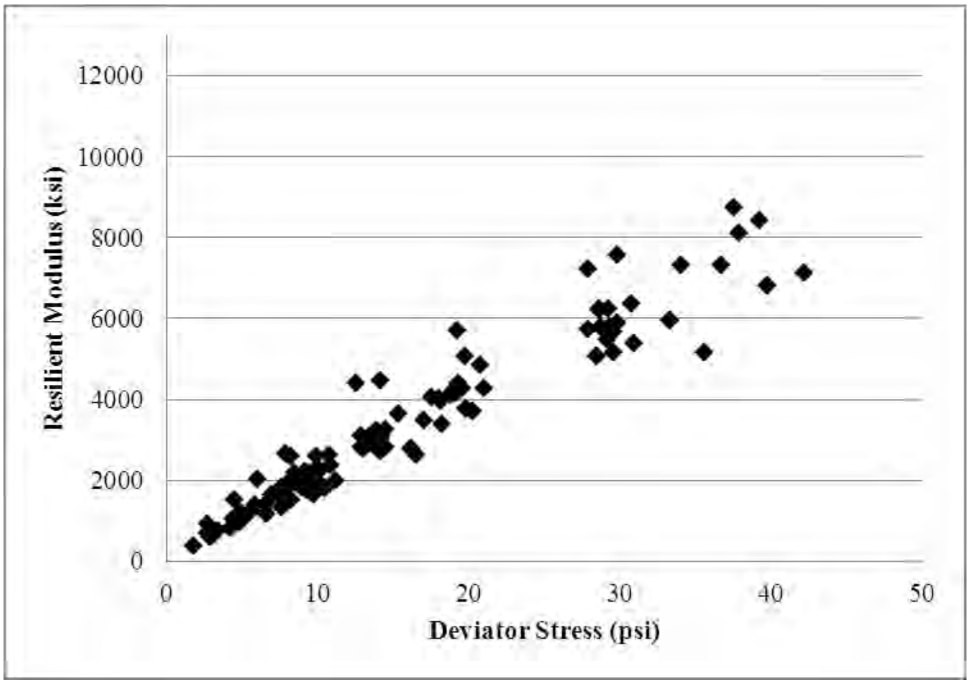


Figure 4.16 M_R distribution for FC = 12% at -5°C

For soils at lower fines content, an increase in resilient modulus was observed as moisture content increased to the optimum moisture content, as shown in Figures 4.17 and 4.18. Furthermore, higher resilient modulus was achieved for 6% fines contents than for 12%, as higher values were obtained for high moisture content (Figure 4.18).

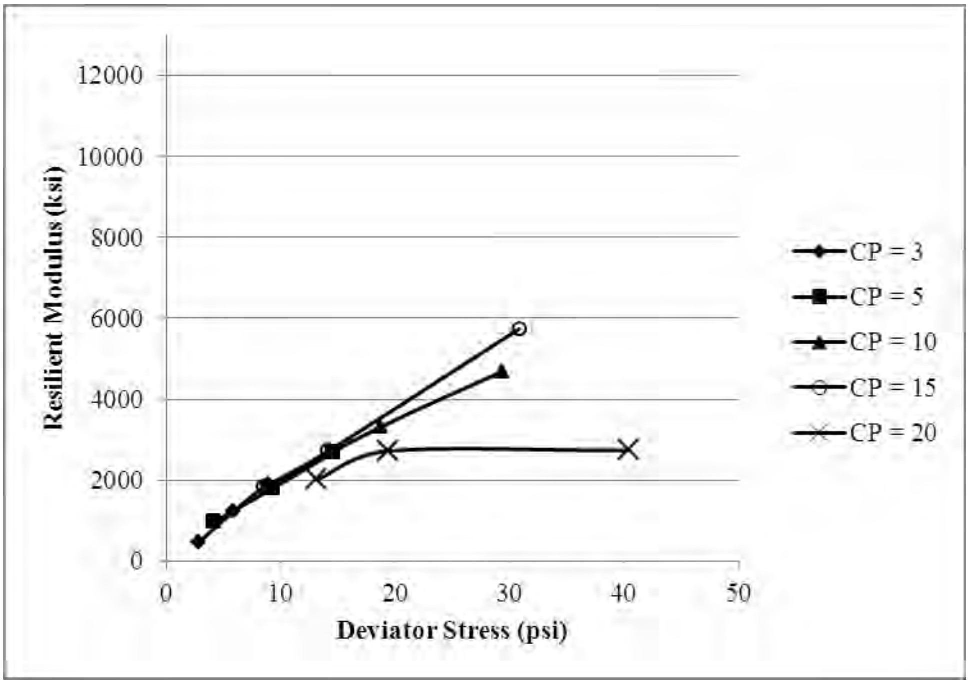


Figure 4.17 M_R for FC = 6%, MC = 3.3%, medium gradient, -5°C

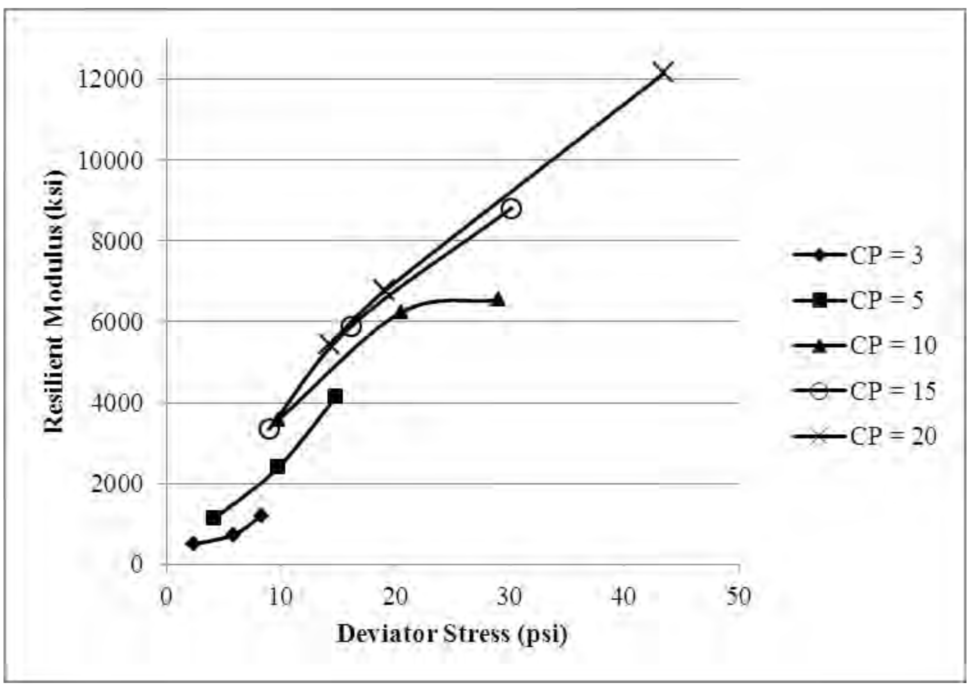


Figure 4.18 M_R for FC = 6%, MC = 6%, medium gradient, -5°C

For these soils, it is apparent that confining pressure is less important than deviator stress, since many of the confining pressure trends overlap. To understand these results, it is necessary to investigate the structure of moist soil when fully frozen. Figure 4.19 presents the structure of a compacted D-1 soil specimen in a fully frozen state at -5°C.

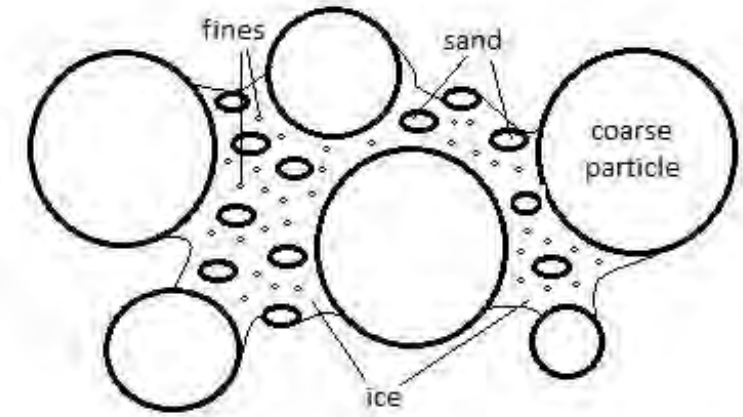


Figure 4.19 Soil particles at -5°C

At low temperatures, because ice is the major bonding material, the major factor in the soil resilient modulus is the amount of ice present in the soil structure. It was found that resilient modulus values for soils at this temperature relied heavily on the amount of ice. Lower fines content together with higher moisture content allowed the greatest ice formation and hence resulted in the largest resilient moduli.

For soils near the freezing point, represented by tests done at -1°C, a different pattern of behavior emerges. Figures 4.20–4.25 show typical behavior of specimens containing 6% and 12% fines tested at -1°C. All of these specimens were frozen at a medium freezing gradient.

A comparison of Figures 4.20–4.22 indicates that the highest resilient modulus was obtained at a moisture content of 5.3%, with a slight decrease for higher moisture contents. Low moisture content contributed the least to specimen resilient modulus at this temperature. Another characteristic related to resilient modulus is the behavior of specimens at high deviator stress. Resilient modulus values peaked at a deviator stress of between 10 and 20 psi and then decreased with increasing deviator stress. This behavior is in marked contrast to the behavior of colder specimens, which increased linearly in resilient modulus over the entire range of deviator stress.

A comparison of Figures 4.23–4.25 indicates that resilient modulus increased slightly as moisture increased from 3.3% to 5.3%, then increased considerably as moisture increased from 5.3% to 6%. Behavior with respect to deviator stress was very similar to the behavior of specimens containing 6% fines. Peak resilient modulus was obtained at deviator stresses near 20 psi; resilient modulus decreased quickly with higher deviator stress.

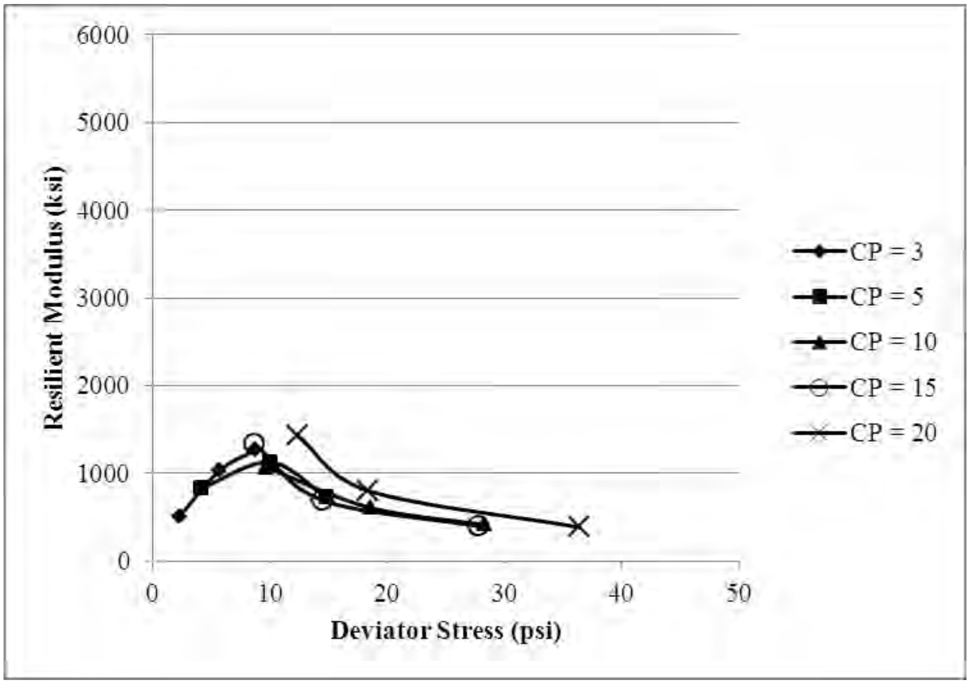


Figure 4.20 M_R for FC = 6%, MC = 3.3%, medium gradient, -1°C

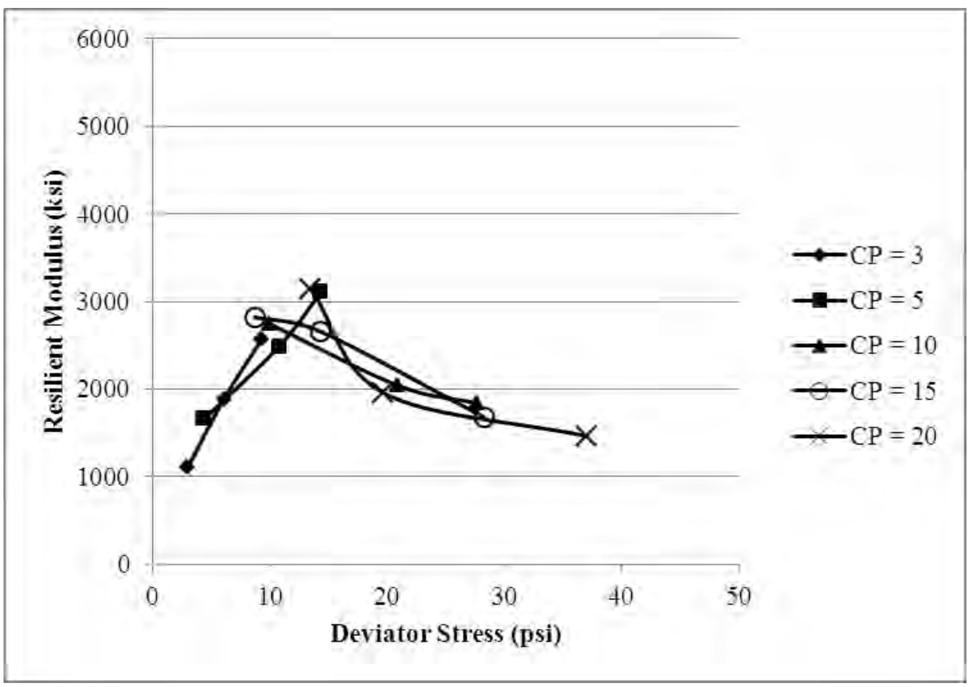


Figure 4.21 M_R for FC = 6%, MC = 5.3%, medium gradient, -1°C

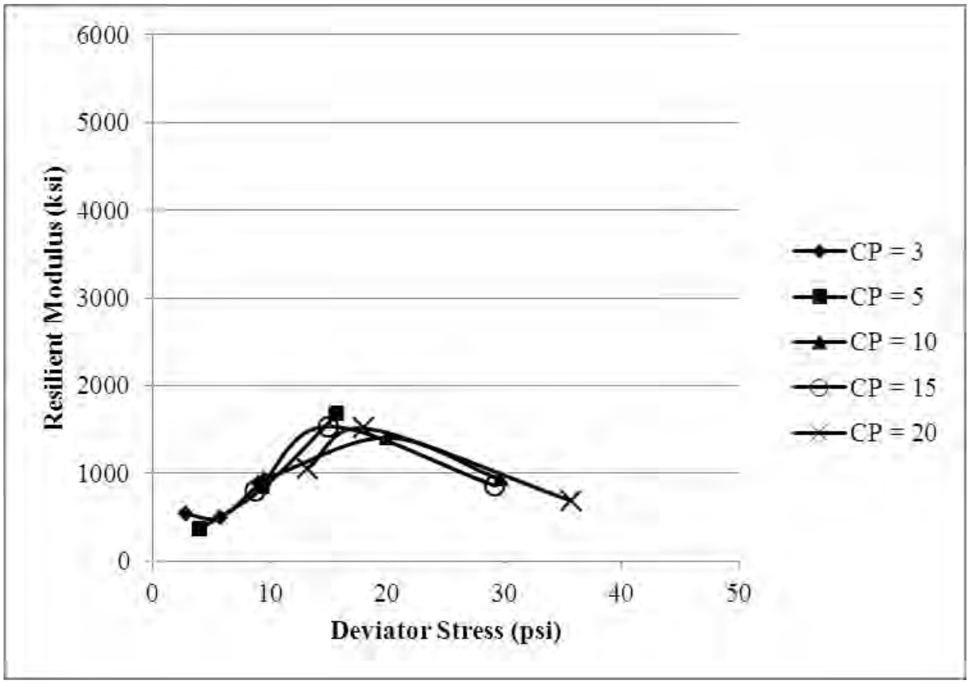


Figure 4.22 M_R for FC = 6%, MC = 6%, medium gradient, -1°C

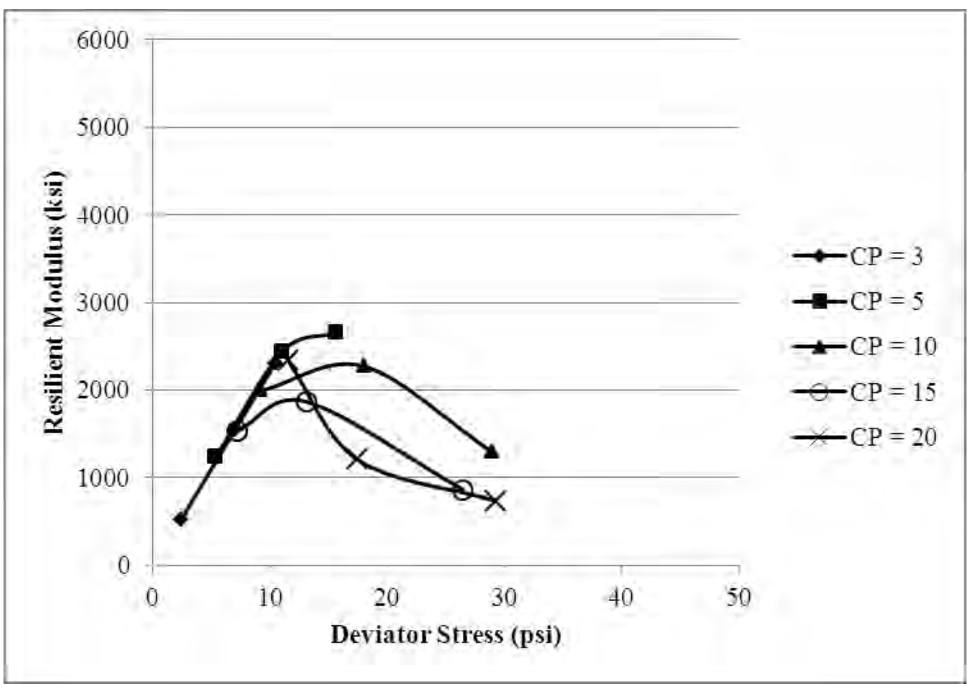


Figure 4.23 M_R for FC = 12%, MC = 3.3%, medium gradient, -1°C

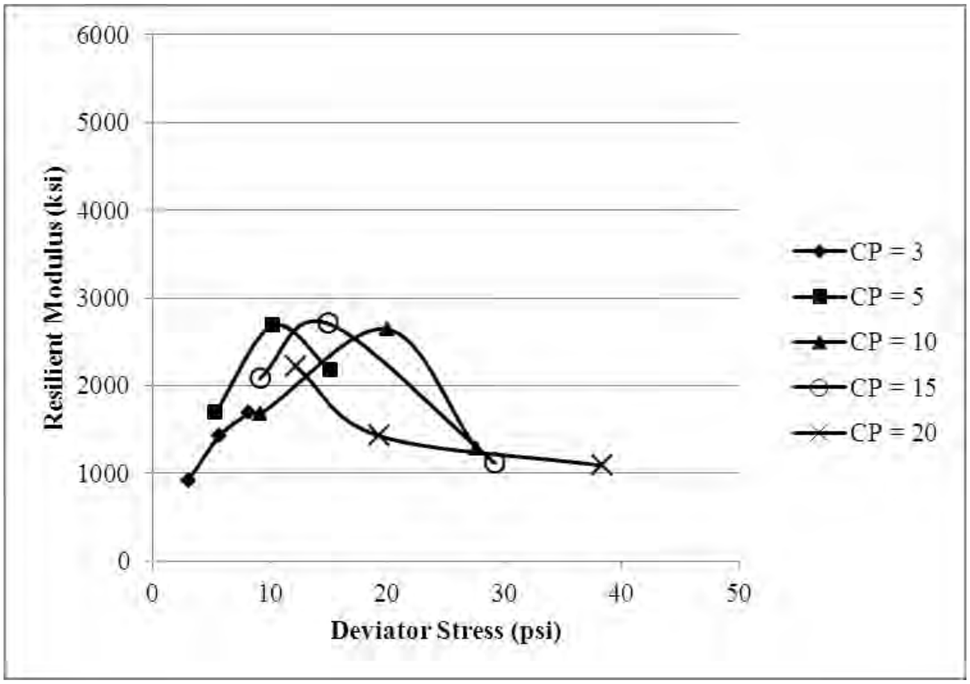


Figure 4.24 M_R for FC = 12%, MC = 5.3%, medium gradient, -1°C

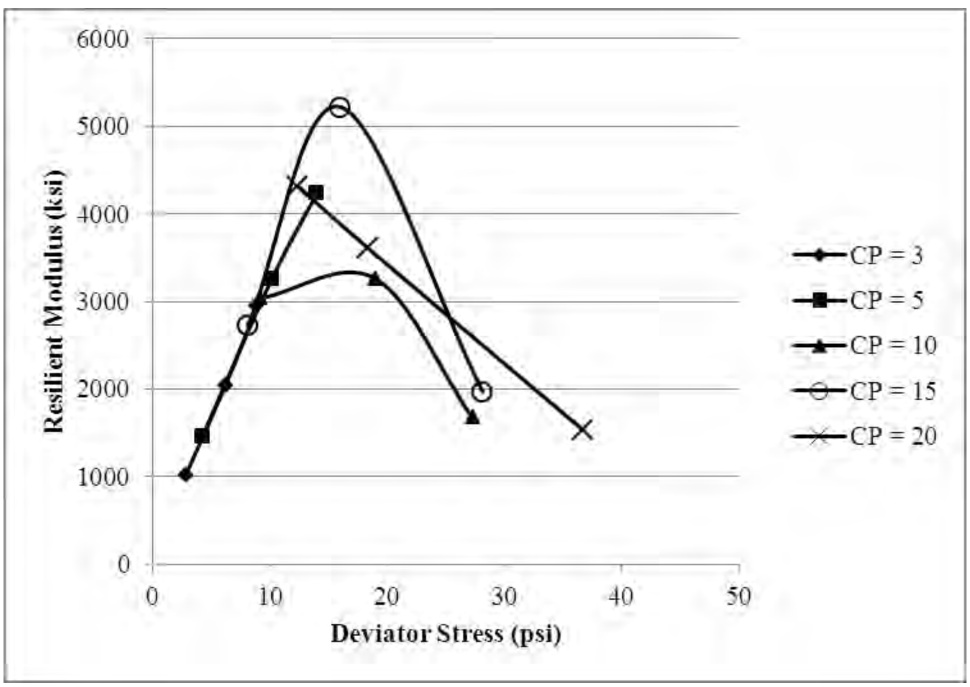


Figure 4.25 M_R for FC = 12%, MC = 6%, medium gradient, -1°C

To summarize these observations, it appeared that at -1°C, higher resilient modulus accompanied a combination of increased fines and increased moisture. Resilient modulus also increased with moisture content for lower fines contents, but did not approach that of the higher fines contents. This result may be due to higher moisture contributing to larger ice crystals remaining in soil pore spaces. More of these pore spaces were found in soil with higher fines content, and therefore the specimen had less of a tendency to collapse, since the remaining ice structure is more effective than the structure of a soil with less water and lower fines.

As soil temperature approaches the freezing point of water, the stiff ice structure begins to disappear. Initial melting takes place in the ice surrounding each soil particle, causing a thin film of water to develop. As a result, the relatively solid ice structure present in fully frozen soils gives way to a combination of ice crystals in the pore spaces and liquid water in a film around each soil particle (see Figure 4.26). Note that this behavior begins to occur while soil is still slighly below freezing.

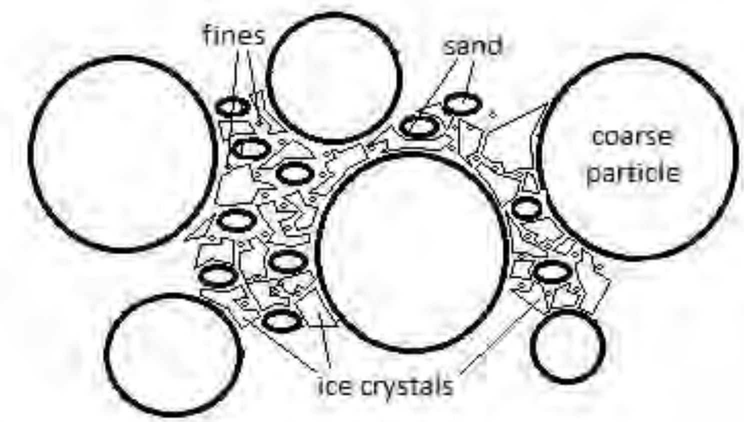


Figure 4.26 Soil particles at -1°C

Once the film of moisture develops, the soil structure loses the cohesion provided by ice bonding. Movement between soil particles and ice crystals in the pore spaces is now possible. Because a large amount of ice still supports the soil structure, increasing resilient modulus is seen at low deviator stress. However, diminished stability in the ice crystals results in a shift at high deviator stresses. The soil softens and becomes weaker even when it is slightly below freezing because of the slow movement of particles at higher stresses.

For testing temperature of 20°C, stress states are best represented by unfrozen specimens. Figures 4.27–4.30 show stress states for each fines content at a moisture content of 5.3%. These figures show that, at room temperature and optimum moisture content, a fines content of 8% obtained the highest resilient modulus values. In general, specimen behavior for fines contents of 6%, 8%, and 12% was similar. For each confining pressure and the associated set of deviator stresses, resilient modulus increased slightly. Increases were generally linear with respect to deviator stress. For fines contents of 10%, resilient modulus decreased at high deviator stresses. The reason for this difference in behavior is unknown.

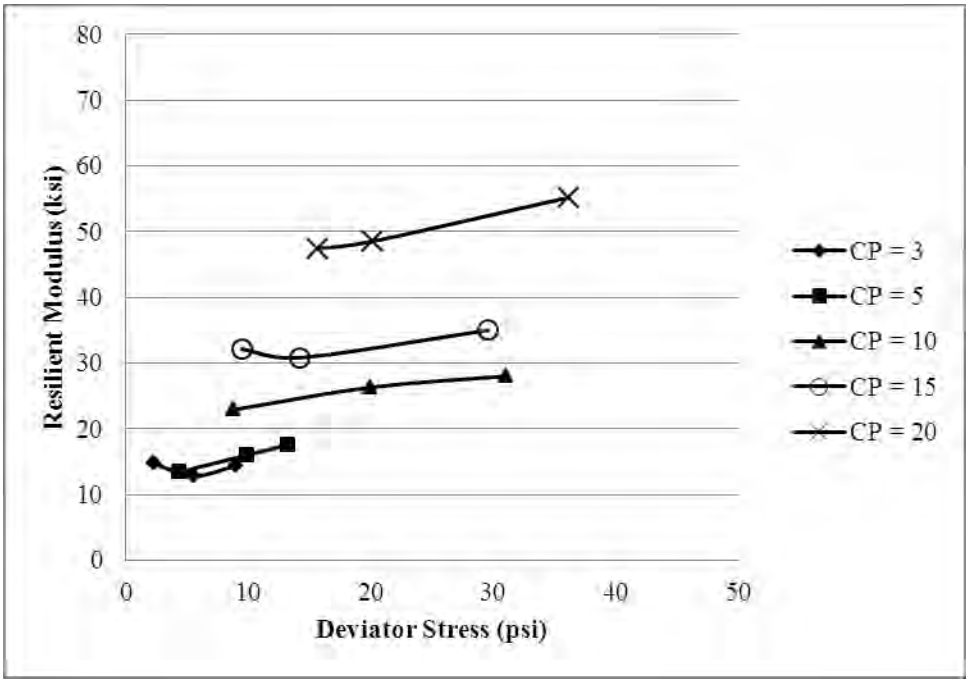


Figure 4.27 M_R for FC = 6%, MC = 5.3%, 20°C

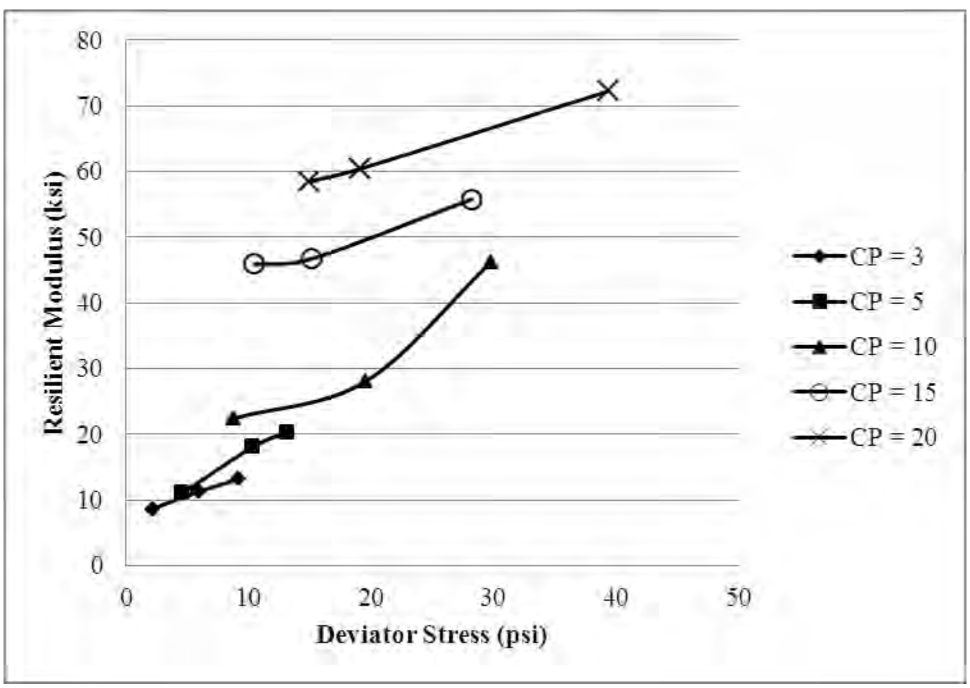


Figure 4.28 M_R for FC = 8%, MC = 5.3%, 20°C

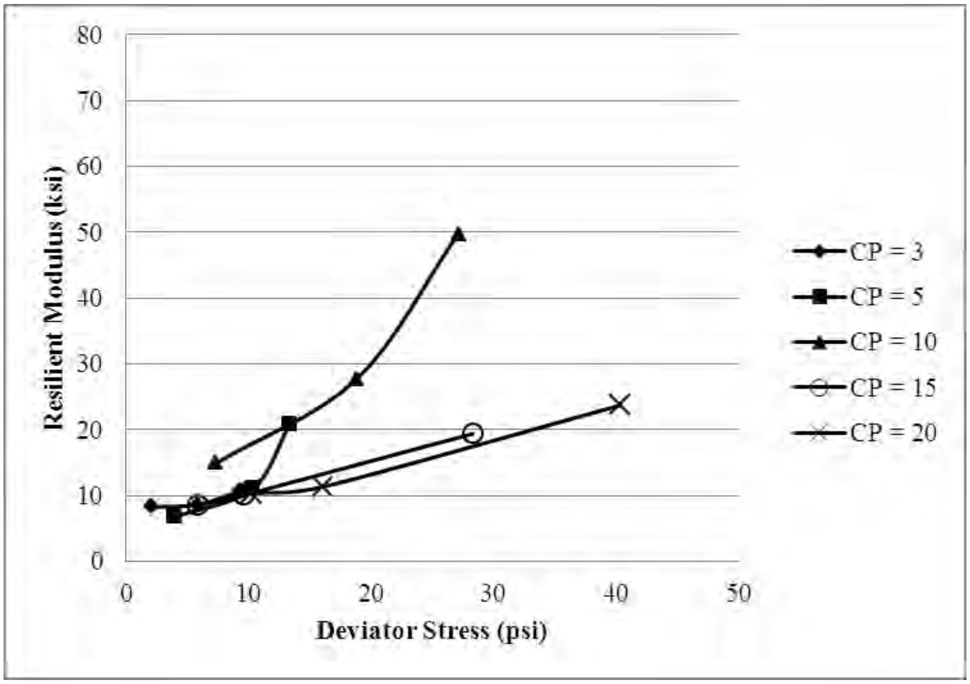


Figure 4.29 M_R for FC = 10%, MC = 5.3%, 20°C

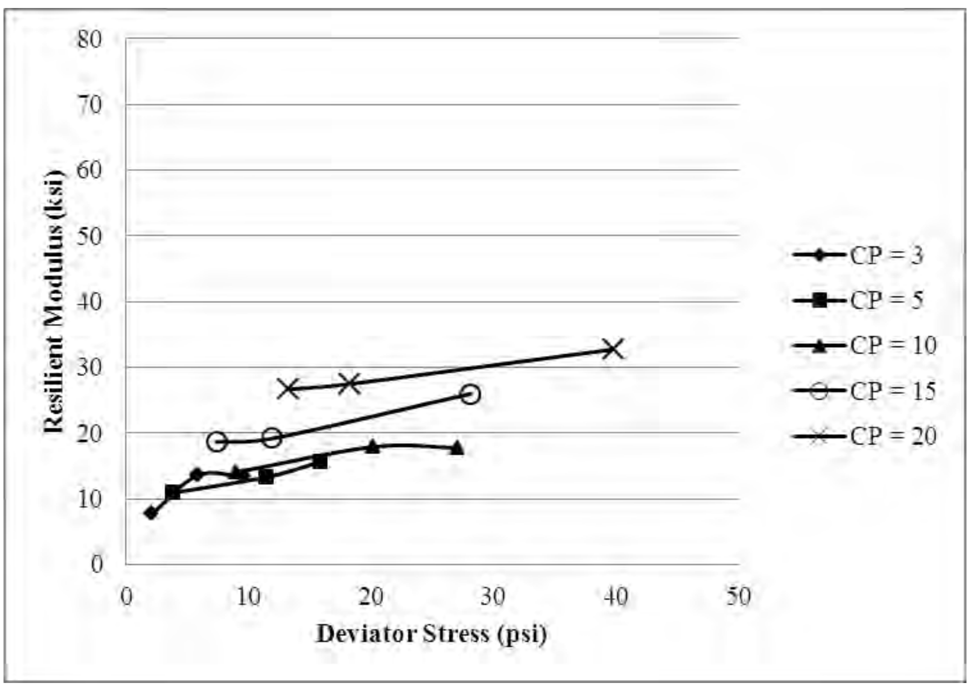


Figure 4.30 M_R for FC = 12%, MC = 5.3%, 20°C

Freeze-Thaw

Resilient modulus tests were conducted at 20°C for both unfrozen and previously frozen specimens. Unfrozen specimens represented soil conditions before any freeze-thaw had occurred, while previously frozen specimens represented soil conditions after one freeze-thaw cycle. Because frozen specimens froze in a closed system and were sealed from air movement thereafter, the moisture contents of the frozen and unfrozen specimens at room temperature were essentially equivalent. For example, the moisture content of a 6% design specimen after freezing usually contained between 5.7% and 5.9% moisture by the time it had thawed for testing at 20°C.

To determine the behavior of soil after a freeze-thaw cycle in a closed system, resilient moduli of soil after one freeze-thaw cycle were compared with those of unfrozen soil. This comparison was done at each of the fifteen confining pressure and deviator stress combinations, and for each of the three freezing gradients. Figures for each combination are presented in the Appendix. Table 4.1 summarizes the results of this comparison. Results are arranged according to fines content, moisture content, and freezing gradient. Columns 4 and 6 represent the percentage of tests that show an increase or decrease, respectively, in resilient modulus after one freeze-thaw cycle. Columns 5 and 7 show the range of these increases and decreases, respectively, as a percentage of the resilient moduli of the corresponding unfrozen soil tests.

While several conclusions can be drawn from this data, some trends for the low moisture content data are clear. Data for optimum moisture content are less consistent and must be described in terms of likelihood.

At 6% fines content and 3.3% moisture content, all specimens experienced an increase in resilient modulus after one freeze-thaw cycle. The increase was between 18% and 357%, depending on freezing gradient. The increase was smaller at the high gradient than at the medium or low gradients, and was largest for the medium gradient. For 5.3% moisture content, however, a low freezing gradient caused a decrease of resilient modulus, from 18% to 62%. A medium freezing gradient had a 93% probability of increasing to 85% in resilient modulus, and a 7% probability of decreasing to 7%. High freezing gradient had a 27% probability of increasing to 10% in resilient modulus, and a 73% probability of decreasing to 54%. Overall, data for 6% fines content indicate (1) that it is very likely for resilient modulus to increase after a freeze-thaw cycle, (2) that higher moisture content lowers the likelihood of the soil improving in resilient modulus after a freeze-thaw cycle, and (3) that a medium freezing gradient provides the most significant increase for both moisture contents.

Table 4.1 Change in MR after one freeze-thaw cycle

1	2	3	4	5			6	7		
Fines Content (%)	**Moisture Content (%)**	**Freezing Gradient**	**Observed Increases (% of tests)**	**Range of Increase (%)**			**Observed Decreases (% of tests)**	**Range of Decrease (%)**		
6	**3.3**	**Low**	100.0	57.8	to	297.9	0.0	-	to	-
		Medium	100.0	57.4	to	357.8	0.0	-	to	-
		High	100.0	18.4	to	195.1	0.0	-	to	-
	5.3	**Low**	0.0	-	to	-	100.0	-18.2	to	-61.2
		Medium	93.3	0.0	to	85.5	6.7	0.0	to	-6.9
		High	26.7	0.0	to	9.7	73.3	0.0	to	-54.8
8	**3.3**	**Low**	0.0	-	to	-	100.0	-0.7	to	-34.3
		Medium	6.7	0.0	to	10.1	93.3	0.0	to	-30.4
		High	0.0	-	to	-	100.0	-23.6	to	-49.4
	5.3	**Low**	0.0	-	to	-	100.0	-11.2	to	-60.3
		Medium	60.0	0.0	to	82.5	40.0	0.0	to	-33.1
		High	33.3	0.0	to	42.1	66.7	0.0	to	-41.8
10	**3.3**	**Low**	100.0	51.9	to	127.6	0.0	-	to	-
		Medium	100.0	3.2	to	42.4	0.0	-	to	-
		High	26.7	0.0	to	2.9	73.3	0.0	to	-10.5
	5.3	**Low**	80.0	0.0	to	192.2	20.0	0.0	to	-38.0
		Medium	93.3	0.0	to	332.8	6.7	0.0	to	-28.3
		High	93.3	0.0	to	391.8	6.7	0.0	to	-24.4
12	**3.3**	**Low**	100.0	8.9	to	105.1	0.0	-	to	-
		Medium	100.0	0.2	to	64.7	0.0	-	to	-
		High	100.0	9.8	to	37.5	0.0	-	to	-
	5.3	**Low**	100.0	61.9	to	257.9	0.0	-	to	-
		Medium	100.0	28.1	to	149.3	0.0	-	to	-
		High	93.3	0.0	to	84.7	6.7	0.0	to	-2.5

At 8% fines content and 3.3% moisture content, nearly all specimens experienced a decrease in resilient modulus after a freeze-thaw cycle. This finding held true for all combinations at all three gradients, with one exception out of 45 comparisons. The decrease of resilient modulus ranged from 0% to 34% for low gradient, to 23% to 49% for high gradient, indicating that high freezing gradient reduces resilient modulus by a greater factor than low freezing gradient. This parallels the conclusion mentioned above, that a high freezing gradient may contribute less to increases in resilient modulus than a low freezing gradient, for soils with low moisture content. For 5.3% moisture content, a low freezing gradient caused a decrease in resilient modulus as well, ranging from 11% to 60%. Medium and high gradients, by contrast, caused some increases. A medium freezing gradient had a 60% probability of increasing 82% in resilient modulus, and a 40% probability of decreasing 33%. A high freezing gradient had a 33% probability of increasing 42% in resilient modulus, and a 67% probability of decreasing 42%. Overall, data for 8% fines content indicate (1) that resilient modulus is very likely to decrease after a freeze-thaw cycle, (2) that higher moisture content may improve the likelihood of the soil improving in resilient modulus after a freeze-thaw cycle, and (3) that a medium freezing gradient provides the most significant increase for both moisture contents. This finding is in contrast to the 6% finding in one sense, because more increases were observed at higher moisture content. However, it parallels the 6% data, in that the medium gradient is optimal.

At 10% fines and 3.3% moisture content, most specimens increased in resilient modulus when frozen at low or medium gradients. This increase ranged from 52% to 127% at low gradient and from 3% to 54% at medium gradient. A high freezing gradient generally caused resilient modulus for this soil to decrease, with a 73% probability of 11% decrease in resilient modulus and a 27% probability of 3% increase. For 5.3% moisture content, most specimens increased considerably in resilient modulus, increasing to 192% for low gradient, 332% for medium gradient, and 392% for high gradient. Probabilities of this increase were 80%, 93%, and 93%, respectively. Corresponding decreases ranged from 38% for low gradient, to 28% for medium gradient and 24% for high gradient. Overall, data for 10% fines content indicate (1) that resilient modulus is likely to increase after a freeze-thaw cycle, 2) that higher moisture content does not significantly reduce the likelihood of increasing resilient modulus and can, in fact, cause greater increases, and 3) that a low gradient is better for lower moisture content and a high gradient is better for higher moisture content.

At 12% fines, all specimens showed an increase in resilient modulus for all tests, with one exception out of the ninety comparisons, which showed a 2.5% decrease. Increases for a moisture content of 3.3% ranged from 9% to 105% for low gradient, to 64% for medium gradient and 10% to 37% for high gradient. Increases were larger for a moisture content of 5.3%, ranging from 62% to 258% for low gradient, to 28% to 149% for medium gradient and 84% for high gradient. Overall, data for 12% fines content indicate (1) that resilient modulus is very likely to increase after a freeze-thaw cycle, (2) that higher moisture content causes a larger increase in resilient modulus, and 3) that a low freezing gradient allows the greatest increases in resilient modulus.

To understand these results, observe that soil that has not experienced a freeze-thaw cycle contains pore spaces that have not been altered by freezing water. Figure 4.31 shows a cross section of unfrozen soil structure.

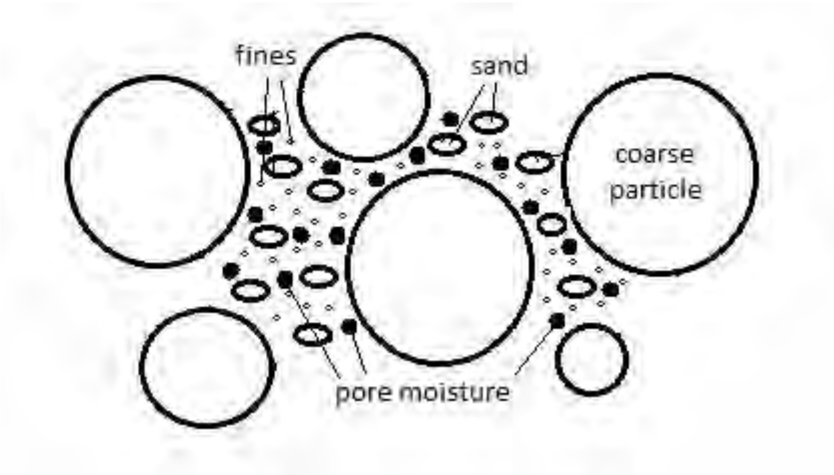


Figure 4.31 Soil particles at 20°C

The previous study (Li et al., 2010), which used an open system that allowed frozen specimens to gain moisture, indicated that soils tend to experience a decrease in resilient modulus after a freeze-thaw cycle. However, this study found that for a closed system and fines contents of 6%, 10%, and 12%, soils tend to increase in resilient modulus after a freeze-thaw cycle, in some cases significantly. A possible reason that low increases and mostly decreases were observed in 8% fines specimens after a freeze-thaw cycle may be that these specimens had the highest resilient moduli in unfrozen tests (see Figures 4.11 and 4.12).

This finding can be explained by first realizing that, after undergoing freezing, specimens in an open system will increase in moisture content, and consequently, the resilient modulus will drop. By contrast, specimens frozen in a closed system will retain approximately the same moisture as unfrozen specimens. In addition, the process of freezing changes the soil structure, making it more compact, as thawing concentrates moisture in the pore spaces rather than around the large soil particles. This factor also can contribute to an increase in resilient modulus.

It was observed that specimens with 12% fines practically always increased in resilient modulus, even more consistently than did specimens with 6% fines. This increase may occur because for any specific moisture content, a soil containing twice the fines will be considerably drier, due to the much larger surface area of the fines. Once this soil is frozen, water is concentrated in the pore spaces and drawn away from the larger particles, reducing the lubricating effect of moisture even more. At the same time, these pore spaces are not as large as the pore spaces in a soil with 6% fines, so the soil structure is more resilient. Furthermore, fines and small particles are better distributed among the large particles, contributing to a bonding effect. Indeed, after testing, specimens with 12% fines were found to be the most difficult to crumble and discard, whereas specimens with 6% fines fell apart easily after testing, if they did not fail outright due to crumbling of surface particles.

Temperature Gradient

The previous study suggested the use of multiple freezing gradients in the preparation of specimens, rather than only one. It was theorized that freezing gradient has an effect on the resilient modulus of aggregates; therefore, that possibility became another focus of this study.

For temperatures below freezing, no clear indication was found that freezing gradient was a major influence on the resilient properties of aggregates. Each of the three gradients was stronger than the other two in roughly equal proportion. With one exception, it was impossible to identify a clear pattern in this difference, which in any case was relatively small.

The exception, mentioned in the Temperature section of this report, is the case of specimens frozen at a high gradient. These specimens were found to generally experience a slight increase in resilient modulus with an increase in temperature from -5 to -3°C. While the reasons for this finding are uncertain, a possible explanation is as follows: The movement of moisture and shrinkage of specimens during freezing at a high gradient could contribute to a buildup of excess ice in the middle of the specimen, where the strain is measured. Since cold ice is brittle, high deviator stresses may have been high enough to introduce fine fractures in this excess ice, causing a reduction in resiliency. The increase in temperature from -5 to -3°C could allow a slight redistribution of particles into these fine openings. This movement could then result in a slight increase in resilient modulus as the aggregate particle distribution is improved.

For temperatures above freezing, trends were investigated using bulk stress relationships. Figures 4.32–4.35 show graphs of resilient modulus and bulk stress at 20°C for specimens at all four fines contents and containing 5.3% moisture. In each case, all three gradients are shown and compared with the resilient data for unfrozen specimens. Observe that specimens prepared with a medium freezing gradient tested the strongest, for a fines content of 6% (Figure 4.32). While slight ambiguity is indicated in Figure 4.33, showing specimens at 8% fines, it is reasonably clear that the medium gradient generally produces the strongest specimens.

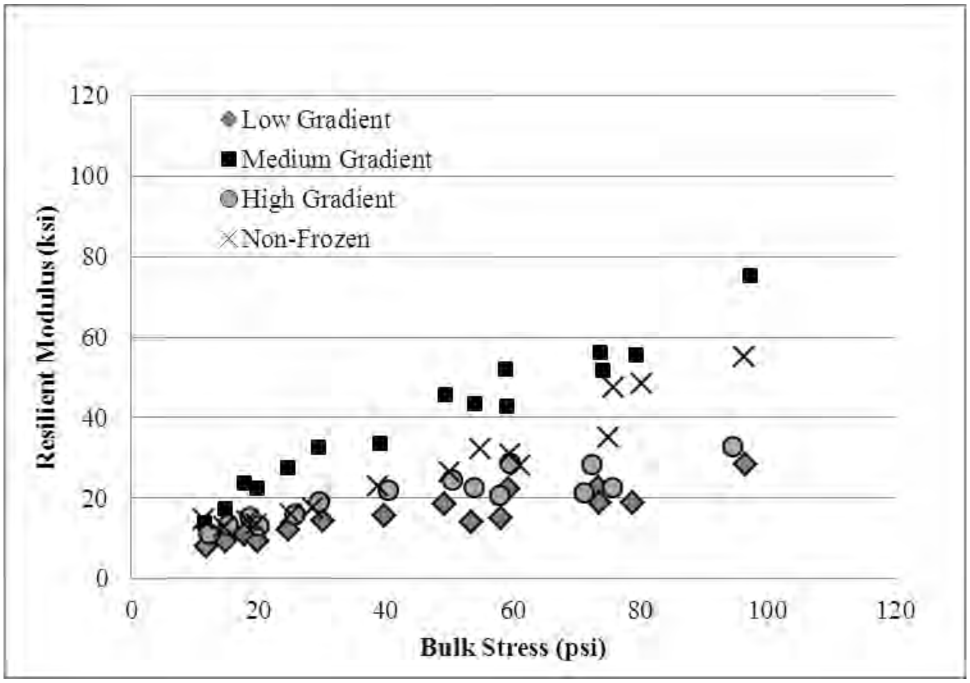


Figure 4.32 M_R vs. bulk stress, FC = 6%, MC = 5.3%, 20°C

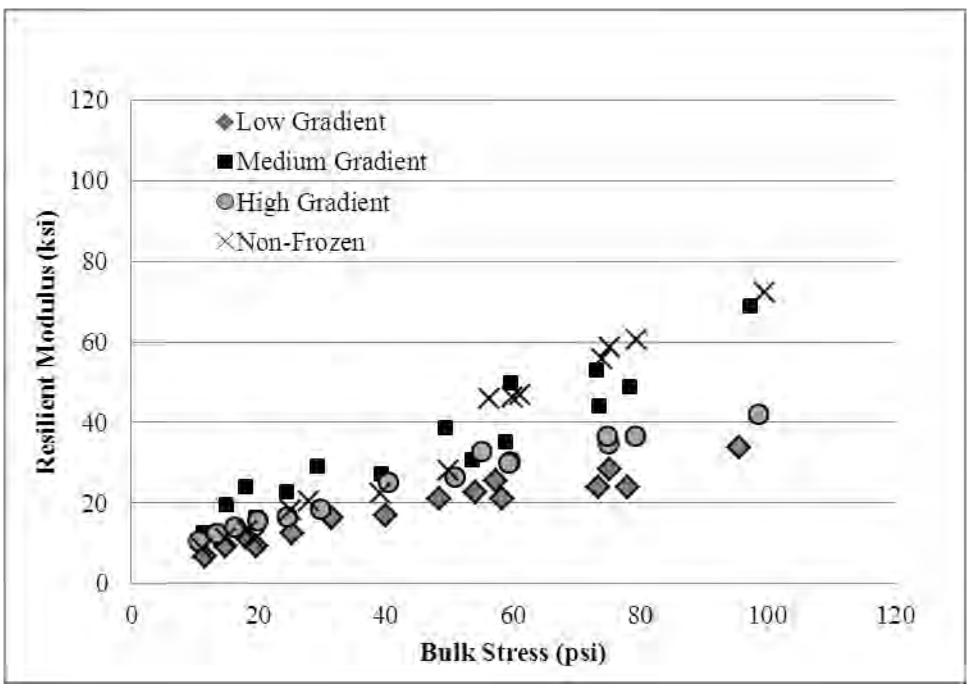


Figure 4.33 M_R vs. bulk stress, FC = 8%, MC = 5.3%, 20°C

For specimens containing 10% fines (Figure 4.34), a high gradient produces slightly higher resilient modulus values than a medium gradient, about 10% relative increase or less. Values for the medium gradient specimens are well above those of the low gradient and unfrozen specimens.

Finally, for specimens containing 12% fines (Figure 4.35), a low gradient clearly produces the largest resilient modulus values, approximately 40% greater than the medium gradient. This is the only definite case where the medium gradient is not the best. However, note that, even in this case, resilient modulus values for the medium gradient are higher than those for the high gradient and unfrozen specimens.

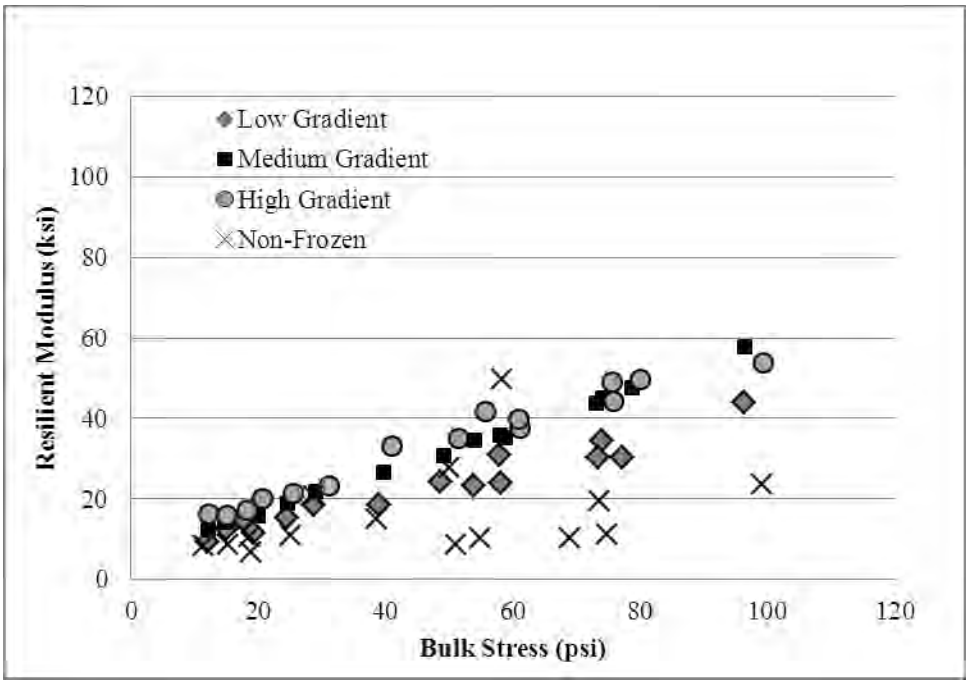


Figure 4.34 M_R vs. bulk stress, FC = 10%, MC = 5.3%, 20°C

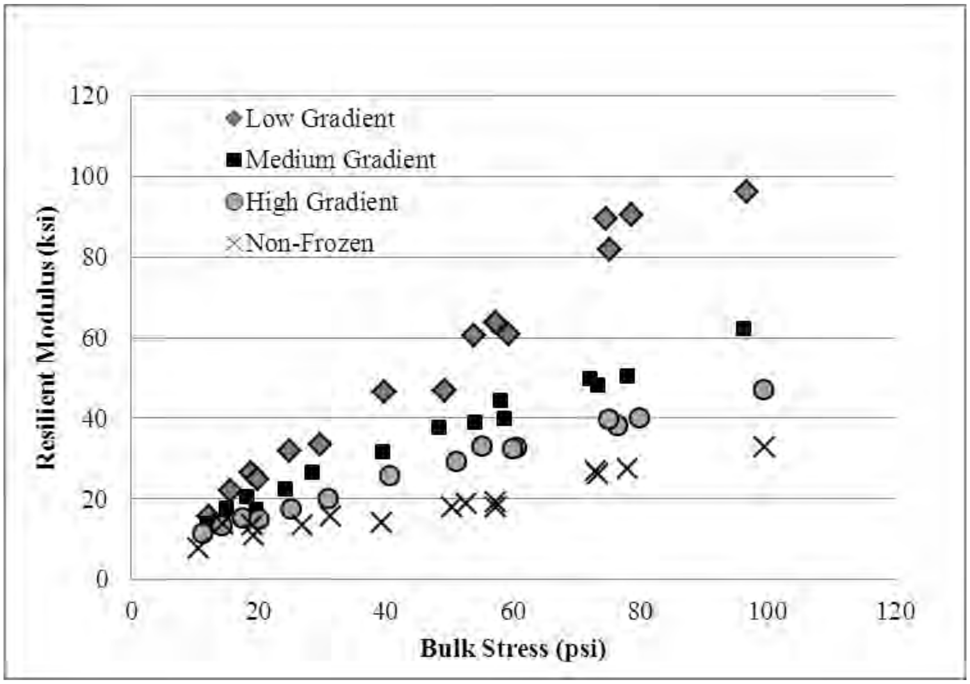


Figure 4.35 M_R vs. bulk stress, FC = 12%, MC = 5.3%, 20°C

It may be considered, based on the information just given, that a medium freezing gradient causes ideal resilient modulus values, while low and high freezing gradients generally cause lower values. Data for a moisture content of 3.3%, while less concentrated and hence more difficult to analyze, support this observation as well. See bulk stress figures for MC = 3.3% in the Appendix.

A number of reasons explain why the medium freezing gradient is effectively the optimum freezing gradient for the specimens tested. Most importantly, low freezing gradients contributed to a slow freezing process that caused maximum frost heave and resultant expansion of the specimens. High freezing gradients, on the other hand, resulted in a rapid freezing boundary layer that shrank the specimens and pulled moisture upward into the middle of the specimens. Both of these conditions may have initiated changes in the pore structure that became influential when the specimens thawed. The medium gradient caused just enough frost heave to distribute the moisture evenly throughout the specimen, allowing specimen soil compaction to be maintained or improved throughout the freezing and thawing processes, regardless of fines content.

M_R Modeling

M_R Modeling for D-1 Materials under Non-frozen Condition

To be consistent with the previous study (Li et al., 2010), Equation 4.1 from the Mechanistic-Empirical Pavement Design Guide (MEPDG) (ARA, Inc., 2000) was chosen as a base model for regression analysis of the M_R data of D-1 materials tested at a temperature of 20°C. Based on research findings of the previous study (Li et al., 2010) and this study, it was found that moisture content, fines content, temperature, stress state, and freeze-thaw cycle could affect resilient properties of D-1 materials. Similar to the study by Li et al. (2011), this study found that the resilient behavior modeling of Fairbanks D-1 material was divided into two parts: frozen and non-frozen.

$$M_R = k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a}+1\right)^{k_3} \tag{4.1}$$

where

p_a	=	normalizing stress (atmospheric pressure, 14.5 psi),
$k_1, k_2, and\ k_3$	=	regression constants,
θ	=	bulk stress $=\sigma_1+\sigma_2+\sigma_3$,
τ_{oct}	=	octahedral shear stress $=\frac{1}{3}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_1-\sigma_3)^2+(\sigma_2-\sigma_3)^2}$, and
σ_d	=	deviator stress $=\sigma_1-\sigma_3$.

To incorporate the influence of fines and moisture contents on the resilient behavior of the D-1 material used, the MEPDG model was modified into Equation 4.2, in which $k_1, k_2, and\ k_3$ were affected by fines and moisture contents. Calibration of the MEPDG model under different bulk stress and octahedral shear stress conditions is simplified to find a combination of the regression constants of c_i to best fit the experimental results using Equation 4.2.

$$M_R = (c_1 + c_2 \times f_c + c_3 \times W_s + c_4 \times f_c \times W_s) \times P_a \times \left(\frac{\theta}{P_a}\right)^{(c_5 + c_6 \times f_c + c_7 \times W_s + c_8 \times f_c \times W_s)} \times \left(\frac{\tau_{oct}}{P_a} + 1\right)^{(c_9 + c_{10} \times f_c + c_{11} \times W_s + c_{12} \times f_c \times W_s)} \quad (4.2)$$

where

f_c = fines content (%),

W_s = moisture content (%), and

c_i = regression constants.

Mathematically, the problem can be described as follows: Calibration of the MEPDG model is done to find an appropriate combination of c_i, which can minimize the overall difference between the experimental data and the theoretical results, as predicted by Equation 4.2. A least-square estimation technique was adopted to best fit the experimental results via minimizing the sum of the squares of the difference (that is, the sum of the squares of the residuals) between the experimental value and the calculated/predicted value by Equation 4.2. The best fit is defined as a combination of regression constants that results in the least error between the experimental results and the predicted values using Equation 4.2. The dependent variable was M_R, and the four independent variables were fines content, moisture content, bulk stress, and deviator stress. Best-fit results are shown in Equations 4.3–4.5. If fines and moisture contents were given, k_i coefficients can be obtained according to Equations 4.3–4.5. Figure 4.36 compares the predicted M_R based on Equation 4.2 and experimental M_R values from laboratory tests. A coefficient of determination (R^2) of 84.2% indicated a good correlation between predicted and measured results. However, when the coefficients from the previous study (Li et al., 2010) were used, the predicted M_R tended to underestimate the experimental results, as shown in Figure 4.37, when experimental M_R values were higher than 40 ksi.

$$k_1 = -6.59 + 1.185 * f_c + 1.111 * W_s - 0.197 * W_s * f_c \quad (4.3)$$

$$k_2 = -0.78 + 0.241 * f_c + 0.966 * W_s - 0.118 * W_s * f_c \quad (4.4)$$

$$k_2 = 5.71 - 0.927 * f_c - 1.551 * W_s + 0.233 * W_s * f_c \quad (4.5)$$

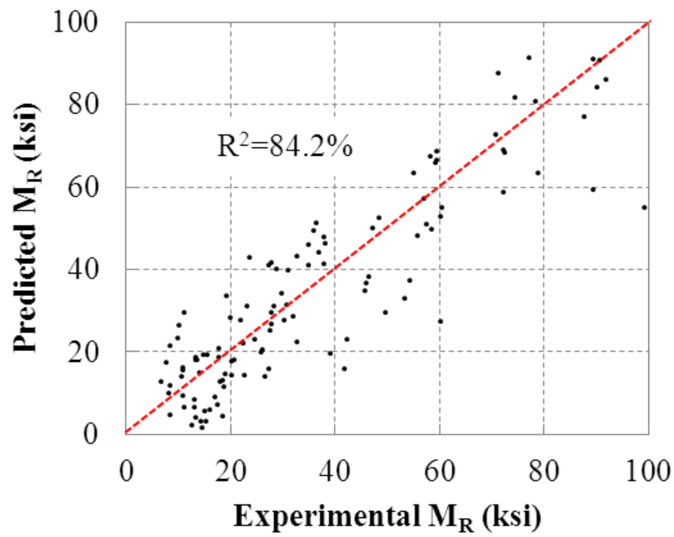


Figure 4.36 Predicted vs. measured M_R (unfrozen, at 20°C)

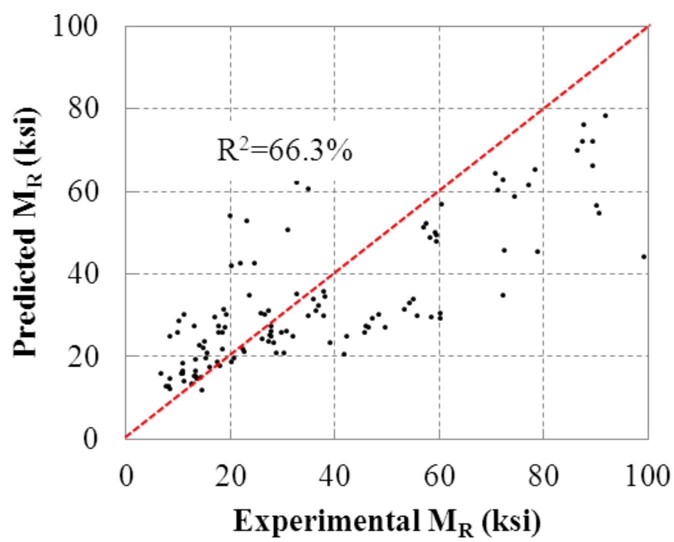


Figure 4.37 Predicted M_R using coefficients from the previous study (Lin et al. 2010) vs. measured M_R

M_R Modeling for D-1 Materials under Frozen Condition

To model the resilient behavior of the D-1 materials under subfreezing temperatures, the same equation proposed in the previous study (Li et al., 2010) was used to predict M_R, as expressed by Equation 4.6, which is a modified version of the model presented in Simonsen et al. (2002). Resilient modulus is a function of abrasion resistance, temperature, and deviatoric stress. Since only D-1 material from the Northern region was used, Equation 4.6 was modified as presented in Equation 4.7 to predict the M_R of D-1 materials from the Northern region under subfreezing condition.

$$M_R = A_r^{k_1} e^{k_2 + k_3/T} \sigma_d^{k_4} \quad (4.6)$$

$$M_R = k_1 e^{k_2 + k_3/T} \sigma_d^{k_4} \quad (4.7)$$

where

A_r = abrasion resistance (percentage loss) obtained by using Micro-Deval tester, and

T = temperature in degree Celsius.

The same least-square estimation technique, which is the same as the M_R model calibration under non-frozen temperature, was used to best fit the experimental results via minimizing the sum of the squares of the difference between the experimental value and the theoretical value predicted by Equation 4.7. Equation 4.8 expresses the regression results for M_R prediction of D-1 materials under subfreezing temperatures. Figure 4.38 compares the predicted M_R based on Equation 4.8 and experimental M_R values from laboratory tests. A coefficient of determination (R^2) of 63.6% was obtained between predicted and measured results. Note that the correlation between predicted and measured M_R values was not strong, especially when the M_R values were higher than 4000 ksi.

$$M_R = 0.9638 \times e^{4.1014 + 0.7054/T} \sigma_d^{0.7346} \; (-10\,^oC < T < -1\,^oC) \quad (4.8)$$

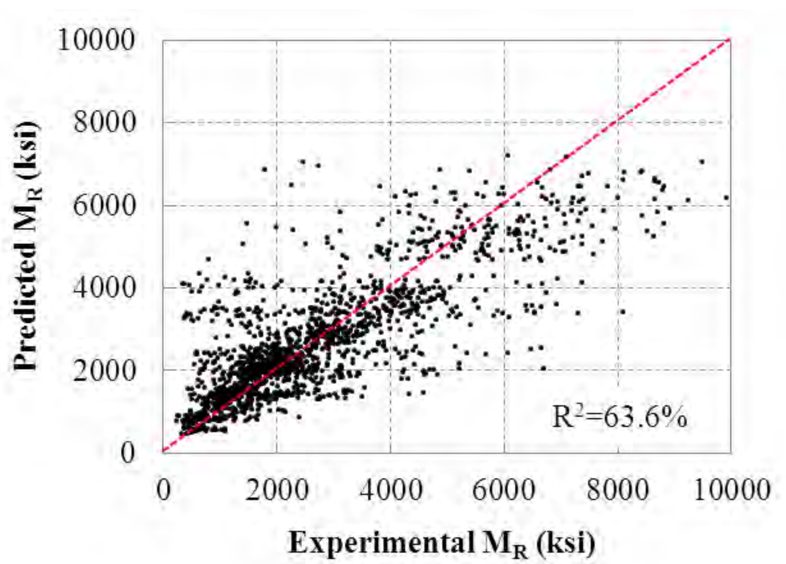


Figure 4.38 Predicted M_R using Equation 4.8 vs. measured M_R at at subfreezing temperatures

The closed system was used for specimen preparation during the freezing process. It was reasonable to assume that the ice content of D-1 material specimens after the freezing process was equal to the initial water content. Since the ice content of the D-1 materials ranged from 3.3% to 6% after freezing, ice content was introduced to the M_R prediction model under subfreezing conditions, as shown in Equation 4.9. After a least-square regression, model parameters were determined and presented in Equation 4.10. Figure 4.39 compares the predicted M_R based on Equation 4.10 and experimental M_R values from laboratory tests. A R^2 value of 65.3% was obtained between predicted and measured results, which indicates a better prediction than using Equation 4.8.

$$M_R = k_1 e^{k_2 + k_3/T} \sigma_d^{k_4} W_s^{k_5} \quad (4.9)$$

$$M_R = 0.9638 \times e^{5.6543+0.5466/T} \sigma_d^{0.7713} W_s^{0.3089} \; (-10\,^oC < T < -1\,^oC) \quad (4.10)$$

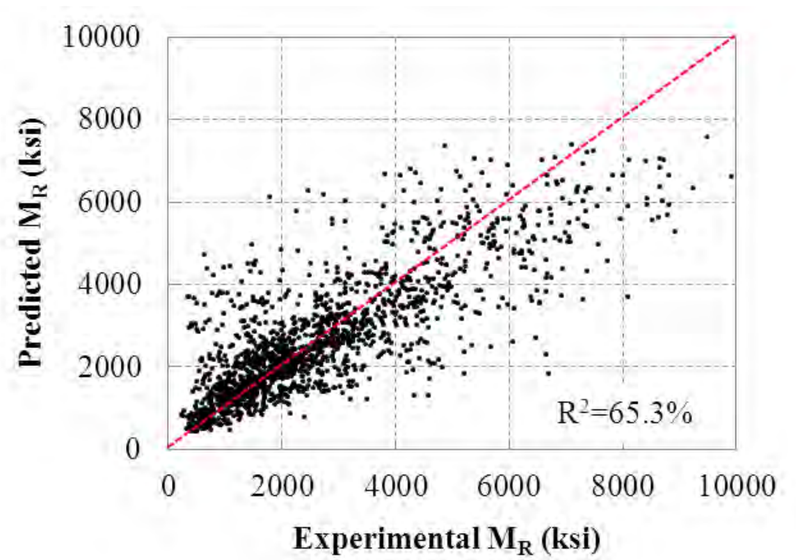


Figure 4.39 Predicted M_R using Equation 4.10 vs. measured M_R at at subfreezing temperatures

Predictive models for the M_R of D-1 granular materials from the Northern region of Alaska can be summarized as follows:

when T > 0°C,

$$M_R = (-6.59 + 1.185 * f_c + 1.111 * W_s - 0.197 * W_s * f_c) * P_a * \left(\frac{\theta}{P_a}\right)^{(-0.78+0.241*f_c+0.966*W_s-0.118*W_s*f_c)}$$

$$\left(\frac{\tau_{oct}}{P_a} + 1\right)^{(5.71-0.927*f_c-1.551*W_s+0.233*W_s*f_c)}$$

when -10°C < T < -1°C,

$$M_R = 0.9638 \times e^{5.6543+0.5466/T} \sigma_d^{\ 0.7713} W_s^{\ 0.3089} \qquad (2.7\ psi < \sigma_d < 36\ psi),$$

where

M_R	=	resilient modulus, ksi,
f_c	=	fines content (decimal),
W_s	=	ice content (decimal),
θ	=	$\sigma_1 + \sigma_2 + \sigma_3$, psi,
$\sigma_1, \sigma_2, \sigma_3$	=	principal stresses, psi,
p_a	=	normalizing stress (atmospheric pressure, 14.5 psi),
τ_{oct}	=	octahedral shear stress $= \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}$, psi,
T	=	temperature, degree Celsius, and
σ_d	=	deviator stress, psi.

CHAPTER 5. CONCLUSIONS

To characterize the resilient behavior of D-1 material, frost heave and repeated-load M_R tests were performed on D-1 granular base course materials from ADOT&PF's Northern region, using different fines (from 6% to 12%) and moisture contents (from 3.3% to 6%), under different temperatures (from -5°C to 20°C) and freeze-thaw (with or without) conditions. After testing was completed, M_R results were obtained and analyzed. Similar to the previous study (Li et al., 2010), to incorporate the MEPDG, regression analysis was performed on M_R data of D-1 materials tested at 20°C without the freeze-thaw cycle. Unlike the study by Li et al. (2010), a closed system was adopted during the freezing process for specimen preparation; thus, water uptake from the water bath was not allowed. Also, three different temperature gradients were applied to investigate frost heave under different temperature gradients during freezing. For regression analysis on M_R data of D-1 materials tested at subfreezing temperatures, a modified model was developed for M_R prediction.

The conclusions are as follows:

1. Frost heave values for some soils were relatively significant when compared with those from the previous study. The major reason for the frost heave difference is thought to be the use of different temperature gradients. In this study, since freezing was conducted in a closed system, both fines content and moisture content remained constant throughout the freezing process. At high freezing gradients, specimens experienced slight shrinkage rather than expansion during freezing. At medium freezing gradients, specimens expanded slightly, approximately 0.1–1.5% of total height. At low freezing gradients, specimens expanded more noticeably, by approximately 0.5–2.0% of total height.

2. Based on the temperature data collected by thermocouples attached to the soil specimens, freezing-front progress within the soil specimens was determined. Under a low temperature gradient, freezing progressed at a relatively constant rate down through the specimen. This slowly moving freezing front allowed moisture to move (redistribute) and freeze in the pore spaces; thus, the frozen soil volume increases as the volume of the moisture increases. A rapidly moving freezing front in the D-1 material causes moisture to freeze quickly in situ and results in limited volume change.

3. For unfrozen soils with fines contents of 8% and above, it was found that the M_R decreased as moisture increased, which was consistent with the previous study (Li et al., 2010).

As moisture content increased from 3.3% to 5.3%, the M_R decreased to 75%. Higher losses accompanied the application of higher deviator stresses. However, for D-1 material with 6% fines content, no significant loss of M_R was identified with increased moisture content.

4. In the previous study by Li et al. (2010), it was found that the impact of fines content varied and depended on moisture content. In this study, it was found that for low moisture content, M_R increased significantly with fines content, but for optimum moisture content, the increase was much less. For both moisture contents, this study found that 8% fines content generally produced the highest resilient moduli for unfrozen specimens at room temperature, which further agrees with the conclusion of the previous study. Furthermore, the M_R of specimens containing 10% and 12% fines generally decreased relative to the M_R of specimens containing 6% fines with increasing deviator stress and confining pressure.

5. For D-1 material under subfreezing temperatures (from -5°C to -1°C), obtained M_R values were within 120 ksi. Mean M_R values decreased with an increase of temperature of D-1 material specimens prepared under low and medium temperature gradients. However, for D-1 material specimens prepared under high temperature gradient, from -5°C to -3°C, mean M_R values increased with increased temperature.

6. Stress state is another important factor that can influence resilient behavior of D-1 material. At -5°C, a nearly linear relationship was found between M_R and deviator stress. However, at -1°C, this linear relationship only existed when the applied deviator stress was low. After reaching the peak M_R value, M_R value decreased with an increase of deviator stress. The effect of deviator stress was temperature-dependent, which is consistent with the previous study (Li et al., 2010). At room temperature (20°C), for D-1 materials with different fines content, it was found that the M_R value slightly increased with an increase of deviator stress.

7. As presented in the previous study by Li et al. (2010), when an open system was used, D-1 materials tended to experience a decrease in M_R after a freeze-thaw cycle due to the increase of moisture content. However, the present study found that for a closed system and fines contents of 6%, 10%, and 12%, without water uptake, soils tend to increase in M_R after a freeze-thaw cycle, in some cases significantly. This increase in M_R occurs because the freezing process changes the soil structure and makes the soil more compact after the freeze-thaw cycle, as compared with specimens without a freeze-thaw cycle.

8. In the previous study (Li et al., 2010), only one temperature gradient was applied for D-1 materials during freezing. In this study, three temperature gradients (low, medium, and high) were applied to specimens during freezing. It was found that temperature gradient did not have any clear influence on the resilient behavior of most of the tested D-1 material at subfreezing temperatures. However, for specimens prepared under different temperature gradients, the medium freezing gradient caused little change in M_R values. Low freezing gradients generally caused frost heave and subsequent lower M_R values.

9. Regressions were performed on the M_R data of D-1 material from the Northern region tested under frozen and unfrozen conditions for prediction of the tested D-1 material at different temperatures, moisture contents, and fines contents. As with the previous study (Li et al., 2010), for the prediction of M_R under unfrozen conditions, fines content and moisture content and the interaction between them were introduced into the model specified in the MEPDG to correlate with k_i coefficients, which are required for flexible pavement design by the MEPDG software. The modified model developed for M_R prediction of D-1 materials at subfreezing temperatures (Li et al., 2010) was also used. To incorporate the influence of ice content on resilient behavior of the tested D-1 material, a new model was presented for M_R prediction of the tested D-1 material at subfreezing temperatures.

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APPENDICES

APPENDIX LISTING

APPENDIX A

TABLE A.1 - LOW GRADIENT DATA RESULTS AT -5°C													
		MOISTURE CONTENT (%)											
		3.3				5.3				6.0			
		σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)
FINES CONTENT (%)	6	3.0	2.8	11.8	400.67	3.1	3.3	12.5	485.09	3.1	2.2	11.4	421.85
		3.0	6.4	15.5	696.53	3.1	7.0	16.1	1069.67	3.1	5.7	14.8	1028.95
		3.0	9.0	18.1	784.58	3.0	10.4	19.6	1642.72	3.1	8.4	17.5	1529.14
		5.0	4.5	19.5	596.78	5.2	5.1	20.6	845.45	5.3	4.1	19.9	776.00
		5.0	8.4	23.5	997.59	5.2	10.4	26.0	1711.13	5.3	10.6	26.4	1964.58
		5.1	12.6	27.7	1144.70	5.2	16.6	32.2	2609.12	5.3	12.7	28.5	2397.39
		10.1	10.2	40.4	1021.20	10.0	10.0	40.0	2049.09	10.1	9.0	39.3	1842.83
		10.1	19.7	49.9	1602.43	10.0	19.3	49.3	4102.58	10.1	21.5	51.8	3672.77
		10.1	29.1	59.3	2289.44	10.0	31.0	61.0	6725.48	10.1	27.1	57.3	4000.57
		15.0	9.3	54.5	1158.11	15.0	8.6	53.6	1710.91	15.2	8.9	54.4	1707.60
		15.0	14.4	59.5	1391.94	15.0	14.8	59.8	3101.05	15.2	14.6	60.1	2810.56
		15.0	29.5	74.6	2005.25	15.0	30.5	75.6	6525.10	15.2	29.9	75.4	5447.73
		20.0	14.0	73.9	1467.37	20.1	12.9	73.2	2372.10	20.1	13.2	73.4	2707.49
		20.0	19.9	79.8	1747.57	20.1	18.2	78.5	4309.40	20.1	19.6	79.8	3851.54
		20.0	41.2	101.2	2464.81	20.1	38.1	98.4	8659.32	20.1	38.6	98.9	7383.89
	8	3.1	3.1	12.3	674.34	3.1	2.9	12.3	758.96	3.1	2.4	11.8	234.98
		3.1	6.0	15.3	1328.01	3.1	7.0	16.3	1638.58	3.1	5.8	15.2	520.73
		3.1	9.4	18.7	2003.72	3.1	9.7	19.0	2392.74	3.1	8.8	18.2	736.08
		5.1	5.1	20.5	1160.57	5.0	5.1	20.3	1330.46	5.3	5.0	20.8	496.05
		5.1	10.3	25.7	2244.11	5.0	9.4	24.5	2415.65	5.3	10.0	25.8	840.50
		5.1	13.8	29.1	2995.80	5.0	18.0	33.1	4059.59	5.3	16.4	32.2	1507.13
		10.1	9.3	39.5	2087.84	10.1	8.8	39.2	2285.04	10.1	9.1	39.5	918.43
		10.1	20.0	50.2	4541.18	10.1	21.0	51.4	5225.00	10.1	20.2	50.6	2024.21
		10.1	28.6	58.8	6089.51	10.1	30.7	61.1	6246.26	10.1	27.8	58.2	2903.58
		15.1	8.6	53.8	2009.54	15.1	8.4	53.7	2160.12	15.1	8.2	53.5	932.38
		15.1	13.5	58.8	3162.38	15.1	16.6	61.8	3891.01	15.1	13.1	58.4	1513.94
		15.1	31.8	77.1	7069.28	15.1	29.2	74.4	6250.09	15.1	27.0	72.3	2906.28
		20.0	13.3	73.3	3003.15	20.1	13.9	74.3	3583.70	20.1	12.8	73.2	1721.50
		20.0	18.9	78.9	4376.02	20.1	17.1	77.4	4415.63	20.1	19.4	79.8	2500.17
		20.0	39.6	99.6	8430.81	20.1	36.8	97.1	7821.31	20.1	35.9	96.3	4278.56
	10	2.9	3.3	12.1	711.66	3.1	3.0	12.1	500.80	3.0	3.0	12.1	679.42
		2.9	6.4	15.1	1285.86	3.1	6.4	15.6	909.74	3.0	7.3	16.4	1705.36
		2.9	9.5	18.2	1838.84	3.1	9.7	18.9	1410.33	3.0	12.2	21.3	2721.48
		5.1	5.1	20.3	1128.23	5.1	4.6	19.9	708.42	5.0	5.4	20.5	1342.93
		5.1	10.1	25.3	2003.50	5.1	10.8	26.1	1686.33	5.0	9.4	24.5	2251.49
		5.1	15.7	31.0	2953.18	5.1	13.8	29.2	2426.70	5.0	16.0	31.0	3797.93
		10.0	9.5	39.5	2062.61	10.1	9.5	39.7	1985.94	10.1	9.6	39.9	2335.56
		10.2	18.9	49.4	3708.57	10.1	20.8	51.0	3738.36	10.1	21.5	51.7	5235.27
		10.1	31.4	61.9	5201.07	10.1	29.5	59.6	4503.53	10.1	32.5	62.8	7759.34
		15.1	9.3	54.5	2073.25	15.1	8.6	54.0	1413.83	14.9	8.6	53.3	2064.96
		15.1	12.9	58.1	2666.15	15.1	13.4	58.8	2252.53	14.9	16.6	61.4	3943.56
		15.1	27.7	73.0	4825.91	15.1	28.6	74.0	5013.21	14.9	30.6	75.4	7302.26
		20.0	13.4	73.5	2820.35	20.1	12.2	72.5	2216.00	20.1	14.5	74.7	3514.46
		20.0	17.4	77.5	3471.45	20.1	19.6	79.9	4192.26	20.0	18.9	79.1	4607.05
		20.0	35.3	95.4	6008.80	20.1	39.3	99.7	8119.16	20.0	41.3	101.4	9497.03
	12	3.3	3.0	12.8	720.16	3.1	3.1	12.4	636.47	3.0	3.4	12.6	745.57
		3.3	5.8	15.6	1394.05	3.1	6.6	15.9	1412.23	3.1	7.7	16.9	1315.53
		3.2	8.7	18.4	2011.20	3.1	9.6	18.9	2119.96	3.1	9.8	19.0	1631.66
		5.1	5.0	20.3	1185.48	5.1	4.9	20.1	971.26	5.1	4.3	19.4	814.03
		5.1	10.8	26.1	2609.83	5.1	9.6	24.9	1718.84	5.1	10.3	25.5	1821.56
		5.1	14.1	29.5	3071.27	5.1	11.2	26.5	2003.49	5.1	16.6	31.8	2609.87
		10.1	8.5	38.7	2033.13	10.1	9.3	39.6	2141.62	10.0	9.9	39.9	1871.81
		10.1	19.0	49.2	4220.44	10.1	21.0	51.3	4272.62	10.0	18.2	48.2	3372.30
		10.1	29.6	59.8	5676.57	10.1	29.6	59.9	5142.45	10.0	29.2	59.2	5488.65
		15.1	8.1	53.6	1946.29	15.1	9.5	54.8	2184.09	15.1	7.7	53.2	1548.51
		15.1	12.9	58.4	3088.73	15.1	14.0	59.3	2911.43	15.1	14.5	59.9	2798.52
		15.1	29.8	75.2	5880.51	15.1	28.8	74.1	5794.74	15.1	30.9	76.3	5383.33
		20.3	13.5	74.3	3108.88	20.1	13.7	73.9	2972.14	20.1	14.0	74.4	2871.76
		20.3	18.1	78.9	4021.84	20.1	17.6	77.8	4059.66	20.1	17.1	77.4	3484.90
		20.3	35.6	96.4	5156.88	20.1	42.2	102.4	7115.85	20.1	36.7	97.0	7320.92

TABLE A.2 - LOW GRADIENT DATA RESULTS AT -3°C

FINES CONTENT (%)	MOISTURE CONTENT (%) 3.3				5.3				6.0			
	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)
6	2.4	2.8	10.0	656.06	3.0	2.6	11.7	581.14	2.8	2.4	11.0	393.84
	2.4	6.4	13.6	1430.27	3.1	6.0	15.1	1399.33	2.8	6.2	14.6	978.28
	2.7	8.5	16.6	1835.86	3.1	9.9	19.1	2283.39	2.8	9.7	18.0	1302.91
	5.1	3.9	19.3	969.14	5.0	4.3	19.4	986.04	5.2	4.8	20.3	795.72
	5.1	9.5	24.9	2000.61	5.0	8.4	23.6	1988.29	5.2	9.8	25.4	1536.22
	5.1	14.5	29.8	2684.32	5.0	13.5	28.6	3142.90	5.2	14.7	30.2	2202.27
	10.1	8.5	38.8	1831.44	10.1	9.1	39.3	2173.31	10.1	9.5	39.8	1558.81
	10.1	19.0	49.3	2902.80	10.1	20.1	50.2	4364.13	10.1	21.3	51.5	3166.67
	10.1	28.7	58.9	2983.32	10.1	29.3	59.5	5114.25	10.1	30.0	60.3	4410.49
	15.1	8.4	53.6	1898.76	15.1	7.9	53.3	1900.43	15.3	7.5	53.4	1413.55
	15.1	13.3	58.5	2527.73	15.1	13.4	58.7	3169.50	15.3	15.1	61.0	2571.99
	15.1	27.4	72.6	3172.00	15.1	28.8	74.2	5628.39	15.3	27.0	72.9	4291.83
	20.1	12.2	72.4	2323.11	20.1	12.7	73.0	3084.73	20.2	10.9	71.5	1998.55
	20.1	18.5	78.6	3309.43	20.1	19.5	79.8	4561.32	20.2	17.3	78.0	2871.31
	20.1	40.7	100.9	2277.27	20.1	38.6	98.9	6679.57	20.2	38.4	99.0	4092.03
8	2.8	3.0	11.4	690.89	3.0	3.0	12.1	737.98	3.2	2.9	12.4	551.60
	3.0	6.2	15.2	1416.21	3.0	6.8	15.7	1602.34	3.2	5.5	15.1	1004.07
	3.0	9.0	18.0	1705.61	3.0	10.8	19.8	2655.88	3.1	8.8	18.2	1399.80
	5.2	5.1	20.6	1146.40	5.0	5.4	20.5	1335.53	5.2	4.2	19.7	758.87
	5.2	9.4	24.9	1737.16	5.0	8.9	24.0	2213.10	5.2	10.7	26.2	1759.50
	5.2	14.3	29.8	2170.17	5.0	17.8	33.0	4333.33	5.2	14.5	29.9	2565.12
	10.0	9.9	39.9	1981.12	10.1	10.1	40.3	2532.41	10.3	9.0	39.8	1679.73
	10.0	19.4	49.5	3011.66	10.1	19.5	49.8	4716.64	10.3	19.6	50.4	3517.85
	10.0	28.7	58.8	3832.72	10.1	28.8	59.0	6807.55	10.3	30.4	61.1	5236.62
	15.1	9.1	54.3	2019.96	15.0	8.2	53.2	2053.53	15.0	8.5	53.6	1631.75
	15.1	14.5	59.8	2752.59	15.0	14.7	59.7	3602.42	15.0	13.9	59.0	2693.25
	15.1	28.3	73.6	3764.84	15.0	28.2	73.2	7093.31	15.0	29.2	74.3	5217.65
	20.1	13.5	73.7	2681.40	20.1	10.6	71.0	2727.83	20.1	13.6	73.9	2588.52
	20.1	17.6	77.7	3228.93	20.1	17.8	78.2	4439.77	20.1	19.4	79.7	3669.36
	20.0	36.7	96.9	4333.69	20.1	35.6	95.9	8704.76	20.1	40.1	100.4	5977.44
10	2.9	3.1	11.6	695.86	3.0	2.8	11.7	794.08	3.0	2.8	12.0	684.70
	3.0	5.8	14.8	1236.26	3.0	6.9	15.8	1693.37	3.0	5.6	14.6	1311.51
	3.0	8.8	17.9	1761.26	3.0	8.8	17.7	2436.85	3.0	9.1	18.2	2114.63
	5.1	4.7	20.0	1037.39	5.1	4.7	19.9	1483.58	5.1	4.2	19.3	1010.42
	5.1	9.7	25.0	1864.35	5.1	9.2	24.4	2592.20	5.1	9.0	24.2	2204.09
	5.1	14.5	29.8	2594.68	5.1	12.8	28.0	3538.99	5.1	14.3	29.5	3505.06
	10.1	9.4	39.7	1898.73	10.1	9.9	40.2	2890.55	10.1	9.4	39.6	2296.22
	10.1	19.8	50.1	3155.07	10.1	19.9	50.2	5509.77	10.1	19.4	49.7	4664.44
	10.1	29.5	59.8	4506.71	10.1	27.7	58.1	7582.61	10.1	30.0	60.3	7065.56
	15.0	9.1	54.3	1907.21	15.1	8.7	54.2	2702.78	15.0	8.3	53.4	1983.44
	15.0	15.4	60.5	2792.21	15.1	15.3	60.8	4748.95	15.0	14.3	59.4	3532.31
	15.0	28.3	73.4	4334.19	15.1	31.9	77.3	8515.78	15.0	27.3	72.4	6449.75
	20.1	13.2	73.5	2543.20	20.2	12.9	73.4	3791.93	20.0	12.4	72.3	2928.49
	20.1	18.3	78.5	3520.21	20.2	17.7	78.2	5109.77	20.0	19.0	78.9	4465.84
	20.1	40.2	100.4	4796.95	20.2	34.7	95.2	8443.35	20.0	38.4	98.2	8001.22
12	3.1	2.5	11.7	556.16	2.6	2.7	10.6	651.82	2.8	2.7	11.1	601.24
	3.1	5.4	14.6	960.68	2.5	5.6	13.2	1121.59	2.8	5.6	13.9	1229.77
	3.1	8.2	17.5	1174.92	2.5	9.7	17.3	2737.99	2.8	8.6	16.9	1938.00
	5.0	3.9	18.9	789.83	5.1	5.1	20.3	1198.54	5.1	4.3	19.5	953.66
	5.0	9.9	24.9	1389.93	5.1	10.0	25.3	2389.12	5.1	12.8	28.0	2961.80
	5.0	14.4	29.4	1733.84	5.1	13.1	28.4	3360.59	5.1	20.9	36.1	4530.84
	10.1	8.2	38.7	1405.45	10.1	8.5	38.9	2397.47	10.1	9.6	40.0	2121.81
	10.1	21.3	51.6	2299.20	10.1	21.1	51.4	4954.82	10.1	18.7	49.1	4058.21
	10.1	29.5	59.8	2511.41	10.1	29.1	59.5	4633.31	10.1	28.2	58.6	6134.32
	15.0	7.7	52.8	1441.34	15.2	8.2	53.7	2499.47	15.1	7.8	53.3	1807.63
	15.1	12.6	57.8	1947.19	15.2	14.8	60.3	4181.58	15.1	14.5	60.0	3293.77
	15.1	26.7	71.8	4195.52	15.2	26.6	72.1	6373.29	15.1	29.4	74.8	6280.35
	20.1	11.9	72.3	2125.69	20.1	12.4	72.8	3892.00	20.0	12.6	72.4	2864.70
	20.1	16.5	76.9	2698.22	20.1	18.3	78.7	5562.95	20.0	16.8	76.7	3817.19
	20.1	34.4	94.7	4598.10	20.1	37.6	98.0	4807.85	20.0	35.2	95.1	7359.05

TABLE A.3 - LOW GRADIENT DATA RESULTS AT -1°C

	MOISTURE CONTENT (%) 3.3				5.3				6.0			
FINES CONTENT (%)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)
6	3.0	2.6	11.7	747.98	3.1	2.6	11.8	511.90	3.2	2.2	11.8	321.56
	3.0	5.5	14.6	1433.74	3.0	6.4	15.5	1097.48	3.2	6.4	16.1	756.02
	3.0	8.1	17.1	1674.68	3.0	11.2	20.3	1766.63	3.2	9.2	18.9	960.00
	5.0	4.2	19.3	1252.24	5.2	4.6	20.3	780.83	5.2	3.8	19.3	524.32
	5.0	9.0	24.0	1694.81	5.2	9.1	24.8	1498.36	5.2	9.9	25.4	1064.92
	5.0	13.0	28.0	1596.80	5.2	13.7	29.4	2062.25	5.2	14.7	30.2	1359.32
	10.0	8.1	38.3	1959.97	10.1	8.0	38.4	1574.95	10.2	9.2	39.7	1180.40
	10.1	19.3	49.5	2053.49	10.1	19.7	50.0	1864.37	10.2	19.8	50.3	1396.21
	10.1	28.5	58.7	2412.91	10.1	28.9	59.2	1720.78	10.1	29.8	60.2	967.70
	15.1	8.2	53.4	1282.58	15.0	6.4	51.5	1389.45	15.4	7.1	53.2	945.13
	15.1	13.6	58.8	1319.07	15.0	13.6	58.7	1943.47	15.4	13.3	59.5	1522.72
	15.1	28.9	74.0	2463.27	15.1	28.8	74.0	1605.06	15.4	29.9	76.0	920.33
	20.1	13.5	73.8	1465.11	20.1	12.0	72.3	1806.74	20.3	13.1	73.9	1581.44
	20.1	18.2	78.4	1543.86	20.1	18.2	78.6	1964.82	20.2	19.3	80.0	1640.27
	20.1	38.2	98.4	3122.79	20.1	36.6	96.9	1636.26	20.3	39.4	100.1	647.57
8	2.8	2.4	11.0	1085.88	2.8	2.8	11.3	617.48	3.1	2.8	12.2	463.70
	2.8	5.7	14.1	2151.51	2.8	6.1	14.4	882.24	3.1	6.4	15.8	1038.97
	3.1	8.5	17.9	3212.31	3.0	9.3	18.1	1295.83	3.1	9.2	18.6	1252.57
	5.0	4.8	19.8	2401.54	5.1	4.7	20.0	1029.30	5.1	4.8	20.3	746.17
	5.0	9.3	24.4	4335.93	5.1	11.0	26.4	1582.82	5.1	11.0	26.4	1440.59
	5.0	14.8	29.8	6700.28	5.1	17.1	32.5	2031.60	5.1	15.1	30.4	1773.66
	10.1	9.4	39.7	4578.08	10.0	9.3	39.2	1589.09	10.3	9.5	40.2	1200.10
	10.1	19.5	49.8	6651.73	10.0	20.7	50.6	2511.21	10.3	20.1	50.8	1934.11
	10.1	29.5	59.8	4468.70	10.1	31.3	61.4	3124.59	10.2	28.8	59.5	2066.51
	15.0	8.7	53.8	3499.82	15.1	8.2	53.6	1568.85	15.2	8.7	54.2	1029.37
	15.0	14.8	59.9	5213.47	15.1	14.1	59.5	2089.75	15.1	14.6	60.0	1708.71
	15.0	27.4	72.5	4582.75	15.1	28.5	73.9	3176.85	15.2	30.2	75.6	2136.48
	19.4	13.3	71.6	4617.81	20.1	12.5	72.8	2027.14	20.2	14.6	75.2	1665.81
	19.4	19.3	77.5	4100.29	20.1	18.9	79.2	2594.57	20.2	20.3	80.9	1820.63
	20.0	38.6	98.7	5438.40	20.1	36.6	96.9	2979.80	20.2	37.8	98.3	1547.82
10	2.8	2.6	10.9	608.64	3.1	3.0	12.3	782.75	3.0	2.8	11.9	699.32
	2.8	5.7	14.0	1300.13	3.1	6.3	15.6	1276.38	3.0	5.9	14.9	1426.80
	2.8	9.4	17.7	2440.25	3.1	8.9	18.2	1561.80	3.0	10.1	19.1	2368.87
	4.7	4.8	19.0	1282.97	5.1	4.5	20.0	1287.03	5.2	4.1	19.8	1006.34
	4.7	10.6	24.8	1025.21	5.1	9.6	25.0	1974.84	5.2	11.4	27.0	2712.61
	5.0	13.8	28.9	889.63	5.2	12.8	28.3	2367.82	5.2	15.6	31.2	3750.07
	10.1	9.5	39.7	1486.47	9.9	9.4	39.0	2661.71	10.1	9.0	39.3	2260.55
	10.1	19.3	49.6	1006.92	9.9	18.9	48.5	3937.04	10.1	18.4	48.7	4519.71
	10.1	28.6	58.8	660.85	9.9	28.9	58.5	3795.77	10.1	30.3	60.6	6506.32
	15.0	8.8	53.9	1971.05	15.1	8.3	53.6	3088.52	15.1	9.1	54.6	2235.83
	15.0	14.0	59.0	1514.79	15.1	14.3	59.6	4693.67	15.1	15.9	61.3	3928.07
	15.0	28.0	73.1	969.33	15.1	30.0	75.2	4486.20	15.1	30.1	75.5	6659.98
	20.1	12.5	72.8	2597.22	20.2	13.4	74.0	4838.86	20.1	12.8	73.2	3165.81
	19.2	17.8	75.4	1610.04	20.2	17.9	78.6	5700.55	20.1	18.1	78.4	4571.17
	20.1	37.6	97.8	782.05	20.2	37.0	97.7	2797.41	20.1	38.5	98.8	5817.34
12	2.5	2.3	10.0	472.69	3.0	2.7	11.7	740.57	3.1	2.7	12.1	652.90
	2.6	6.2	13.9	1209.49	3.0	5.7	14.8	1382.65	3.1	5.7	15.2	1260.04
	2.6	9.0	16.7	1186.03	3.0	10.4	19.5	1602.89	3.1	9.1	18.3	1789.50
	5.2	4.1	19.6	775.57	5.1	4.9	20.1	1007.64	5.1	4.5	19.8	1123.09
	5.2	9.8	25.3	1058.80	5.1	9.3	24.6	1497.20	5.1	10.9	26.2	2379.35
	5.2	12.3	27.8	996.58	5.1	12.4	27.6	2155.34	5.1	11.9	27.1	2134.89
	10.1	7.6	37.8	791.09	10.1	9.0	39.2	2280.13	10.1	8.5	38.7	2003.40
	10.1	17.9	48.2	602.18	10.1	19.5	49.7	1728.13	10.1	18.0	48.2	3182.08
	10.1	28.2	58.5	492.17	10.1	29.6	59.8	1658.75	10.1	26.4	56.6	3984.23
	15.1	7.3	52.4	781.15	15.0	9.0	54.1	1673.20	15.1	8.3	53.6	1988.30
	15.1	13.7	58.9	647.75	15.0	16.0	61.1	2241.82	15.1	15.3	60.5	3136.97
	15.0	26.8	71.9	508.53	15.0	29.9	74.9	1665.26	15.1	27.3	72.6	3598.16
	20.1	12.2	72.4	628.15	19.9	12.6	72.2	2179.18	20.1	13.5	73.8	3092.86
	20.0	18.1	78.3	572.07	19.9	18.8	78.4	2197.83	20.1	19.9	80.1	3889.92
	20.0	36.1	96.2	465.58	19.8	34.1	93.7	1288.77	20.1	41.0	101.2	3114.01

TABLE A.4 - LOW GRADIENT DATA RESULTS AT 20°C (one freeze-thaw cycle)													
		MOISTURE CONTENT (%)											
		3.3				5.3				6.0			
		σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)
FINES CONTENT (%)	6	2.7	2.5	10.5	57.27	3.1	2.5	11.8	7.85	-	-	-	-
		2.7	5.8	13.8	36.96	3.1	5.4	14.7	9.12	-	-	-	-
		2.7	8.5	16.5	36.45	3.1	8.6	17.9	10.98	-	-	-	-
		5.1	4.7	20.0	52.73	5.2	4.2	19.8	9.28	-	-	-	-
		5.1	9.1	24.4	44.91	5.2	9.0	24.6	12.06	-	-	-	-
		5.1	13.3	28.6	45.41	5.2	14.5	30.1	14.35	-	-	-	-
		10.1	9.4	39.6	64.88	10.1	9.4	39.8	15.51	-	-	-	-
		10.1	20.3	50.5	63.03	10.1	18.7	49.1	18.59	-	-	-	-
		10.1	28.0	58.2	64.15	10.1	28.8	59.2	22.30	-	-	-	-
		15.2	9.3	54.9	79.32	15.1	8.2	53.4	13.86	-	-	-	-
		15.2	14.7	60.4	73.68	15.1	12.9	58.2	14.90	-	-	-	-
		15.2	28.0	73.7	80.10	15.1	28.1	73.4	22.53	-	-	-	-
		19.9	14.0	73.7	91.24	20.2	12.8	73.5	18.79	-	-	-	-
		19.9	18.3	78.0	89.87	20.2	18.1	78.8	18.80	-	-	-	-
		19.9	37.5	97.2	95.61	20.2	35.7	96.4	28.41	-	-	-	-
	8	2.7	2.6	10.8	41.55	3.1	2.3	11.7	6.79	-	-	-	-
		2.7	5.6	13.8	32.32	3.1	5.5	14.8	9.21	-	-	-	-
		2.7	8.5	16.6	32.58	3.1	8.6	17.9	11.68	-	-	-	-
		5.2	5.0	20.6	48.10	5.1	4.2	19.6	9.09	-	-	-	-
		5.2	10.1	25.7	43.20	5.1	10.0	25.3	12.46	-	-	-	-
		5.2	14.8	30.5	43.55	5.1	16.1	31.5	16.25	-	-	-	-
		10.1	11.1	41.5	66.51	10.1	9.8	40.1	16.97	-	-	-	-
		10.1	20.2	50.6	64.25	10.1	18.0	48.3	20.90	-	-	-	-
		10.1	28.6	58.9	64.28	10.1	27.0	57.3	25.32	-	-	-	-
		15.1	9.6	55.0	87.88	15.1	8.6	54.0	22.48	-	-	-	-
		15.1	14.1	59.5	80.80	15.1	12.8	58.2	21.17	-	-	-	-
		15.1	28.3	73.7	82.43	15.1	29.7	75.1	28.27	-	-	-	-
		20.1	13.4	73.7	82.28	20.2	12.9	73.5	23.79	-	-	-	-
		20.1	18.7	79.0	83.07	20.2	17.4	77.9	23.98	-	-	-	-
		20.1	37.4	97.7	84.38	20.2	35.0	95.6	33.67	-	-	-	-
	10	1.7	2.2	7.5	53.94	3.2	2.4	12.0	9.37	-	-	-	-
		1.7	5.3	10.6	53.71	3.2	5.5	15.0	12.37	-	-	-	-
		1.7	7.9	13.1	51.72	3.2	8.2	17.7	14.75	-	-	-	-
		5.2	4.8	20.4	86.38	5.1	3.9	19.3	11.47	-	-	-	-
		5.2	11.0	26.4	63.70	5.1	9.2	24.6	15.41	-	-	-	-
		5.2	14.1	29.5	64.80	5.1	13.4	28.8	18.47	-	-	-	-
		10.2	10.2	40.7	90.51	10.1	8.7	39.0	18.62	-	-	-	-
		10.2	19.8	50.3	90.39	10.1	18.3	48.6	24.33	-	-	-	-
		10.2	27.2	57.7	93.00	10.1	27.5	57.8	30.88	-	-	-	-
		15.2	8.8	54.3	120.05	15.1	8.4	53.9	23.29	-	-	-	-
		15.2	14.8	60.2	114.11	15.1	12.6	58.0	23.94	-	-	-	-
		15.2	28.7	74.2	116.67	15.1	28.5	73.9	34.26	-	-	-	-
		20.2	13.6	74.2	149.89	20.2	12.8	73.4	30.24	-	-	-	-
		20.2	20.4	81.1	139.18	20.2	16.7	77.2	30.11	-	-	-	-
		20.2	38.9	99.6	137.18	20.2	35.7	96.3	43.83	-	-	-	-
	12	3.2	2.4	12.1	59.46	3.1	2.8	12.2	15.53	-	-	-	-
		3.2	6.0	15.7	37.26	3.1	6.2	15.6	21.96	-	-	-	-
		3.2	9.3	19.0	37.89	3.1	9.5	18.9	26.53	-	-	-	-
		4.9	4.4	19.0	52.96	5.1	4.7	19.8	24.77	-	-	-	-
		4.9	9.9	24.5	42.42	5.1	9.8	25.0	31.78	-	-	-	-
		4.9	14.3	28.9	43.77	5.1	14.5	29.7	33.50	-	-	-	-
		10.1	9.6	39.8	68.67	10.2	9.3	39.9	46.52	-	-	-	-
		10.1	19.4	49.6	62.91	10.2	18.6	49.1	46.80	-	-	-	-
		10.1	27.9	58.1	63.99	10.2	26.8	57.3	63.51	-	-	-	-
		15.1	9.1	54.3	94.82	15.1	8.6	53.9	60.63	-	-	-	-
		15.1	14.1	59.3	80.08	15.1	14.0	59.3	60.89	-	-	-	-
		15.1	29.2	74.4	78.94	15.1	29.9	75.1	81.68	-	-	-	-
		20.1	13.2	73.5	133.36	20.1	14.4	74.6	89.41	-	-	-	-
		20.1	18.1	78.3	113.76	20.1	18.3	78.5	90.43	-	-	-	-
		20.1	39.2	99.4	102.07	20.1	36.6	96.8	96.00	-	-	-	-

APPENDIX B

TABLE B.1 - MEDIUM GRADIENT DATA RESULTS AT -5°C

FINES CONTENT (%)	MOISTURE CONTENT (%)											
	3.3				5.3				6.0			
	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)
6	3.2	2.9	12.6	465.75	3.2	2.9	12.4	636.29	3.1	2.4	11.8	493.22
	3.2	5.8	15.6	1214.51	3.2	6.9	16.5	1452.69	3.1	5.9	15.3	735.75
	3.2	8.8	18.6	1908.34	3.2	8.6	18.2	1855.27	3.1	8.3	17.7	1204.37
	5.1	4.2	19.5	972.39	5.1	4.7	20.1	1102.99	5.1	4.2	19.4	1120.28
	5.1	9.3	24.6	1798.52	5.1	10.4	25.8	1930.36	5.1	9.7	25.0	2386.22
	5.1	14.6	29.9	2687.17	5.1	17.4	32.8	2809.49	5.1	14.8	30.1	4131.48
	10.0	9.1	39.0	1874.32	10.2	9.5	40.1	2173.34	10.1	9.8	40.3	3583.94
	10.0	18.7	48.8	3312.42	10.2	20.8	51.3	3462.41	10.1	20.5	50.9	6224.71
	10.0	29.4	59.4	4687.53	10.2	32.0	62.5	4346.67	10.2	29.0	59.5	6544.55
	15.1	8.5	53.8	1821.16	15.1	8.7	54.0	2250.74	15.1	9.0	54.1	3347.38
	15.1	14.2	59.4	2714.26	15.1	15.7	61.0	3054.73	15.1	16.2	61.3	5895.12
	15.1	30.9	76.1	5743.09	15.1	27.1	72.3	4382.16	15.1	30.2	75.3	8812.72
	20.2	13.2	73.9	2010.15	20.1	13.3	73.6	3418.33	20.2	14.3	74.9	5426.47
	20.2	19.4	80.1	2718.94	20.1	18.5	78.7	4156.69	20.2	19.1	79.6	6757.41
	20.2	40.4	101.2	2734.79	20.1	39.5	99.7	5386.60	20.2	43.5	104.1	12147.4
8	3.2	2.9	12.5	415.87	3.2	2.9	12.6	729.19	2.7	2.6	10.7	635.53
	3.2	6.9	16.5	903.55	3.2	5.8	15.4	1327.92	2.7	6.7	14.8	1487.40
	3.2	9.6	19.2	1202.71	3.2	8.5	18.1	1821.92	2.7	10.3	18.4	2143.97
	5.1	4.9	20.2	634.66	5.1	4.7	20.1	1102.57	4.9	5.3	20.0	1261.64
	5.1	10.7	26.0	1631.80	5.1	10.7	26.1	2529.45	4.9	9.1	23.9	1976.70
	5.1	13.8	29.2	1690.08	5.1	14.5	29.9	3652.37	4.9	12.5	27.2	2620.73
	10.1	9.7	40.0	1672.21	10.1	9.5	39.7	2147.86	10.1	9.4	39.6	2098.23
	10.1	18.6	48.9	2847.25	10.0	18.2	48.4	4212.35	10.1	18.5	48.8	4130.73
	10.1	28.6	58.9	5308.15	10.0	29.9	60.1	6741.59	10.1	28.3	58.6	6208.14
	15.2	9.0	54.5	1294.88	15.1	8.7	54.0	2432.33	15.1	9.3	54.6	2200.17
	15.2	16.0	61.4	2463.79	15.1	16.2	61.5	3944.11	15.1	13.4	58.7	3168.93
	15.2	31.6	77.1	4535.71	15.1	29.4	74.7	7971.67	15.1	32.7	78.0	7453.16
	20.0	13.6	73.6	1854.53	20.1	14.0	74.2	3754.55	20.0	14.4	74.3	3462.13
	20.0	18.7	78.7	3016.75	20.1	18.6	78.8	4876.03	20.0	19.7	79.7	4764.92
	20.0	42.3	102.3	6069.05	20.1	39.6	99.7	10320.3	20.0	37.7	97.6	8650.31
10	3.1	3.0	12.2	634.99	2.9	2.7	11.6	620.56	3.1	2.1	11.3	385.36
	3.1	6.5	15.7	1361.12	3.2	6.2	15.8	1430.59	3.1	5.9	15.1	1068.51
	3.1	9.5	18.7	2031.36	3.2	9.0	18.7	1879.24	3.1	9.8	19.0	1672.97
	5.2	4.4	20.1	968.84	5.2	5.0	20.5	1159.07	5.1	4.2	19.6	746.26
	5.2	10.6	26.2	2274.10	5.2	10.1	25.6	2194.16	5.1	12.3	27.6	2048.96
	5.2	15.7	31.3	3284.47	5.2	14.6	30.1	3036.49	5.1	16.5	31.9	2776.49
	10.0	9.4	39.5	2134.82	10.1	9.5	39.9	2092.05	10.2	10.2	40.8	1843.53
	10.0	20.7	50.8	4503.73	10.1	20.1	50.5	4250.62	10.2	21.9	52.4	3199.59
	10.0	26.6	56.6	4898.85	10.2	27.6	58.1	5663.71	10.2	32.3	62.9	4156.91
	15.2	8.3	53.8	1814.73	15.1	7.9	53.2	2040.67	15.1	8.6	53.9	1615.29
	15.2	12.9	58.5	2741.40	15.1	14.8	60.0	3285.59	15.1	16.6	61.9	3028.34
	15.2	29.4	74.9	6103.78	15.1	28.5	73.8	5709.93	15.1	29.9	75.2	3798.77
	20.1	13.6	73.9	2830.12	20.1	11.4	71.6	2908.50	20.2	13.1	73.6	2408.49
	20.1	19.0	79.3	4094.49	20.1	18.3	78.5	4293.95	20.2	19.8	80.3	3530.56
	20.1	34.6	94.9	6742.89	20.1	35.1	95.3	6861.12	20.2	39.9	100.4	4882.75
12	3.2	1.8	11.4	381.27	3.2	2.7	12.3	686.78	3.1	2.7	12.0	907.20
	3.2	5.6	15.2	1183.30	3.2	7.6	17.1	1578.43	3.0	6.1	15.2	2030.55
	3.2	8.9	18.5	1817.12	3.2	10.5	20.0	1803.50	3.1	8.3	17.5	2578.09
	5.1	4.8	20.0	1079.90	5.1	4.7	19.9	1022.82	5.2	4.5	20.0	1505.18
	5.1	10.9	26.1	2378.64	5.1	9.6	24.8	1982.41	5.2	9.9	25.4	2575.63
	5.1	13.1	28.3	2772.87	5.1	14.4	29.6	2820.36	5.2	13.9	29.4	3223.72
	10.1	10.1	40.4	2198.78	10.2	9.2	39.7	2209.26	10.1	8.5	38.7	2192.04
	10.1	18.9	49.1	4117.17	10.2	19.6	50.2	4277.92	10.1	19.7	50.0	5056.31
	10.1	30.8	61.1	6351.11	10.2	27.9	58.5	5730.78	10.1	27.9	58.2	7227.82
	15.1	8.6	53.8	1913.04	15.1	7.7	53.1	1829.77	15.1	7.9	53.2	2660.20
	15.1	14.2	59.5	3072.52	15.1	13.4	58.9	3074.32	15.1	14.2	59.4	4460.10
	15.1	29.2	74.5	6224.79	15.2	29.3	74.8	5802.46	15.1	29.8	75.1	7561.13
	20.3	12.9	73.7	2809.99	20.2	13.3	73.8	2948.65	20.1	12.5	72.7	4388.72
	20.3	19.1	80.0	4131.04	20.2	19.3	79.8	4407.99	20.1	19.3	79.5	5698.45
	20.3	37.9	98.7	8095.43	20.2	39.2	99.7	8420.71	20.1	37.5	97.7	8730.38

TABLE B.2 - MEDIUM GRADIENT DATA RESULTS AT -3°C													
		MOISTURE CONTENT (%)											
		3.3				5.3				6.0			
		σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)
FINES CONTENT (%)	6	3.1	2.4	11.8	568.11	3.1	2.8	12.1	667.93	3.1	2.7	12.1	532.47
		3.1	5.9	15.2	1401.18	3.1	6.0	15.3	1421.26	3.2	6.1	15.6	1126.38
		3.1	8.5	17.8	1907.47	3.1	9.2	18.5	2203.11	3.2	8.5	17.9	1441.74
		5.0	5.0	20.2	1205.42	5.1	4.4	19.7	1101.90	5.2	4.6	20.1	911.94
		5.0	9.7	24.8	2194.06	5.1	9.5	24.9	2458.39	5.2	9.1	24.6	1593.46
		5.1	14.2	29.3	2986.48	5.1	15.7	31.1	3815.30	5.2	13.3	28.8	2399.10
		9.9	8.5	38.1	2117.92	10.1	9.1	39.5	2198.50	10.1	8.5	38.8	1647.45
		10.1	17.3	47.6	3482.08	10.1	20.3	50.7	3132.16	10.1	19.8	50.2	3755.42
		10.1	28.3	58.6	5151.73	10.1	30.8	61.3	4815.29	10.1	28.1	58.5	4662.45
		15.1	8.6	53.8	1982.76	15.1	8.8	54.1	2173.55	15.1	9.0	54.3	1826.64
		15.1	13.1	58.4	2985.89	15.1	15.6	60.9	3021.05	15.1	13.9	59.2	2945.20
		15.1	27.2	72.4	5012.51	15.1	30.0	75.3	4681.18	15.1	26.7	72.0	4509.40
		20.1	12.8	73.1	2916.87	20.3	12.8	73.6	3094.57	20.1	12.7	72.9	2617.10
		20.1	17.5	77.8	4014.98	20.3	17.6	78.4	3108.85	20.1	17.6	77.9	3570.88
		20.1	34.0	94.3	5768.09	20.3	38.4	99.2	5641.83	20.1	38.7	99.1	4352.79
	8	3.2	3.0	12.7	680.62	3.1	2.8	12.1	721.09	2.9	2.7	11.4	609.91
		3.2	5.9	15.7	1332.96	3.1	6.5	15.8	1653.06	2.9	5.8	14.4	1319.45
		3.2	10.1	19.8	2169.55	3.1	9.4	18.6	2191.99	2.9	7.4	16.1	1648.58
		5.1	4.6	20.0	1043.16	5.2	4.7	20.3	1187.45	4.9	4.5	19.1	1006.67
		5.1	8.3	23.7	1808.00	5.2	10.7	26.3	2503.05	5.1	8.8	23.9	1919.21
		5.1	14.3	29.7	3085.17	5.2	14.4	30.0	3423.75	5.1	14.1	29.3	3212.72
		10.1	10.6	40.8	2389.97	10.2	8.9	39.5	2261.45	10.1	9.3	39.7	2106.33
		10.1	18.6	48.9	4174.37	10.2	20.0	50.5	4721.02	10.1	18.9	49.3	4228.89
		10.1	31.5	61.7	6398.55	10.2	34.6	65.2	6287.95	10.1	26.6	57.0	5536.97
		14.8	9.7	54.2	2253.39	15.1	8.2	53.6	2145.52	15.1	9.0	54.4	1961.90
		14.8	15.6	60.1	3613.07	15.1	14.8	60.1	3312.42	15.1	13.2	58.6	2922.09
		14.8	30.1	74.6	6283.21	15.1	30.9	76.2	7368.94	15.1	26.5	71.9	5558.68
		20.0	15.3	75.4	3547.54	20.1	12.6	72.8	3003.91	20.0	14.2	74.2	3182.12
		20.0	20.0	80.0	4504.97	20.1	16.5	76.7	3798.27	20.0	17.9	78.0	4017.01
		20.0	40.6	100.6	7365.28	20.1	38.1	98.3	8662.62	20.0	33.3	93.4	7077.75
	10	2.9	2.9	11.5	798.90	3.1	2.8	12.1	635.37	2.9	2.4	11.2	445.26
		2.9	6.0	14.6	1806.93	3.0	5.5	14.6	1268.79	2.9	6.9	15.7	1284.37
		2.9	9.4	18.0	2721.28	3.0	8.0	17.2	1831.02	3.0	10.3	19.2	1951.65
		5.0	4.5	19.7	1350.48	5.1	4.8	20.0	1161.81	5.1	4.6	20.0	870.38
		5.0	9.4	24.6	2645.25	5.1	9.0	24.2	2200.99	5.1	10.9	26.3	2096.53
		5.0	14.4	29.5	3842.17	5.1	13.7	28.9	3255.24	5.1	14.6	30.0	2850.80
		10.0	9.1	39.3	2707.37	10.1	9.2	39.4	2354.12	10.0	8.4	38.5	1630.58
		10.0	19.6	49.7	5495.01	10.1	19.9	50.1	4922.68	10.0	21.0	51.1	4007.18
		10.0	26.6	56.7	6667.10	10.1	26.7	56.9	5797.31	10.0	29.9	59.9	4339.61
		15.1	7.7	53.0	2215.31	15.1	8.4	53.6	2131.02	15.1	8.6	54.1	1667.07
		15.1	13.0	58.3	3880.43	15.1	15.6	60.8	3725.86	15.1	15.2	60.6	2963.64
		15.1	30.0	75.3	7747.74	15.1	27.6	72.7	5669.66	15.1	27.7	73.1	3866.90
		20.1	12.8	73.0	3789.44	20.1	12.9	73.1	3257.85	20.1	12.2	72.5	2422.31
		20.1	18.5	78.7	5164.16	20.1	18.1	78.3	4384.43	20.1	20.1	80.3	3933.92
		20.1	36.2	96.4	8930.59	20.1	37.2	97.4	7190.45	20.1	38.1	98.3	5141.70
	12	2.8	2.3	10.8	467.05	3.2	2.7	12.2	709.78	3.1	2.5	11.9	382.91
		2.9	6.0	14.6	1304.67	3.1	6.3	15.6	1571.76	3.1	5.5	14.9	836.78
		2.9	8.9	17.5	1901.02	3.1	8.3	17.6	1864.78	3.1	8.3	17.7	1187.87
		4.8	5.1	19.4	1084.42	5.1	4.9	20.0	1208.24	5.1	4.4	19.7	679.78
		4.8	9.9	24.3	2158.97	5.1	9.1	24.3	2063.15	5.1	9.3	24.5	1227.83
		5.1	14.2	29.4	2969.54	5.1	13.3	28.5	2993.41	5.1	13.9	29.1	1613.21
		10.1	10.1	40.5	2177.04	10.0	9.5	39.6	2346.15	10.2	10.0	40.4	1372.49
		10.1	19.4	49.8	3997.09	10.0	21.8	51.9	4885.78	10.1	19.6	50.0	2724.97
		10.1	30.2	60.6	4752.14	10.0	30.9	61.0	6516.42	10.1	29.1	59.5	3781.80
		15.0	10.0	55.1	2158.85	15.0	8.7	53.9	2244.80	15.1	9.0	54.4	1454.39
		15.0	15.5	60.6	3350.26	15.0	13.9	59.0	3416.69	15.1	14.5	59.8	2342.76
		15.0	29.0	74.1	4893.40	15.0	29.7	74.8	6990.81	15.1	28.4	73.7	3976.59
		20.1	13.8	74.1	3005.67	20.1	12.8	72.9	3269.70	20.1	12.7	73.0	2235.29
		20.1	18.8	79.0	4090.99	20.1	18.2	78.4	4455.81	20.1	19.0	79.3	3234.14
		20.1	37.0	97.2	6247.75	20.1	35.9	96.1	6951.63	20.1	39.1	99.4	5080.86

TABLE B.3 - MEDIUM GRADIENT DATA RESULTS AT -1°C													
		MOISTURE CONTENT (%)											
		3.3				5.3				6.0			
		σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)
FINES CONTENT (%)	6	3.1	2.3	11.7	515.41	3.2	3.0	12.6	1104.03	2.9	2.8	11.5	541.07
		3.1	5.7	15.1	1033.58	3.2	6.1	15.8	1890.43	2.9	5.7	14.5	499.25
		3.1	8.8	18.2	1267.45	3.2	9.3	19.0	2565.58	2.9	9.1	17.8	885.79
		5.1	4.1	19.3	834.21	5.1	4.4	19.7	1658.07	5.1	4.0	19.5	365.24
		5.0	10.0	25.1	1128.39	5.1	10.8	26.1	2489.71	5.1	9.4	24.8	840.78
		5.0	14.8	30.0	729.71	5.1	14.3	29.7	3108.87	5.2	15.7	31.2	1679.48
		10.1	9.6	40.0	1071.18	10.1	9.9	40.3	2748.78	10.1	9.5	39.8	934.01
		10.1	18.5	48.9	609.89	10.2	20.9	51.4	2041.54	10.1	19.9	50.2	1407.60
		10.1	28.3	58.7	415.68	10.2	27.6	58.1	1841.81	10.1	29.7	60.0	926.22
		14.9	8.7	53.4	1338.79	15.1	8.7	54.0	2822.19	15.1	8.8	54.1	796.26
		14.9	14.4	59.2	697.84	15.1	14.3	59.7	2655.27	15.1	14.9	60.3	1534.98
		14.9	27.7	72.5	400.10	15.1	28.2	73.6	1681.21	15.1	29.2	74.5	862.27
		20.1	12.3	72.7	1436.56	20.0	13.5	73.5	3144.36	20.3	13.2	74.1	1052.31
		20.1	18.3	78.6	807.08	20.0	19.7	79.7	1955.97	20.3	18.1	78.9	1515.25
		20.1	36.4	96.7	386.66	20.0	37.0	97.0	1465.01	20.3	35.7	96.6	688.86
	8	3.2	2.3	11.8	517.24	3.2	2.8	12.3	923.46	2.8	2.5	11.0	548.02
		3.2	5.2	14.7	1162.32	3.2	6.3	15.8	1689.84	2.8	5.5	14.0	1236.94
		3.2	8.3	17.8	1788.87	3.1	9.3	18.7	1974.40	2.8	8.8	17.2	1981.50
		5.1	4.3	19.5	973.33	5.1	4.4	19.6	1508.53	5.1	4.4	19.8	982.01
		5.1	9.7	24.9	2062.78	5.1	9.8	25.0	2192.65	5.1	9.1	24.5	1997.54
		5.0	13.7	28.8	2084.55	5.1	14.3	29.5	1677.90	5.1	12.8	28.2	2517.33
		10.1	8.9	39.2	1868.96	10.1	9.1	39.4	2163.57	10.0	8.4	38.4	1777.41
		10.1	16.4	46.7	1842.03	10.1	18.8	49.1	1733.61	10.0	18.5	48.4	3432.83
		10.1	31.5	61.7	987.78	10.1	28.2	58.5	1397.82	10.0	27.7	57.7	3994.00
		15.0	7.4	52.5	1523.35	15.1	8.5	53.8	2379.06	15.0	7.1	52.2	1418.02
		15.0	12.9	58.0	1545.39	15.1	13.8	59.1	2545.72	15.0	12.7	57.8	2348.45
		15.1	43.3	88.6	809.38	15.1	29.2	74.5	1534.69	15.0	28.4	73.5	4351.54
		20.1	12.9	73.2	1333.05	20.0	12.6	72.7	2799.33	20.1	11.1	71.4	2349.62
		20.1	19.4	79.7	1537.39	20.0	19.5	79.6	2228.41	20.1	16.9	77.1	3342.78
		20.1	34.2	94.4	642.53	20.0	39.2	99.3	1509.11	20.1	31.2	91.4	4986.54
	10	3.1	2.2	11.5	431.93	3.1	2.7	12.0	948.67	3.2	2.8	12.4	501.77
		3.1	7.2	16.5	1110.37	3.1	6.1	15.4	2124.69	3.2	5.8	15.4	1016.82
		3.1	8.6	17.8	736.31	3.1	9.5	18.8	3183.31	3.2	9.8	19.4	1538.77
		5.1	4.6	19.9	774.21	5.1	4.9	20.2	1645.26	5.1	4.5	19.7	821.36
		5.1	10.1	25.4	1147.05	5.1	9.7	25.0	3322.97	5.1	10.3	25.5	1504.82
		5.1	14.5	29.8	672.55	5.1	15.5	30.7	4433.19	5.1	15.0	30.2	1924.10
		10.3	9.1	39.8	1182.67	10.2	9.5	40.1	3238.95	10.2	9.4	40.0	1359.51
		10.3	16.6	47.3	661.55	10.2	20.0	50.6	5141.73	10.2	20.7	51.3	2349.44
		10.3	27.1	57.9	366.85	10.2	29.1	59.7	6408.03	10.2	29.7	60.3	2601.96
		15.1	6.9	52.3	939.20	15.0	8.7	53.8	2758.46	15.1	7.4	52.8	1170.70
		15.1	14.0	59.4	1605.78	15.0	14.6	59.7	4257.91	15.1	13.7	59.1	1959.18
		15.1	27.7	73.0	415.85	15.0	30.7	75.8	6927.55	15.1	29.0	74.3	2326.73
		20.4	13.7	74.9	1513.22	20.1	12.5	72.9	4196.18	20.1	12.0	72.4	1792.28
		20.4	17.8	79.1	1567.12	20.1	18.2	78.6	5354.87	20.1	19.2	79.5	2127.97
		20.4	36.5	97.7	361.60	20.1	37.7	98.1	6949.79	20.1	37.1	97.4	2785.41
	12	3.0	2.4	11.5	518.71	3.1	3.0	12.4	923.98	2.9	2.8	11.5	1020.27
		3.0	7.0	16.1	1548.73	3.1	5.7	15.0	1427.39	2.9	6.2	14.9	2048.41
		3.0	10.5	19.6	2312.17	3.1	8.2	17.6	1691.10	2.9	8.9	17.6	2949.22
		5.2	5.4	20.9	1239.64	5.0	5.3	20.4	1692.34	5.2	4.2	19.9	1459.90
		5.2	11.1	26.6	2442.45	5.1	10.2	25.4	2686.55	5.2	10.1	25.8	3255.30
		5.2	15.6	31.0	2653.64	5.1	15.2	30.4	2169.54	5.2	14.0	29.7	4235.55
		10.1	9.2	39.6	1993.48	10.0	9.1	39.2	1672.88	10.2	9.1	39.7	3036.84
		10.1	18.0	48.4	2273.26	10.0	20.0	50.1	2644.52	10.2	18.9	49.5	3264.34
		10.1	29.0	59.4	1291.51	10.0	27.6	57.7	1288.78	10.2	27.3	57.8	1674.90
		15.1	7.2	52.6	1532.42	15.1	9.1	54.3	2081.80	15.3	8.1	54.0	2726.92
		15.1	13.1	58.4	1869.10	15.1	14.9	60.1	2711.67	15.3	16.0	61.9	5222.12
		15.1	26.5	71.9	864.30	15.1	28.3	74.4	1120.26	15.3	28.1	74.0	1974.47
		20.1	11.5	71.9	2336.87	20.1	12.2	72.4	2215.12	20.3	12.4	73.2	4317.05
		20.1	17.5	77.9	1206.61	20.1	19.3	79.5	1430.69	20.3	18.4	79.2	3607.80
		20.1	29.3	89.7	735.42	20.1	38.3	98.5	1090.54	20.3	36.7	97.5	1528.02

TABLE B.4 - MEDIUM GRADIENT DATA RESULTS AT 20°C (one freeze-thaw cycle)												
	MOISTURE CONTENT (%)											
	3.3				5.3				6.0			
FINES CONTENT (%)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)
6	2.9	2.5	11.1	29.60	3.0	2.7	11.6	13.71	3.1	2.3	11.6	34.16
	3.1	5.6	14.9	29.27	3.0	5.9	14.8	17.21	3.1	6.4	15.7	33.90
	3.1	8.4	17.7	30.91	3.0	8.9	17.9	23.47	3.1	9.3	18.6	40.55
	5.2	4.9	20.4	41.80	5.1	4.5	19.8	22.44	5.2	3.9	19.6	33.48
	5.2	9.6	25.1	40.27	5.1	9.3	24.6	27.50	5.2	11.1	26.8	41.82
	5.2	13.2	28.7	41.44	5.1	14.2	29.5	32.33	5.2	15.5	31.2	47.06
	10.1	9.1	39.5	68.02	10.1	8.9	39.2	33.41	10.2	8.4	39.0	40.76
	10.1	17.8	48.2	64.03	10.1	19.2	49.5	45.66	10.2	18.5	49.0	30.88
	10.1	26.1	56.5	63.69	10.1	28.5	58.8	51.96	-	-	-	-
	15.1	8.8	54.1	92.03	15.1	8.8	54.1	43.44	-	-	-	-
	15.1	14.7	60.1	80.16	15.1	13.8	59.1	42.60	-	-	-	-
	15.1	27.2	72.5	80.21	15.1	28.5	73.8	56.09	-	-	-	-
	20.1	14.0	74.3	101.61	20.1	13.8	74.1	51.66	-	-	-	-
	20.1	18.2	78.4	97.26	20.1	19.1	79.4	55.51	-	-	-	-
	20.1	35.2	95.4	95.39	20.1	37.0	97.3	75.11	-	-	-	-
8	2.9	2.2	10.8	46.11	3.2	1.9	11.4	12.36	3.1	2.1	11.4	4.35
	2.9	5.3	14.0	32.84	3.1	5.5	14.9	19.41	3.1	5.5	14.8	7.17
	3.1	8.2	17.5	34.45	3.1	8.7	18.1	24.00	3.1	8.9	18.2	8.93
	5.1	5.0	20.4	46.53	5.1	4.3	19.7	16.16	5.1	3.9	19.1	5.38
	5.1	9.8	25.3	43.58	5.1	9.1	24.5	22.74	-	-	-	-
	5.1	14.5	29.9	44.37	5.1	13.9	29.3	28.94	-	-	-	-
	10.1	9.5	39.8	69.18	10.2	8.7	39.3	26.92	-	-	-	-
	10.1	19.2	49.4	67.43	10.2	18.9	49.5	38.51	-	-	-	-
	10.1	27.2	57.5	67.84	10.2	29.1	59.7	49.53	-	-	-	-
	15.1	8.8	54.1	98.82	15.1	8.5	53.6	30.71	-	-	-	-
	15.1	13.9	59.1	86.84	15.1	13.7	58.9	34.86	-	-	-	-
	15.1	27.9	73.2	85.31	15.1	28.0	73.2	52.71	-	-	-	-
	20.0	13.8	73.7	107.93	20.1	13.2	73.6	43.85	-	-	-	-
	20.0	18.6	78.5	103.88	20.1	18.0	78.5	48.83	-	-	-	-
	19.9	34.6	94.5	100.68	20.1	36.8	97.3	68.78	-	-	-	-
10	3.2	2.1	11.7	43.27	3.1	2.8	12.1	12.06	3.1	2.6	11.9	4.50
	3.1	6.2	15.6	29.37	3.1	5.6	14.9	13.99	3.1	6.1	15.4	7.47
	3.1	9.3	18.7	30.78	3.1	9.0	18.3	16.76	3.1	8.8	18.1	9.88
	5.2	5.1	20.7	42.69	5.1	4.8	20.1	15.56	4.9	4.1	18.9	6.36
	5.2	9.9	25.6	40.43	5.1	9.4	24.7	18.74	4.9	9.6	24.5	10.32
	5.2	14.0	29.7	41.56	5.1	13.8	29.1	21.64	4.9	14.3	29.1	13.67
	10.1	9.7	40.0	67.65	10.2	9.2	39.7	26.38	10.1	9.3	39.7	12.64
	10.1	19.1	49.5	63.73	10.2	18.8	49.3	30.61	10.1	19.7	50.1	18.06
	10.1	27.7	58.0	61.93	10.1	27.6	58.0	35.67	10.2	29.3	59.8	22.71
	14.6	9.5	53.3	84.89	15.1	8.9	54.1	34.31	15.1	8.2	53.6	15.94
	14.6	13.9	57.7	77.18	15.1	13.6	58.9	35.12	15.1	12.7	58.1	16.26
	14.6	28.0	71.8	77.76	15.1	27.9	73.1	43.66	15.1	28.8	74.2	24.69
	19.5	14.7	73.2	98.09	20.1	13.8	74.1	44.79	20.0	12.6	72.7	19.34
	19.5	18.5	77.0	95.01	20.1	18.4	78.7	47.51	20.0	18.0	78.0	27.84
	19.5	34.8	93.4	94.91	20.1	36.3	96.6	57.67	20.0	36.3	96.4	50.65
12	3.2	1.8	11.5	47.75	3.1	2.6	11.9	13.75	-	-	-	-
	3.2	6.2	15.8	30.94	3.1	5.7	15.0	17.37	-	-	-	-
	3.2	9.4	19.0	32.22	3.1	9.0	18.3	20.44	-	-	-	-
	5.1	5.2	20.5	39.93	5.0	4.6	19.7	17.26	-	-	-	-
	5.1	10.7	25.9	40.25	5.0	9.1	24.3	22.36	-	-	-	-
	5.1	14.8	30.0	41.03	5.0	13.4	28.5	26.50	-	-	-	-
	10.1	10.6	41.0	62.05	10.1	9.3	39.6	31.37	-	-	-	-
	10.1	20.0	50.5	61.06	10.1	18.3	48.5	37.51	-	-	-	-
	10.1	28.2	58.6	61.33	10.1	27.8	58.0	44.24	-	-	-	-
	15.0	9.6	54.8	78.63	15.1	8.7	54.0	38.82	-	-	-	-
	15.0	14.8	59.9	73.63	15.1	13.4	58.7	39.81	-	-	-	-
	15.0	26.3	71.4	75.89	15.1	26.8	72.1	49.62	-	-	-	-
	20.0	13.3	73.5	93.40	20.1	13.0	73.3	47.98	-	-	-	-
	20.0	19.1	79.2	90.82	20.1	17.8	78.1	50.20	-	-	-	-
	20.0	35.9	96.0	91.86	20.1	36.1	96.3	62.14	-	-	-	-

APPENDIX C

TABLE C.1 - HIGH GRADIENT DATA RESULTS AT -5°C													
		MOISTURE CONTENT (%)											
		3.3				5.3				6.0			
		σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)
FINES CONTENT (%)	6	3.1	2.8	12.1	270.13	3.1	2.7	12.0	593.98	2.4	2.4	9.5	480.12
		3.1	5.8	15.0	444.52	3.1	5.7	15.0	1020.67	2.3	7.9	14.9	1540.73
		3.1	8.7	18.0	555.86	3.1	9.0	18.2	1569.63	2.3	11.0	18.0	2029.06
		5.0	4.6	19.7	515.20	5.1	4.4	19.7	975.37	5.2	4.8	20.3	950.72
		5.0	10.3	25.4	915.56	5.1	8.7	23.9	1736.50	5.2	12.0	27.5	2275.09
		5.0	14.2	29.3	1214.45	5.1	15.9	31.2	2632.66	5.2	16.2	31.7	2704.50
		9.6	9.5	38.3	967.93	10.1	10.2	40.5	2456.05	10.1	9.5	39.7	1904.37
		9.6	18.9	47.7	1326.89	10.1	19.4	49.6	4585.73	10.1	20.8	51.1	3466.20
		9.6	26.8	55.7	1422.53	10.1	26.6	56.8	5737.88	10.1	33.3	63.5	5326.70
		15.0	8.2	53.3	721.62	15.2	8.5	54.0	2075.29	15.4	8.9	55.2	1833.21
		15.0	15.5	60.6	1354.16	15.1	16.2	61.6	3962.18	15.4	14.9	61.2	2615.11
		15.0	30.3	75.5	1468.39	15.1	28.4	73.8	6272.03	15.4	32.3	78.6	5243.32
		20.1	12.3	72.5	946.64	20.1	10.9	71.3	2694.93	19.9	13.7	73.4	2627.97
		20.1	18.7	78.8	1283.17	20.1	15.3	75.7	3715.80	19.9	18.0	77.8	3334.91
		20.1	39.9	100.1	1802.85	20.1	34.4	94.7	7409.66	19.9	37.4	97.1	5688.03
	8	3.1	2.5	11.9	411.77	3.1	3.0	12.4	789.54	3.1	2.4	11.7	555.59
		3.1	6.0	15.3	1015.25	3.1	6.1	15.5	1603.55	3.1	5.9	15.1	1296.18
		3.1	9.4	18.8	1560.86	3.1	8.8	18.2	2233.50	3.1	9.7	18.9	2073.10
		5.1	4.9	20.2	873.51	5.1	4.8	20.0	1271.04	5.2	4.8	20.3	1063.51
		5.1	9.4	24.8	1568.05	5.1	10.1	25.3	2591.45	5.2	9.8	25.3	2068.18
		5.1	11.5	26.9	1742.15	5.1	16.1	31.4	4261.57	5.2	13.0	28.5	2769.88
		10.1	9.5	39.9	1488.70	10.2	8.8	39.4	2294.17	10.1	8.6	38.9	1846.02
		10.1	19.6	49.9	3191.33	10.2	19.9	50.5	3182.77	10.1	18.1	48.4	3511.62
		10.1	28.8	59.2	4414.67	10.2	28.7	59.2	4847.68	10.1	29.7	59.9	5252.73
		15.1	8.9	54.1	1614.18	15.1	7.8	52.9	1201.81	15.1	7.9	53.1	1648.77
		15.1	13.7	58.9	2320.66	15.0	12.4	57.6	2218.44	15.1	12.9	58.1	2689.82
		15.1	26.9	72.1	4554.49	15.1	29.2	74.4	4557.24	15.1	28.6	73.8	5280.92
		20.1	14.1	74.5	2563.69	20.1	13.6	73.9	3174.40	20.0	13.1	73.1	2823.95
		20.1	17.4	77.8	3130.66	20.1	19.5	79.8	2937.85	20.0	19.5	79.6	3754.37
		20.1	35.4	95.7	5918.95	20.1	35.4	95.7	4442.67	20.0	39.0	99.1	7493.58
	10	3.1	2.6	11.9	642.49	3.2	2.8	12.4	276.75	3.1	2.5	11.7	428.80
		3.1	6.3	15.6	1496.99	3.2	6.1	15.7	622.89	3.1	6.5	15.9	1115.56
		3.1	8.6	17.9	2093.68	3.2	9.1	18.7	886.85	3.1	10.1	19.5	1661.29
		5.1	5.1	20.5	1257.64	5.1	5.1	20.5	549.92	5.1	5.0	20.2	876.12
		5.1	11.2	26.5	2640.59	5.1	10.1	25.6	1106.61	5.1	9.7	24.9	1560.15
		5.1	14.4	29.7	3472.50	5.1	14.1	29.6	1545.24	5.1	13.4	28.7	2223.42
		10.1	9.9	40.2	2359.12	10.2	10.4	41.0	1132.33	10.2	9.5	40.0	1597.13
		10.1	19.5	49.8	4665.21	10.2	19.7	50.3	1964.96	10.2	18.2	48.7	3122.27
		10.1	26.0	56.3	6287.79	10.2	32.2	62.8	3121.84	10.2	27.1	57.6	4605.71
		15.1	8.7	54.1	2131.46	15.2	8.9	54.4	890.10	14.9	10.5	55.2	2064.29
		15.2	14.8	60.2	3544.60	15.1	15.0	60.5	1718.80	14.9	15.1	59.9	2757.67
		15.2	27.4	72.8	6656.97	15.2	28.8	74.3	3131.62	15.0	30.7	75.7	4753.14
		20.1	13.8	74.1	3534.54	20.1	13.9	74.2	1484.23	20.2	13.4	74.1	2749.94
		20.1	17.4	77.7	4392.36	20.1	17.7	78.1	1762.78	20.2	20.2	80.9	3837.96
		20.1	36.2	96.4	8793.59	20.1	36.8	97.2	3817.99	20.2	37.5	98.2	6584.23
	12	3.1	3.3	12.7	729.18	3.2	2.9	12.6	606.84	2.9	2.3	11.1	361.86
		3.2	7.0	16.5	1638.91	3.2	6.7	16.4	1171.40	3.1	5.8	15.1	940.78
		3.2	8.1	17.6	1818.07	3.2	8.3	18.0	1517.30	3.1	8.7	18.0	1396.53
		5.1	4.5	19.8	1033.92	5.2	4.9	20.4	972.34	5.0	4.6	19.8	751.53
		5.1	10.0	25.4	2306.04	5.2	9.8	25.3	1708.88	5.0	8.9	24.0	1394.57
		5.1	15.4	30.8	3646.99	5.2	16.2	31.7	2793.60	5.1	12.9	28.1	1890.29
		10.1	8.7	38.8	1955.21	10.2	10.1	40.8	1917.80	10.1	9.1	39.5	1501.87
		10.0	20.8	50.9	4836.07	10.2	20.2	51.0	3709.04	10.1	18.8	49.2	2992.30
		10.0	28.7	58.8	6235.23	10.2	28.5	59.2	5077.30	10.1	25.6	56.0	3945.98
		15.1	8.0	53.2	1842.80	15.2	9.3	54.8	1764.77	15.0	8.8	54.0	1434.47
		15.0	14.5	59.5	3268.07	15.2	13.9	59.4	2803.67	15.0	12.8	57.9	2008.15
		15.0	28.7	73.6	6191.89	15.2	33.3	78.8	5953.61	15.0	26.5	71.6	4106.49
		19.8	13.9	73.4	3095.73	20.2	14.2	74.7	2710.80	20.0	12.7	72.6	1963.22
		19.8	18.1	77.5	3965.38	20.2	19.8	80.4	3757.01	20.0	18.5	78.5	3023.26
		19.8	34.0	93.3	7326.43	20.2	39.8	100.3	6816.04	20.0	35.3	95.3	5526.08

TABLE C.2 - HIGH GRADIENT DATA RESULTS AT -3°C													
		MOISTURE CONTENT (%)											
		3.3				5.3				6.0			
		σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)
FINES CONTENT (%)	6	3.1	2.7	11.9	651.14	3.1	2.8	12.0	674.77	3.1	2.1	11.3	634.11
		3.1	5.9	15.2	1492.81	3.1	5.8	15.0	1476.69	3.0	6.2	15.2	1837.63
		3.1	8.4	17.7	2025.84	3.1	9.2	18.4	2239.33	3.0	11.6	20.6	3245.98
		5.1	4.2	19.6	1053.66	5.1	4.8	20.0	1185.23	5.1	4.0	19.4	1244.16
		5.1	9.1	24.6	2189.73	5.1	11.9	27.2	2918.28	5.1	8.7	24.1	2552.39
		5.1	14.6	30.0	3265.24	5.1	13.8	29.0	3345.12	5.1	12.7	28.1	3808.82
		10.1	9.6	39.9	2421.16	10.1	10.0	40.3	2505.58	10.1	8.8	39.2	2808.35
		10.1	20.8	51.2	4327.97	10.1	20.4	50.7	4945.92	10.1	17.0	47.4	5046.12
		10.1	29.5	59.9	5623.20	10.1	28.4	58.7	6908.45	10.1	28.4	58.8	5963.97
		15.2	8.7	54.3	2181.69	15.0	9.5	54.5	2383.92	15.1	9.5	54.9	2887.92
		15.2	14.1	59.7	3489.61	15.1	15.1	60.3	3995.37	15.1	14.6	60.0	4569.89
		15.2	28.3	73.9	5601.30	15.1	28.1	73.2	7042.65	15.1	27.0	72.4	6632.63
		20.0	13.3	73.4	3248.26	20.1	12.9	73.1	3194.41	20.1	14.3	74.6	4498.34
		20.0	17.5	77.6	4211.70	20.1	18.3	78.5	4687.38	20.1	16.4	76.6	4802.63
		20.1	34.9	95.1	6436.68	20.1	37.8	98.0	9249.86	20.1	37.5	97.7	6951.97
	8	3.1	3.2	12.4	692.95	3.1	2.5	11.9	562.67	3.1	2.4	11.6	541.54
		3.0	6.3	15.4	1253.33	3.2	5.9	15.4	1289.22	3.1	5.6	14.8	1282.41
		3.1	8.5	17.6	1673.10	3.2	9.6	19.1	2111.67	3.0	10.0	19.1	2155.02
		5.1	4.4	19.6	905.90	5.2	4.4	19.9	975.78	5.1	4.2	19.4	966.35
		5.1	10.0	25.2	2087.29	5.2	9.6	25.1	2102.75	5.1	9.6	24.9	2102.88
		5.1	13.2	28.4	2570.40	5.2	13.8	29.2	2993.71	5.1	16.6	31.9	2637.52
		10.1	8.5	38.7	1757.93	10.1	9.1	39.6	1380.93	10.1	8.7	39.0	1893.07
		10.1	18.3	48.5	3445.27	10.1	18.3	48.7	2642.52	10.1	21.7	52.0	3585.87
		10.1	26.6	56.8	3955.33	10.1	27.6	58.0	3956.48	10.1	28.4	58.7	5650.23
		15.1	7.5	52.7	1568.66	15.1	7.8	53.2	1182.49	15.1	7.4	52.6	1707.26
		15.1	14.2	59.4	2879.86	15.1	13.6	59.0	2002.70	15.1	13.7	59.0	2833.26
		15.1	30.9	76.2	5111.02	15.1	28.1	73.5	3819.49	15.1	27.9	73.1	5508.77
		20.1	13.7	73.9	2879.63	20.2	13.5	74.2	1863.58	20.1	13.1	73.4	2673.22
		20.1	17.3	77.5	3426.59	20.2	18.3	79.0	2696.01	20.1	15.4	75.6	3496.87
		20.1	35.7	95.9	5223.98	20.2	38.1	98.8	7217.05	20.1	35.7	96.0	7204.47
	10	2.9	2.7	11.4	552.04	3.2	2.5	12.2	358.95	3.2	2.7	12.3	614.14
		3.0	6.0	15.1	1092.21	3.2	6.8	16.4	1074.73	3.1	6.3	15.8	1371.62
		3.0	9.7	18.7	1793.19	3.2	8.3	18.0	1256.38	3.2	9.3	18.9	2021.19
		5.0	5.3	20.4	1133.01	5.1	5.1	20.5	780.04	5.1	4.6	20.0	1050.88
		5.0	9.4	24.5	1778.38	5.1	9.8	25.2	1417.00	5.1	9.7	25.0	2332.04
		5.0	14.2	29.3	2594.92	5.1	13.6	29.1	2200.41	5.1	14.1	29.4	3387.96
		10.0	10.3	40.3	2252.82	10.3	8.9	40.0	1454.35	10.3	9.8	40.6	2418.98
		10.0	18.1	48.1	3766.83	10.3	19.6	50.6	3332.64	10.3	19.8	50.5	4797.70
		10.1	28.8	59.1	5249.84	10.3	29.0	60.0	5107.62	10.3	31.0	61.7	8645.62
		15.0	8.8	53.9	1997.37	15.3	8.4	54.1	1500.82	15.1	8.6	53.9	2326.26
		15.0	14.3	59.4	3195.27	15.2	15.6	61.4	2831.26	15.1	15.4	60.7	3426.99
		15.0	27.1	72.2	4928.93	15.2	27.0	72.7	4602.88	15.1	29.4	74.8	7368.51
		20.0	11.9	71.9	2803.62	20.3	13.0	73.8	2212.14	20.0	11.6	71.7	3361.29
		20.0	17.5	77.5	3803.67	20.3	17.6	78.4	2988.24	20.0	18.2	78.2	5089.46
		20.0	33.0	93.0	5741.92	20.3	40.3	101.2	6685.65	20.1	38.1	98.4	9914.49
	12	3.0	3.2	12.3	715.06	3.1	2.7	12.1	605.58	3.1	2.7	12.1	631.88
		3.0	6.8	15.8	1557.21	3.1	5.9	15.2	1296.98	3.1	5.7	15.0	1233.24
		3.1	8.4	17.6	1810.79	3.1	8.9	18.3	1887.02	3.1	9.0	18.3	1945.30
		5.1	4.4	19.6	984.15	5.2	4.8	20.2	1016.34	5.1	4.1	19.5	924.76
		5.1	9.6	24.8	2190.54	5.2	9.5	24.9	1997.06	5.1	12.4	27.8	2683.65
		5.1	13.5	28.8	2720.77	5.2	13.6	29.1	2883.00	5.1	16.4	31.8	3052.79
		10.0	9.0	38.9	1952.74	10.4	8.6	39.7	1939.96	10.1	9.8	40.1	2128.48
		10.0	17.9	47.8	3091.40	10.4	18.8	49.9	4246.81	10.1	18.2	48.5	3722.33
		10.0	27.0	56.9	3237.28	10.4	27.5	58.6	5736.86	10.1	30.9	61.3	5279.02
		15.1	7.8	53.0	1698.75	15.1	8.6	53.9	1965.62	15.2	8.2	53.7	1822.95
		15.1	13.8	59.0	2787.70	15.1	14.2	59.5	3250.61	15.2	12.8	58.3	2748.62
		15.1	27.2	72.4	3665.76	15.1	29.0	74.2	6438.83	15.2	29.9	75.5	5303.10
		20.1	12.8	73.0	2667.73	20.2	13.6	74.3	3101.27	20.2	12.3	73.0	2674.64
		20.1	17.8	78.0	3210.67	20.2	20.5	81.2	4840.02	20.2	19.4	80.1	4139.86
		20.1	34.0	94.3	3874.60	20.2	40.4	101.0	8822.04	20.2	37.2	97.9	6834.78

TABLE C.3 - HIGH GRADIENT DATA RESULTS AT -1°C

	MOISTURE CONTENT (%)											
	3.3				5.3				6.0			
FINES CONTENT (%)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)
6	3.1	2.8	12.1	640.61	2.9	3.0	11.8	653.32	3.2	2.2	11.7	423.97
	3.0	6.2	15.3	1444.34	2.9	6.5	15.2	1487.47	3.2	7.0	16.4	1343.20
	3.0	8.5	17.6	1859.78	2.9	9.3	17.9	2194.53	3.2	8.3	17.8	1117.18
	5.0	4.2	19.4	1011.56	4.9	4.5	19.2	1080.46	5.2	3.6	19.1	712.73
	5.1	9.2	24.3	1706.04	4.9	9.7	24.4	2209.24	5.2	10.8	26.3	1296.30
	5.0	15.2	30.3	2314.37	5.1	12.9	28.1	3113.62	5.2	15.4	30.9	1420.87
	10.1	9.6	39.8	1832.86	9.7	8.9	38.2	2069.90	10.1	8.4	38.7	892.34
	10.1	20.4	50.6	2024.15	9.8	19.0	48.3	4396.11	10.1	19.1	49.3	1256.49
	10.1	29.3	59.5	1353.59	9.7	28.8	58.0	6551.04	10.1	29.7	60.0	1048.55
	15.0	8.2	53.1	1491.42	14.8	8.4	52.9	1988.19	15.0	7.3	52.3	918.57
	15.0	14.5	59.4	2086.87	14.8	13.8	58.2	3288.04	15.0	13.6	58.6	1244.94
	15.0	27.7	72.7	1405.50	14.8	27.4	71.8	6101.53	15.0	26.5	71.6	1161.35
	20.1	11.3	71.6	1725.08	20.1	13.0	73.2	3005.60	20.2	12.9	73.6	1334.26
	20.1	17.3	77.6	1953.18	20.1	18.5	78.7	4285.78	20.3	18.6	79.3	1498.26
	20.1	37.4	97.7	1247.67	20.1	36.9	97.1	7381.79	20.3	36.1	96.8	979.49
8	3.1	3.0	12.2	685.17	3.1	3.0	12.4	383.69	3.2	2.7	12.3	528.76
	3.1	7.2	16.4	1685.48	3.1	6.2	15.6	961.96	3.2	6.5	16.0	1161.70
	3.0	9.4	18.5	2094.42	3.2	8.6	18.1	1381.02	3.2	9.1	18.7	1683.93
	5.3	4.4	20.1	1042.19	5.1	4.3	19.8	648.09	5.1	4.5	19.9	934.29
	5.3	8.2	24.0	1823.41	5.1	9.2	24.4	1357.38	5.1	9.3	24.8	1678.00
	5.3	14.3	30.0	3058.28	5.1	14.0	29.3	2153.67	5.1	13.6	29.0	2229.22
	10.1	9.4	39.7	2086.79	10.2	10.1	40.8	1645.21	10.1	10.1	40.4	1832.75
	10.1	18.9	49.2	3705.48	10.2	19.7	50.3	2828.96	10.1	17.1	47.4	2925.75
	10.1	28.2	58.4	2225.52	10.2	28.3	58.9	5971.12	10.1	28.0	58.4	3641.88
	14.9	9.0	53.8	2119.55	15.0	8.1	53.2	1345.45	15.2	8.2	53.9	1526.22
	14.9	14.7	59.4	3155.19	15.0	13.0	58.0	3418.52	15.2	14.2	59.8	2540.84
	14.9	28.6	73.3	2786.43	15.0	28.4	73.4	6550.82	15.2	30.3	75.9	3892.77
	20.0	11.8	71.8	2640.45	20.1	11.3	71.7	1926.51	20.1	12.2	72.5	2171.42
	20.0	18.1	78.1	2911.37	20.1	16.7	77.1	2651.20	20.1	18.5	78.9	3097.37
	20.0	37.1	97.0	2076.78	20.1	35.0	95.4	4669.14	20.1	37.0	97.3	3839.66
10	2.9	3.3	12.0	658.19	3.2	2.9	12.4	706.76	3.1	3.0	12.4	593.57
	3.0	6.6	15.8	1396.86	3.1	6.9	16.4	1445.92	3.1	6.6	15.9	1224.66
	3.0	9.4	18.5	1984.69	3.1	8.4	17.8	1720.67	3.1	9.2	18.3	1643.43
	5.0	4.4	19.4	887.25	5.2	5.0	20.5	1074.62	5.1	4.2	19.5	955.99
	5.0	9.0	24.0	1929.06	5.2	9.2	24.7	2049.91	5.1	8.9	24.2	1744.53
	5.1	14.6	29.9	2474.98	5.2	15.3	30.7	3122.83	5.1	13.7	29.0	2626.38
	10.5	9.2	40.6	2120.40	10.2	9.6	40.2	2322.03	10.2	8.8	39.3	2176.97
	10.5	18.9	50.3	2528.70	10.2	19.8	50.4	4457.98	10.2	17.3	47.8	3190.34
	10.2	26.1	56.6	1519.24	10.2	27.6	58.1	5827.67	10.2	27.3	57.8	4310.93
	15.0	6.9	51.8	1728.36	15.1	7.3	52.7	1852.44	15.2	7.2	52.8	1549.77
	15.0	12.8	57.9	2701.21	15.1	13.9	59.3	3426.84	15.2	13.6	59.1	2382.28
	15.0	25.6	70.7	2160.24	15.1	30.3	75.7	6376.57	15.2	28.0	73.5	4506.80
	20.1	11.8	72.1	2793.71	20.1	13.6	74.0	3468.27	19.9	12.8	72.6	2945.08
	20.1	17.8	78.1	3163.99	20.1	17.5	77.8	4277.85	19.9	19.1	78.9	3748.37
	20.1	35.3	95.6	1493.26	20.1	36.2	96.6	6683.53	19.9	37.0	96.8	4807.07
12	2.9	3.1	11.7	442.40	3.2	3.0	12.4	750.51	3.2	2.8	12.3	876.32
	2.7	6.7	15.0	797.82	3.2	6.3	15.7	1560.93	3.2	6.1	15.6	2106.45
	2.8	9.1	17.4	991.58	3.1	9.3	18.8	2376.69	3.2	10.1	19.6	3200.47
	5.0	4.3	19.4	782.01	4.9	4.9	19.7	1243.06	5.1	4.8	20.0	1542.10
	5.0	8.8	23.9	1182.78	4.9	9.9	24.5	2472.75	5.1	10.7	25.8	3546.92
	5.0	14.0	29.0	1080.68	4.9	12.9	27.5	3293.74	5.1	13.7	28.9	4638.26
	9.8	8.9	38.2	1219.26	10.1	8.6	39.0	2146.84	10.2	8.9	39.5	2913.08
	9.8	18.5	47.8	738.34	10.1	18.4	48.8	4150.87	10.2	19.1	49.7	6487.84
	9.8	26.3	55.6	543.08	10.1	27.9	58.3	5239.82	10.2	28.8	59.3	8106.02
	15.1	7.4	52.7	1179.68	15.2	7.6	53.2	1873.90	15.1	8.1	53.5	2772.90
	15.1	12.5	57.7	1473.45	15.2	13.7	59.3	3270.01	15.1	14.4	59.7	4775.50
	15.1	27.0	72.3	613.30	15.2	27.3	72.8	5160.38	15.1	28.2	73.6	7306.18
	20.0	12.5	72.4	1505.83	19.9	11.8	71.4	3005.15	20.1	14.1	74.4	4593.72
	20.0	17.3	77.3	1370.19	19.9	17.0	76.6	4200.35	20.1	18.3	78.6	6081.20
	20.0	34.3	94.4	509.79	19.9	34.5	94.1	3983.44	20.1	35.6	96.0	6446.10

TABLE C.4 - HIGH GRADIENT DATA RESULTS AT 20°C (one freeze-thaw cycle)

FINES CONTENT (%)	MOISTURE CONTENT (%) 3.3 σ_3 (psi)	3.3 σ_d (psi)	3.3 σ_B (psi)	3.3 M_R (ksi)	5.3 σ_3 (psi)	5.3 σ_d (psi)	5.3 σ_B (psi)	5.3 M_R (ksi)	6.0 σ_3 (psi)	6.0 σ_d (psi)	6.0 σ_B (psi)	6.0 M_R (ksi)
6	3.1	3.2	12.5	21.64	3.1	2.8	12.1	11.12	-	-	-	-
	3.1	6.4	15.7	22.02	3.1	6.1	15.3	13.31	-	-	-	-
	3.1	9.5	18.8	24.23	3.1	9.3	18.6	15.44	-	-	-	-
	5.0	5.4	20.4	29.14	5.1	4.7	20.0	12.95	-	-	-	-
	5.1	10.2	25.4	30.45	5.1	10.2	25.6	16.00	-	-	-	-
	5.1	13.8	29.0	31.96	5.1	14.2	29.6	19.26	-	-	-	-
	10.2	9.7	40.5	49.26	10.2	9.7	40.3	21.84	-	-	-	-
	10.2	18.1	48.8	48.37	10.2	19.8	50.3	24.38	-	-	-	-
	10.2	27.7	58.4	49.12	10.2	29.0	59.6	28.60	-	-	-	-
	15.1	9.7	54.9	59.32	15.1	8.6	53.9	22.75	-	-	-	-
	15.1	14.7	60.0	56.94	15.1	12.5	57.8	20.69	-	-	-	-
	15.1	28.2	73.4	60.26	15.1	27.0	72.3	28.33	-	-	-	-
	20.0	14.6	74.8	69.94	19.7	12.1	71.2	21.41	-	-	-	-
	20.0	18.6	78.8	69.33	19.7	16.3	75.5	22.65	-	-	-	-
	20.0	35.7	95.9	71.74	19.7	35.3	94.4	32.87	-	-	-	-
8	3.1	2.8	12.2	24.76	2.8	2.2	10.6	10.45	-	-	-	-
	3.1	6.1	15.5	23.01	2.8	5.0	13.3	12.33	-	-	-	-
	3.1	9.1	18.5	24.26	2.8	7.9	16.2	13.92	-	-	-	-
	5.0	5.0	19.9	30.65	5.1	4.6	19.9	15.60	-	-	-	-
	5.1	9.7	25.0	30.83	5.1	9.2	24.5	16.47	-	-	-	-
	5.1	14.3	29.6	32.12	5.1	14.5	29.8	18.50	-	-	-	-
	10.1	10.3	40.7	50.36	10.1	9.9	40.3	25.22	-	-	-	-
	10.1	19.7	50.0	51.37	10.1	20.4	50.8	26.55	-	-	-	-
	10.1	28.1	58.4	51.72	10.1	29.0	59.4	30.18	-	-	-	-
	14.9	9.4	54.1	66.50	15.2	9.4	55.0	32.78	-	-	-	-
	14.9	15.1	59.7	62.35	15.2	13.7	59.3	29.99	-	-	-	-
	15.0	28.6	73.5	65.51	15.2	29.4	75.0	34.73	-	-	-	-
	19.7	13.8	73.0	77.65	20.1	14.6	74.8	36.74	-	-	-	-
	20.0	19.3	79.4	78.28	20.1	19.0	79.2	36.59	-	-	-	-
	20.0	36.0	96.1	80.39	20.1	38.4	98.5	42.05	-	-	-	-
10	3.1	3.1	12.4	27.21	3.2	2.6	12.1	16.38	-	-	-	-
	3.1	6.5	15.8	25.44	3.2	5.5	15.0	15.92	-	-	-	-
	3.1	9.4	18.7	27.28	3.2	8.7	18.2	17.28	-	-	-	-
	5.1	5.2	20.6	34.48	5.2	4.9	20.6	20.12	-	-	-	-
	5.1	10.1	25.5	34.61	5.2	9.7	25.4	21.45	-	-	-	-
	5.1	14.5	29.9	36.46	5.2	15.4	31.1	23.20	-	-	-	-
	9.9	10.0	39.9	55.87	10.3	10.2	41.0	33.10	-	-	-	-
	9.9	19.4	49.2	56.12	10.3	20.7	51.5	35.00	-	-	-	-
	9.9	27.5	57.3	57.81	10.3	30.3	61.1	37.63	-	-	-	-
	15.1	9.9	55.2	74.68	15.3	9.8	55.7	41.62	-	-	-	-
	15.1	15.7	61.0	71.49	15.3	14.9	60.8	39.72	-	-	-	-
	15.1	28.2	73.4	74.39	15.3	29.7	75.7	44.28	-	-	-	-
	20.1	14.4	74.7	89.22	20.0	15.4	75.5	48.95	-	-	-	-
	20.1	17.6	77.8	89.17	20.0	20.0	80.1	49.58	-	-	-	-
	20.1	34.7	94.9	91.79	20.0	39.3	99.3	53.93	-	-	-	-
12	3.1	3.0	12.1	39.84	2.9	2.3	11.1	11.34	-	-	-	-
	3.0	6.3	15.4	32.07	2.9	5.3	14.1	13.23	-	-	-	-
	3.0	9.6	18.7	33.10	2.9	8.6	17.4	15.31	-	-	-	-
	5.1	5.5	20.8	44.49	5.2	4.6	20.0	14.99	-	-	-	-
	5.1	10.8	26.0	42.72	5.2	9.7	25.2	17.47	-	-	-	-
	5.1	15.5	30.8	44.11	5.2	15.5	31.0	20.21	-	-	-	-
	9.4	10.5	38.6	65.12	10.3	9.8	40.6	25.84	-	-	-	-
	9.7	19.6	48.6	66.35	10.3	20.3	51.1	29.42	-	-	-	-
	9.7	27.7	56.7	65.78	10.3	29.7	60.5	32.78	-	-	-	-
	14.8	9.2	53.5	99.52	15.3	9.3	55.1	33.16	-	-	-	-
	14.8	15.3	59.6	86.20	15.3	14.2	59.9	32.52	-	-	-	-
	14.8	29.5	73.7	84.84	15.3	30.6	76.4	38.16	-	-	-	-
	20.0	15.7	75.6	108.71	20.3	14.0	74.9	39.72	-	-	-	-
	19.9	20.5	80.3	104.70	20.3	19.0	79.8	39.95	-	-	-	-
	19.9	36.7	96.5	103.26	20.3	38.4	99.2	47.12	-	-	-	-

APPENDIX D

TABLE D.1 - DATA RESULTS AT 20°C (no freezing)													
		MOISTURE CONTENT (%)											
		3.3				5.3				6.0			
		σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)	σ_3 (psi)	σ_d (psi)	σ_B (psi)	M_R (ksi)
FINES CONTENT (%)	6	3.1	2.6	12.0	15.34	3.1	2.2	11.5	14.73	-	-	-	-
		3.1	6.0	15.3	18.47	3.1	5.5	14.7	12.79	-	-	-	-
		3.1	9.1	18.4	15.20	3.1	9.0	18.2	14.38	-	-	-	-
		5.1	4.5	19.8	13.25	5.1	4.3	19.6	13.39	-	-	-	-
		5.1	10.0	25.3	17.21	5.1	9.9	25.1	16.01	-	-	-	-
		5.1	15.0	30.3	18.91	5.1	13.2	28.4	17.55	-	-	-	-
		10.1	9.2	39.4	20.24	10.0	8.7	38.9	22.87	-	-	-	-
		10.1	19.1	49.3	24.83	10.1	19.9	50.1	26.30	-	-	-	-
		10.1	27.5	57.7	22.06	10.1	31.0	61.2	28.01	-	-	-	-
		15.1	7.8	53.2	20.10	15.1	9.4	54.8	32.15	-	-	-	-
		15.1	13.2	58.5	23.22	15.1	14.2	59.5	30.81	-	-	-	-
		15.1	29.2	74.4	31.11	15.1	29.6	75.0	34.99	-	-	-	-
		19.8	13.6	73.0	32.95	20.0	15.7	75.8	47.40	-	-	-	-
		19.8	18.8	78.1	35.01	20.0	20.1	80.2	48.51	-	-	-	-
		19.8	34.8	94.1	60.61	20.0	36.1	96.2	55.20	-	-	-	-
	8	3.1	3.2	12.6	41.86	3.0	2.1	11.1	8.63	-	-	-	-
		3.1	6.6	16.0	39.13	3.0	5.9	14.9	11.24	-	-	-	-
		3.1	9.5	18.9	42.51	3.0	9.2	18.2	13.15	-	-	-	-
		5.1	5.2	20.6	60.30	5.0	4.6	19.4	10.98	-	-	-	-
		5.1	10.6	26.0	53.48	4.9	10.3	25.1	18.06	-	-	-	-
		5.1	15.2	30.6	54.53	4.9	13.1	27.9	20.31	-	-	-	-
		9.9	9.4	39.1	99.47	10.1	8.8	39.1	22.39	-	-	-	-
		10.1	19.6	49.8	79.09	10.1	19.5	49.9	28.04	-	-	-	-
		10.1	27.2	57.4	72.62	10.0	29.8	59.8	46.19	-	-	-	-
		15.1	8.3	53.6	103.92	15.3	10.5	56.4	45.87	-	-	-	-
		15.1	13.2	58.5	90.22	15.3	15.1	61.0	46.70	-	-	-	-
		15.1	27.6	72.9	90.82	15.3	28.2	74.1	55.78	-	-	-	-
		20.1	12.4	72.8	125.15	20.1	15.0	75.2	58.49	-	-	-	-
		20.1	17.7	78.2	117.75	20.1	19.1	79.3	60.42	-	-	-	-
		20.1	33.4	93.8	105.22	20.1	39.4	99.6	72.25	-	-	-	-
	10	3.1	2.8	12.2	30.38	3.1	2.0	11.4	8.27	-	-	-	-
		3.1	5.9	15.2	28.42	3.1	5.8	15.2	8.59	-	-	-	-
		3.1	9.1	18.5	29.84	3.1	9.3	18.6	10.64	-	-	-	-
		5.0	5.1	20.3	37.96	4.9	4.0	18.8	6.72	-	-	-	-
		5.0	10.1	25.2	36.93	4.9	10.3	25.1	10.98	-	-	-	-
		5.0	14.8	29.9	38.32	5.1	13.3	28.7	20.80	-	-	-	-
		10.3	10.8	41.6	59.57	10.4	7.3	38.5	14.89	-	-	-	-
		10.3	20.7	51.4	58.47	10.4	18.8	50.0	27.68	-	-	-	-
		10.3	30.4	61.2	59.53	10.4	27.1	58.3	49.77	-	-	-	-
		15.1	9.3	54.7	77.38	15.1	5.8	51.0	8.46	-	-	-	-
		15.1	15.0	60.4	71.45	15.1	9.6	54.8	10.05	-	-	-	-
		15.1	27.9	73.3	74.56	15.1	28.3	73.5	19.38	-	-	-	-
		19.9	14.4	74.2	87.46	19.6	10.2	69.0	10.35	-	-	-	-
		19.9	20.0	79.8	86.67	19.6	16.0	74.8	11.30	-	-	-	-
		19.9	37.1	96.9	89.52	19.6	40.4	99.1	23.72	-	-	-	-
	12	3.0	2.9	11.8	28.99	2.8	2.1	10.6	7.72	-	-	-	-
		2.9	5.9	14.7	27.35	2.9	5.8	14.4	13.56	-	-	-	-
		3.0	8.8	17.8	28.00	3.1	9.6	19.0	13.39	-	-	-	-
		5.0	5.0	20.1	36.50	5.2	3.8	19.3	10.88	-	-	-	-
		5.0	9.8	24.9	36.07	5.2	11.5	27.0	13.31	-	-	-	-
		5.0	14.0	29.1	37.95	5.2	15.9	31.4	15.63	-	-	-	-
		10.1	10.1	40.3	59.30	10.1	9.0	39.3	14.05	-	-	-	-
		10.1	19.5	49.7	57.12	10.1	20.1	50.5	17.89	-	-	-	-
		10.1	28.6	58.8	57.58	10.1	27.0	57.4	17.74	-	-	-	-
		15.0	9.5	54.5	78.45	15.1	7.4	52.6	18.63	-	-	-	-
		15.0	14.8	59.8	70.94	15.1	11.9	57.2	19.17	-	-	-	-
		15.0	28.3	73.3	72.46	15.1	28.1	73.4	25.98	-	-	-	-
		20.1	13.4	73.7	92.09	19.9	13.2	73.0	26.65	-	-	-	-
		20.1	19.0	79.4	87.89	19.9	18.3	77.9	27.47	-	-	-	-
		20.1	35.5	95.9	89.49	19.9	39.8	99.6	32.74	-	-	-	-

APPENDIX E

TABLE E.1 PERMANENT DEFORMATION DATA										
Data values are in units of inches (in).		MOISTURE CONTENT (%)								
		3.3			5.3			6.0		
		GRADIENT								
FINES CONTENT (%)	TEMPERATURE (°C)	L	M	H	L	M	H	L	M	H
6	-5	0.1633	0.0252	0.1510	0.0296	0.0092	0.0085	0.0170	0.0220	0.0124
	-3	0.0798	0.0095	0.0043	0.0315	0.0115	0.0092	0.0215	0.0496	0.0758
	-1	0.1013	0.0702	0.0719	0.0839	0.0454	0.0442	0.1219	0.2221	0.1122
	20		5.2305			2.1779			-	
	20	0.1871	0.1480	0.2505	3.0224	0.9002	2.3889	-	-	-
8	-5	0.0125	0.0280	0.0149	0.0061	0.0081	0.0666	0.0104	0.0107	0.0498
	-3	0.0274	0.0145	0.0227	0.0052	0.0069	0.1346	0.0405	0.0136	0.0303
	-1	0.0408	0.1064	0.0564	0.0972	0.0583	0.0494	0.2203	0.0874	0.1233
	20		2.4287			0.4644			-	
	20	0.3247	0.1226	0.2073	2.2930	1.2069	1.3240	-	-	-
10	-5	0.0081	0.0108	0.0032	0.0342	0.0132	0.0055	0.0140	0.0264	0.0077
	-3	0.0080	0.0039	0.0214	0.0167	0.0126	0.0071	0.0305	0.0211	0.0187
	-1	0.1813	0.0632	0.0435	0.0549	0.0462	0.0460	0.0558	0.0656	0.1212
	20		0.1838			6.7394			-	
	20	0.1416	0.2062	0.1607	1.9328	0.7992	0.8494	-	5.3850	-
12	-5	0.0061	0.0136	0.0096	0.0162	0.0167	0.0152	0.0107	0.0156	0.0136
	-3	0.0270	0.0197	0.0135	0.0550	0.0111	0.0066	0.0171	0.0170	0.0091
	-1	0.2079	0.0331	0.0510	0.0827	0.0671	0.1082	0.0486	0.0747	0.0368
	20		0.2192			3.7495			-	
	20	0.9596	0.1432	0.1220	1.7766	1.1302	1.5861	-	-	-

Note: Values for 20 degrees that are equivalent for all gradients represent the measurements for the specimens not subjected to a freeze-thaw cycle.

APPENDIX F

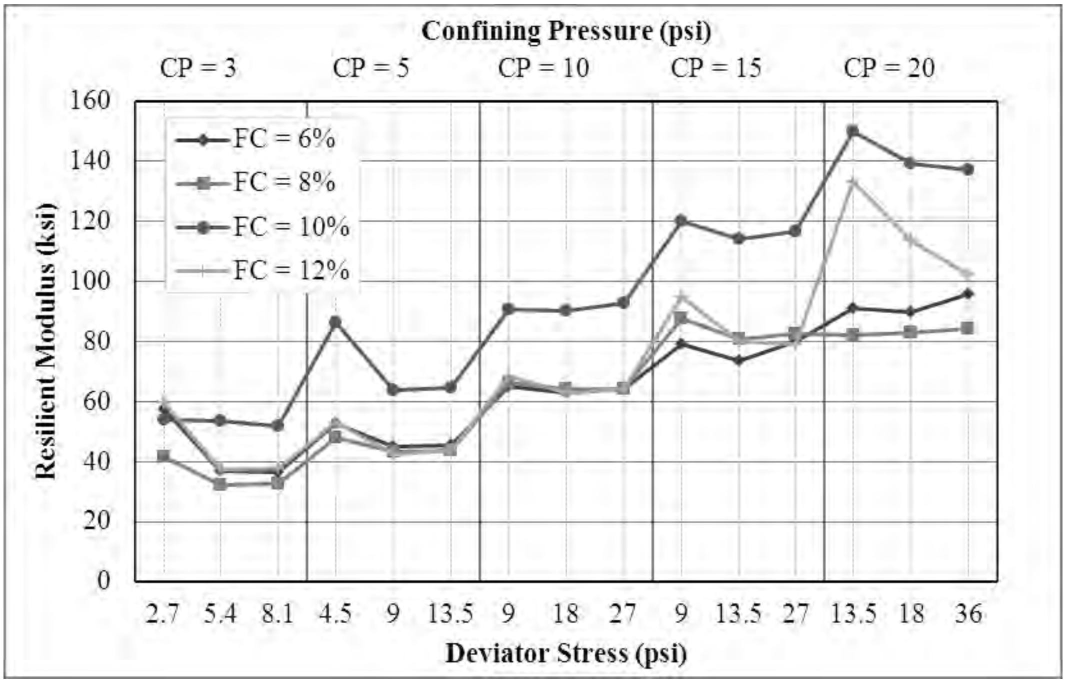

Figure F.1. M_R at varying fines contents (MC = 3.3%, Low Gradient, 20° C)

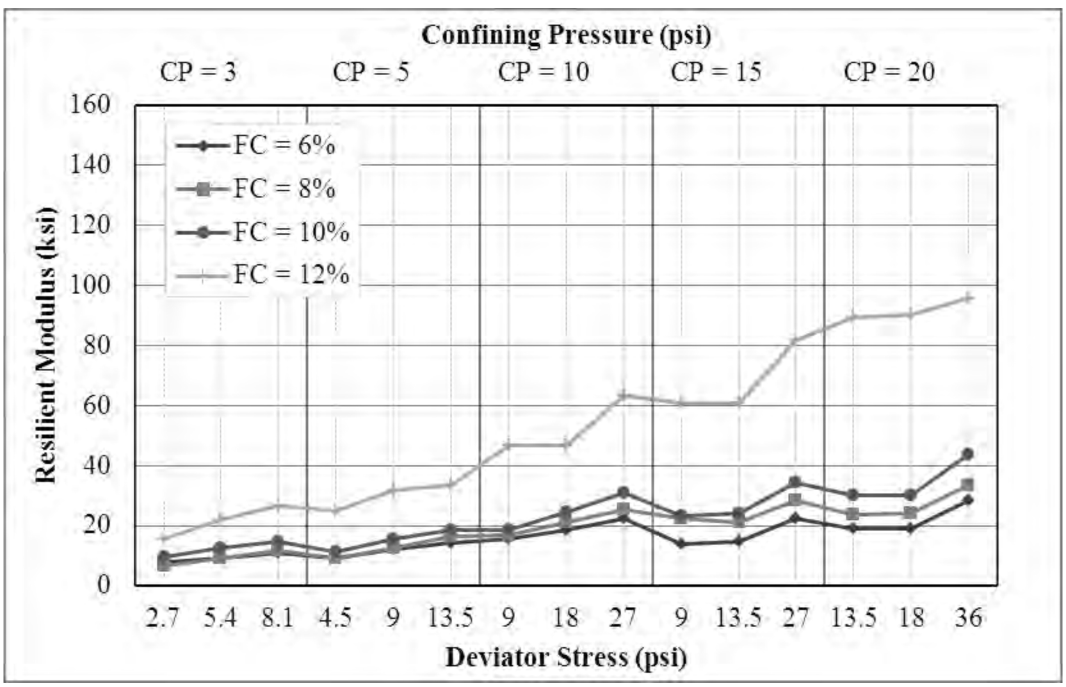

Figure F.2. M_R at varying fines contents (MC = 5.3%, Low Gradient, 20° C)

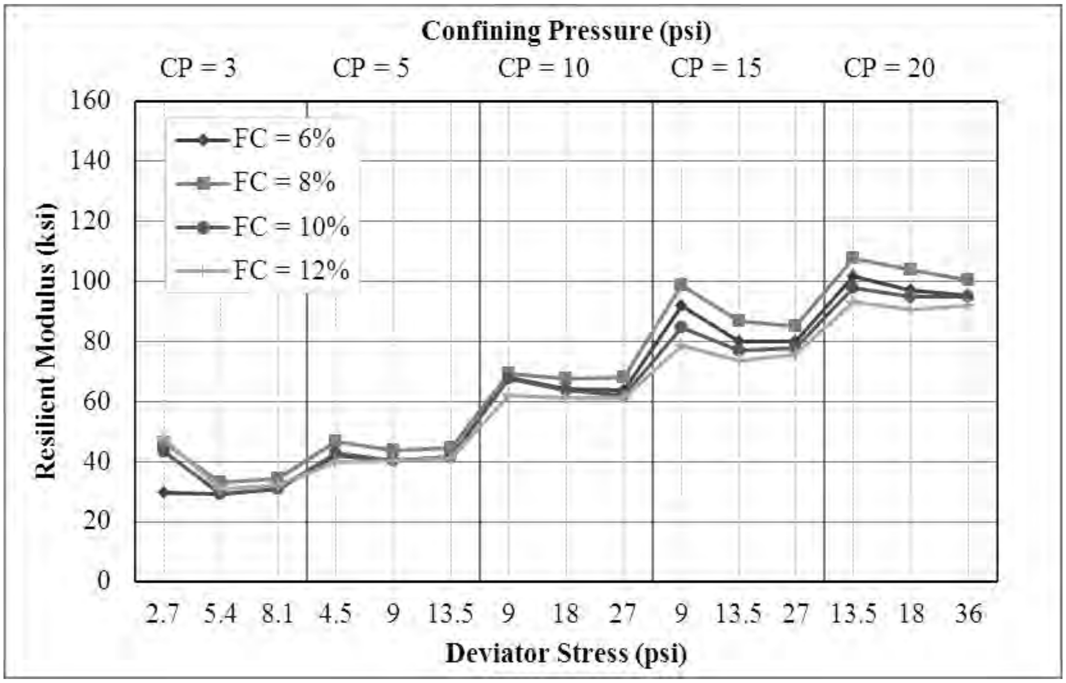

Figure F.3. M_R at varying fines contents (MC = 3.3%, Medium Gradient, 20° C)

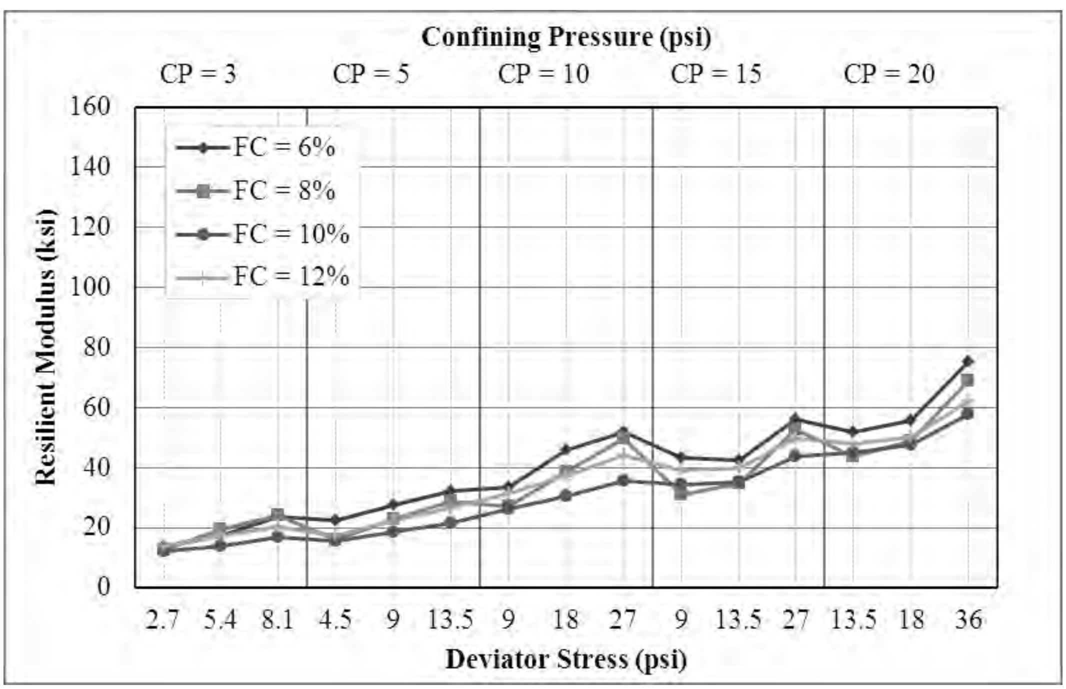

Figure F.4. M_R at varying fines contents (MC = 5.3%, Medium Gradient, 20° C)

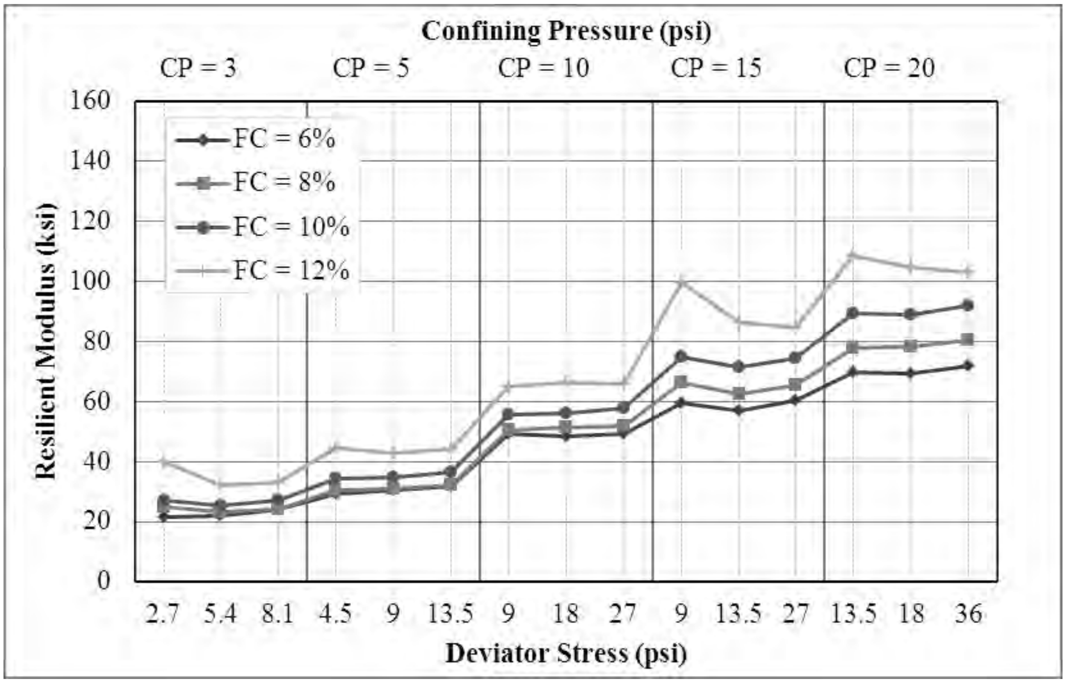

Figure F.5. M_R at varying fines contents (MC = 3.3%, High Gradient, 20° C)

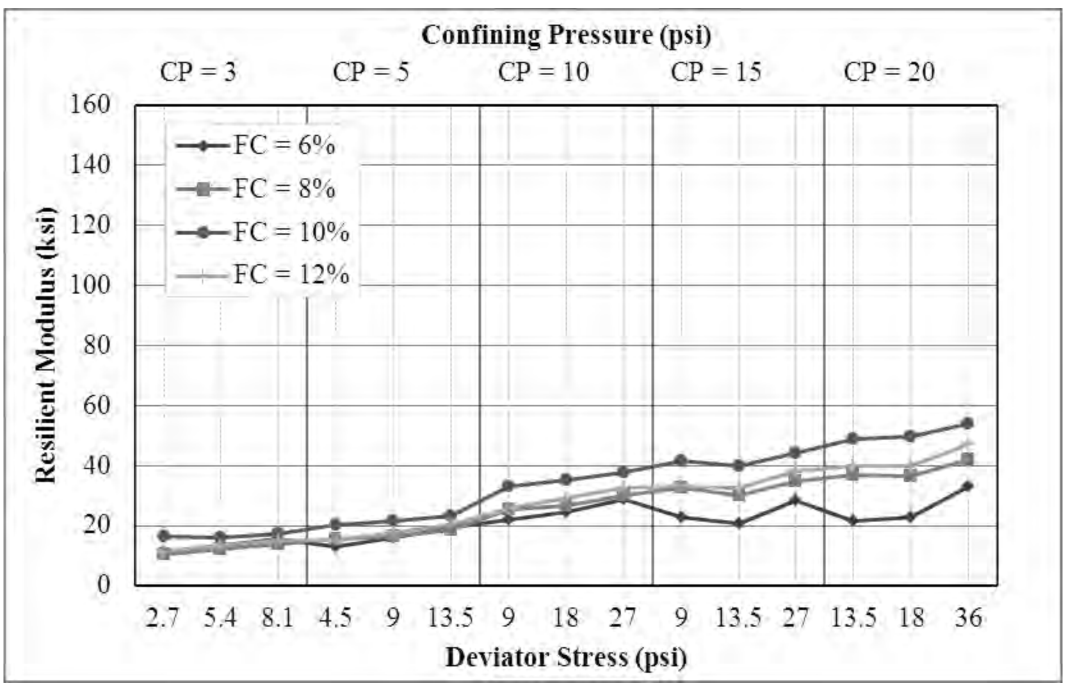

Figure F.6. M_R at varying fines contents (MC = 5.3%, High Gradient, 20° C)

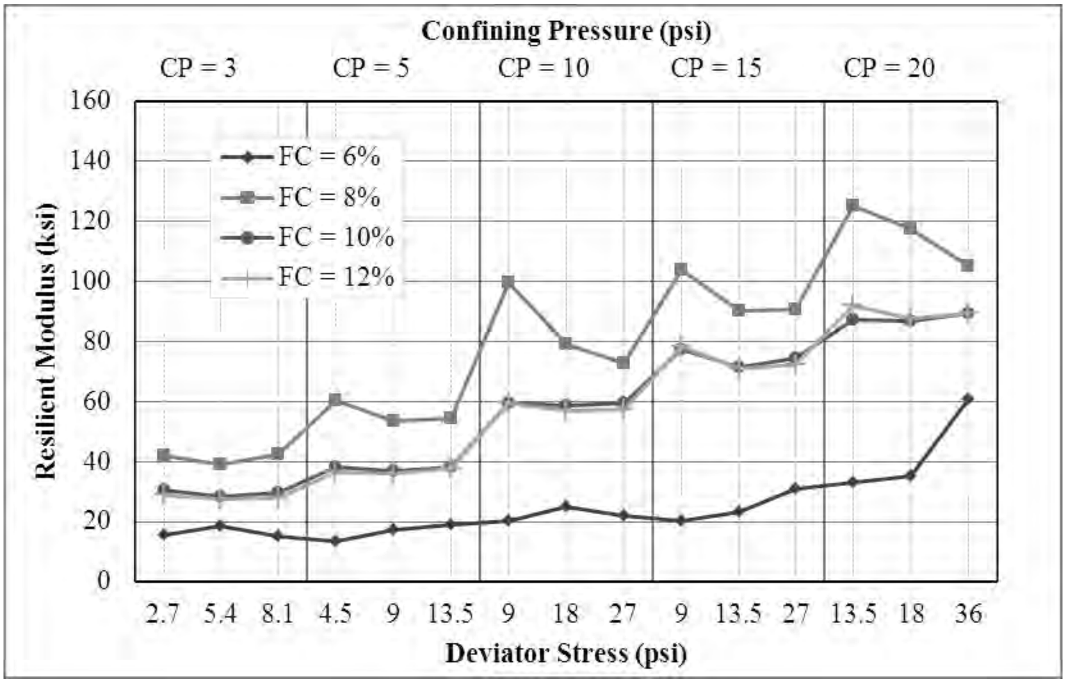

Figure F.7. M_R at varying fines contents (MC = 3.3%, Non-Frozen, 20° C)

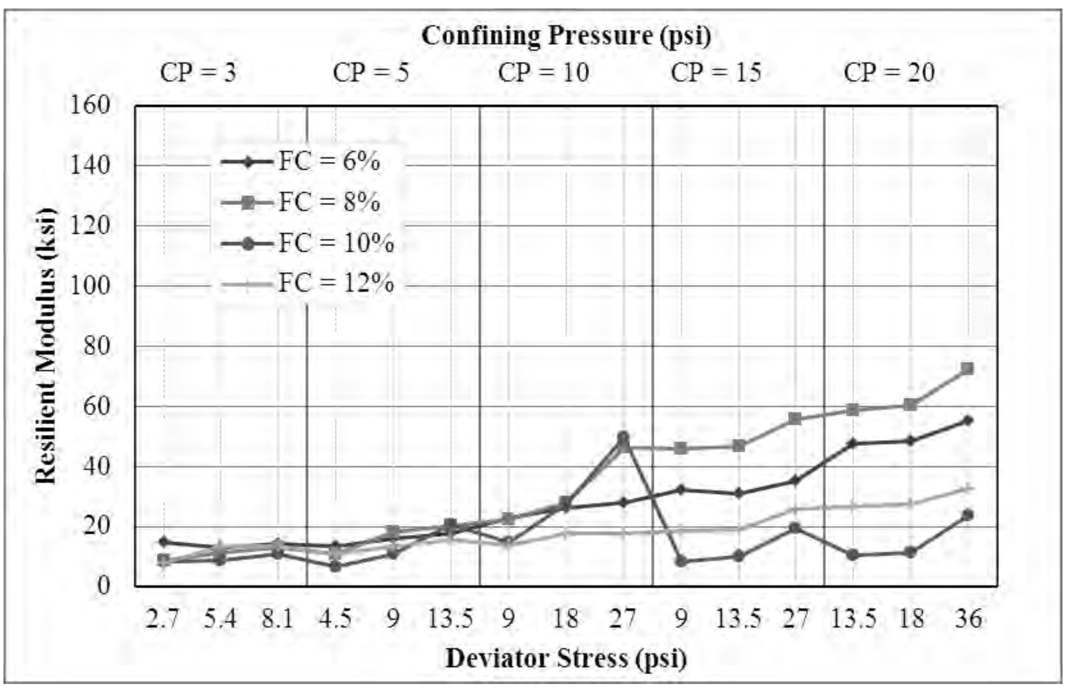

Figure F.8. M_R at varying fines contents (MC = 5.3%, Non-Frozen, 20° C)

APPENDIX G

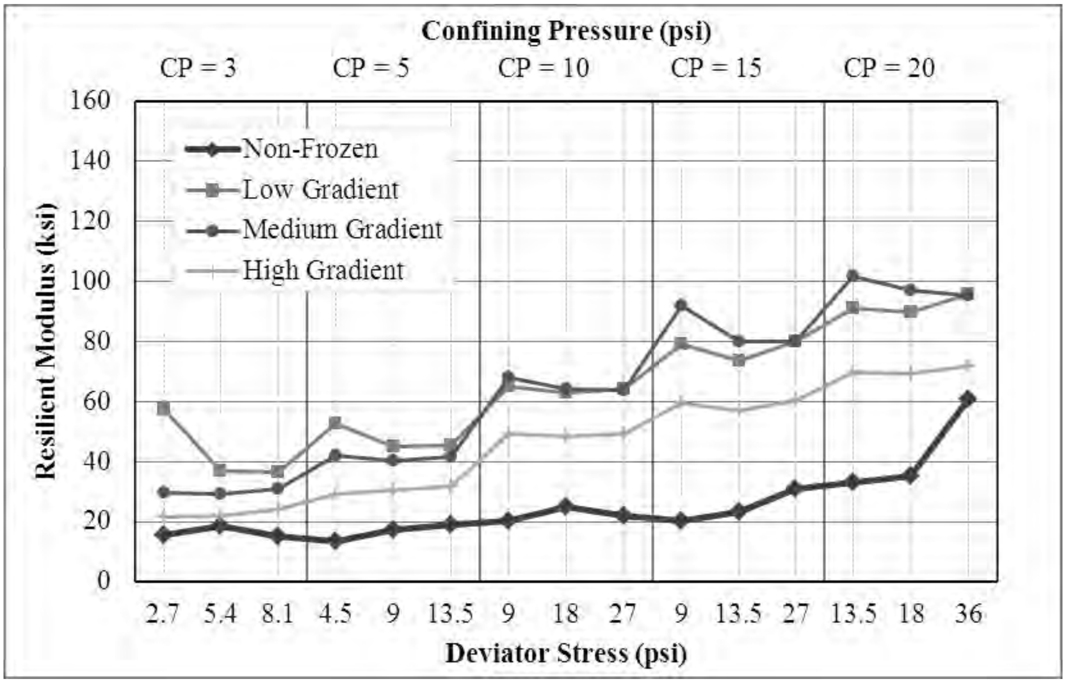

Figure G.1. M_R before and after freeze-thaw, for varying freezing gradients (FC = 6%, MC = 3.3%, 20° C)

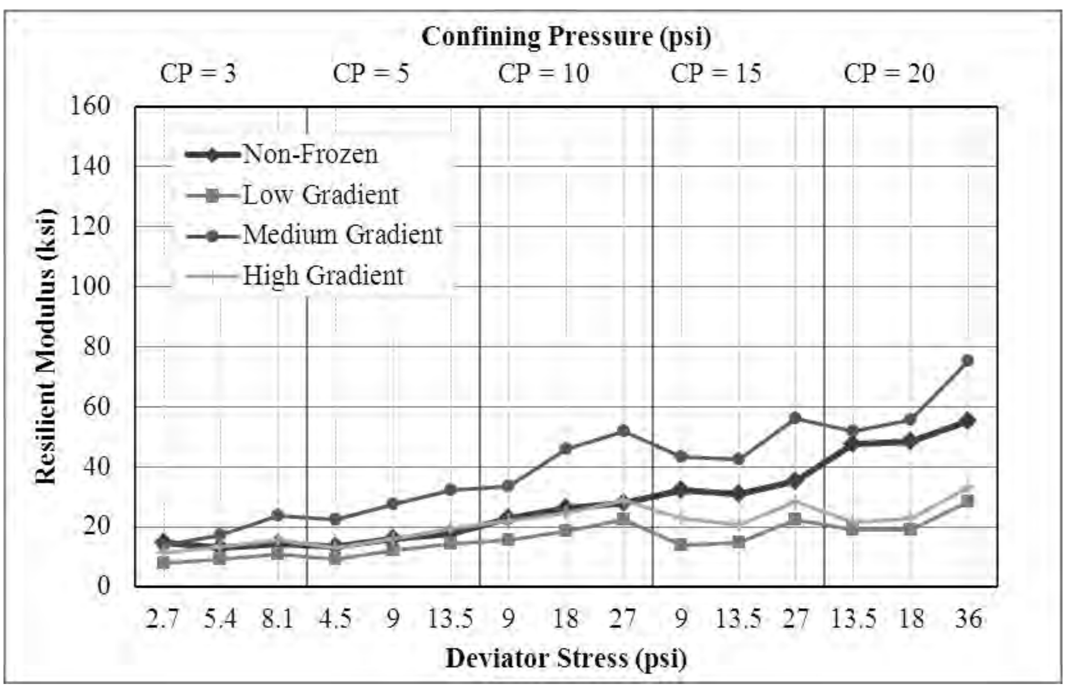

Figure G.2. M_R before and after freeze-thaw, for varying freezing gradients (FC = 6%, MC = 5.3%, 20° C)

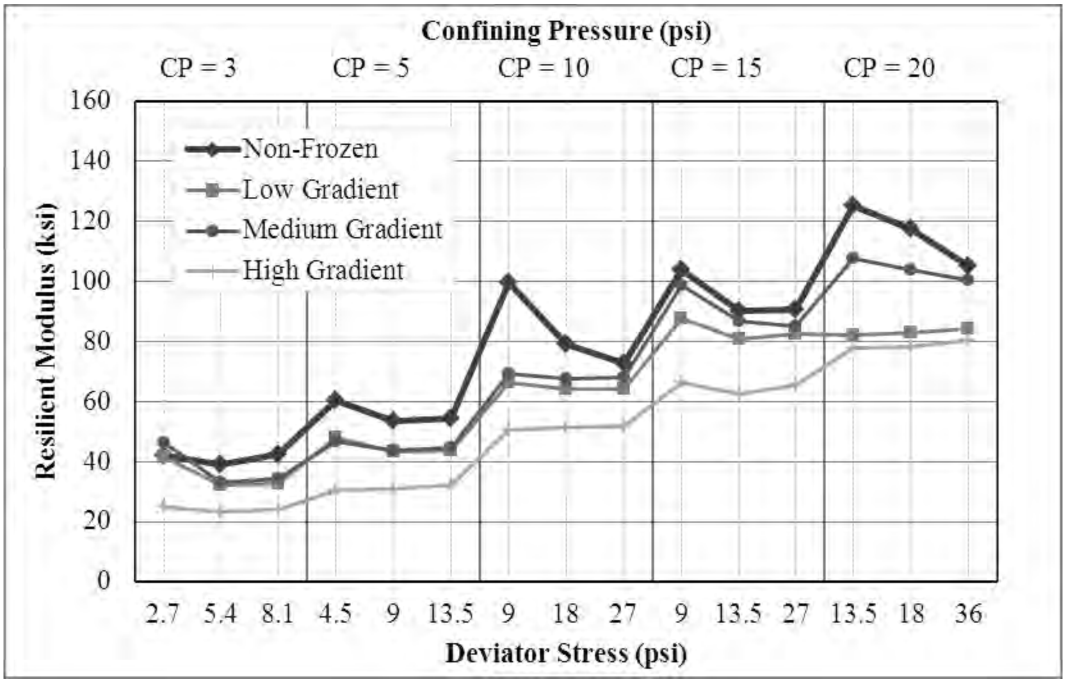

Figure G.3. M_R before and after freeze-thaw, for varying freezing gradients (FC = 8%, MC = 3.3%, 20° C)

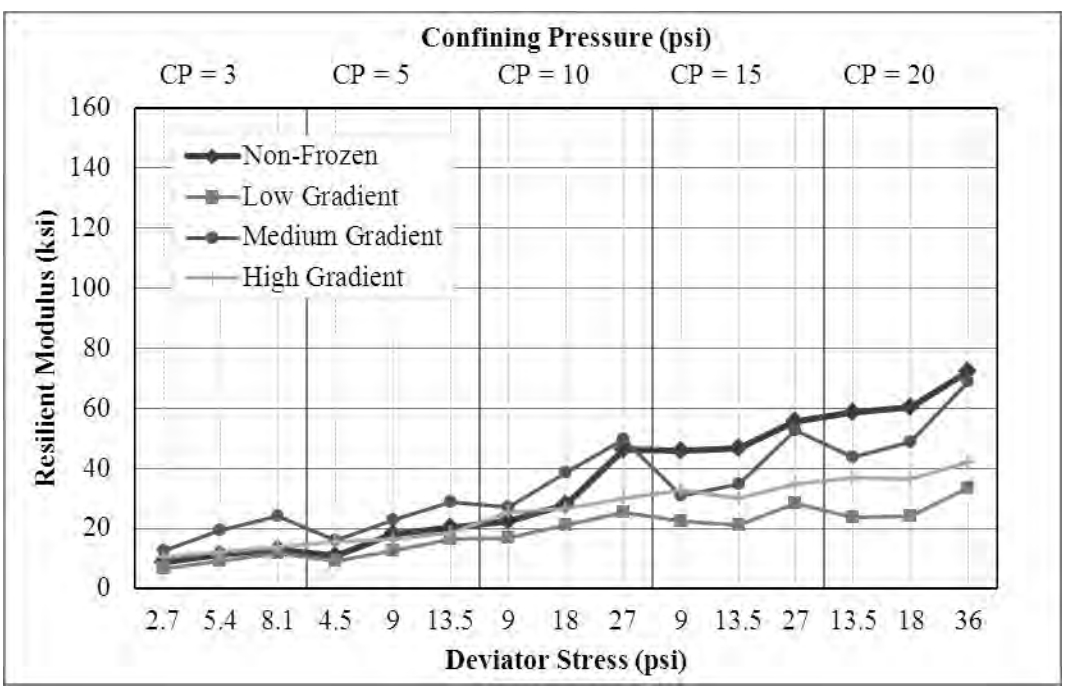

Figure G.4. M_R before and after freeze-thaw, for varying freezing gradients (FC = 8%, MC = 5.3%, 20° C)

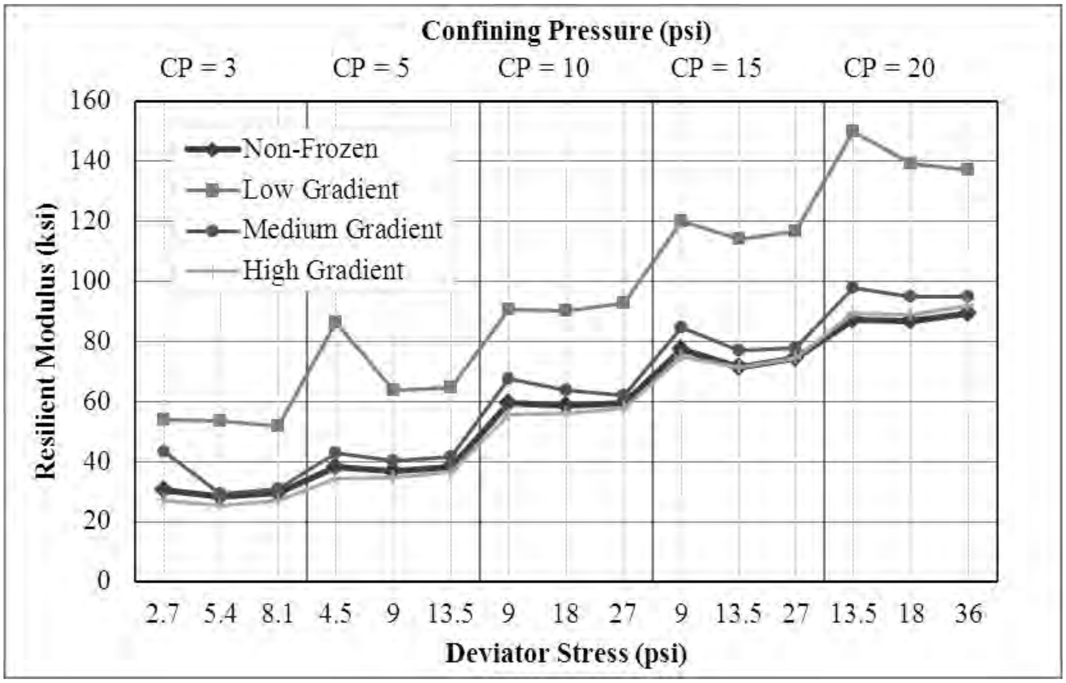

Figure G.5. M_R before and after freeze-thaw, for varying freezing gradients (FC = 10%, MC = 3.3%, 20° C)

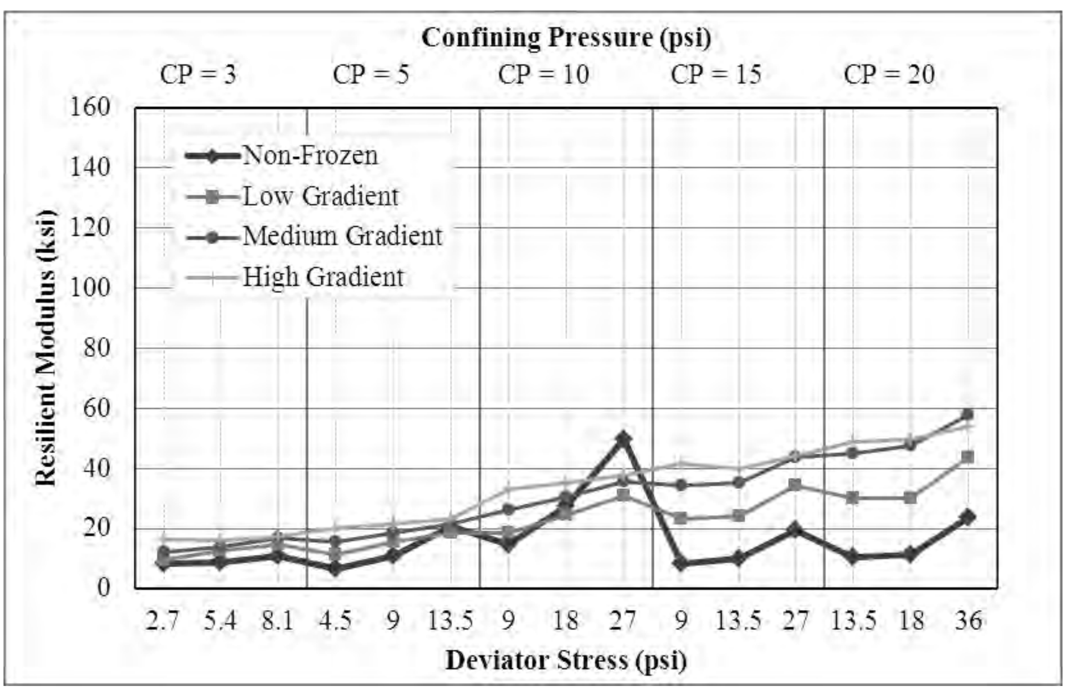

Figure G.6. M_R before and after freeze-thaw, for varying freezing gradients (FC = 10%, MC = 5.3%, 20° C)

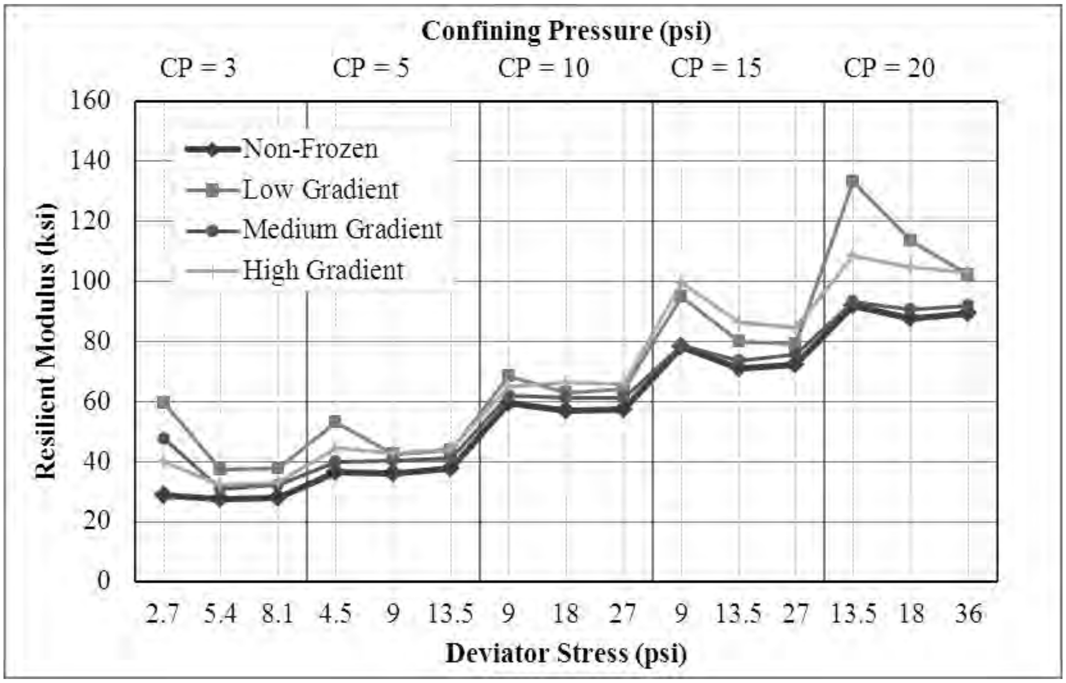

Figure G.7. M_R before and after freeze-thaw, for varying freezing gradients (FC = 12%, MC = 3.3%, 20° C)

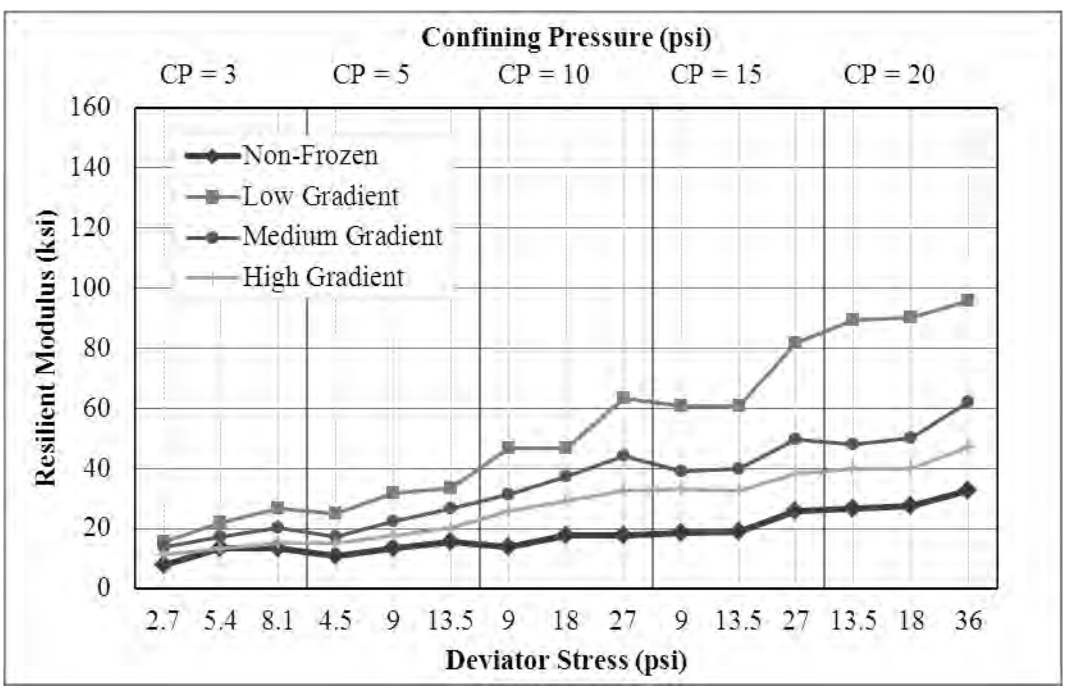

Figure G.8. M_R before and after freeze-thaw, for varying freezing gradients (FC = 12%, MC = 5.3%, 20° C)

APPENDIX H

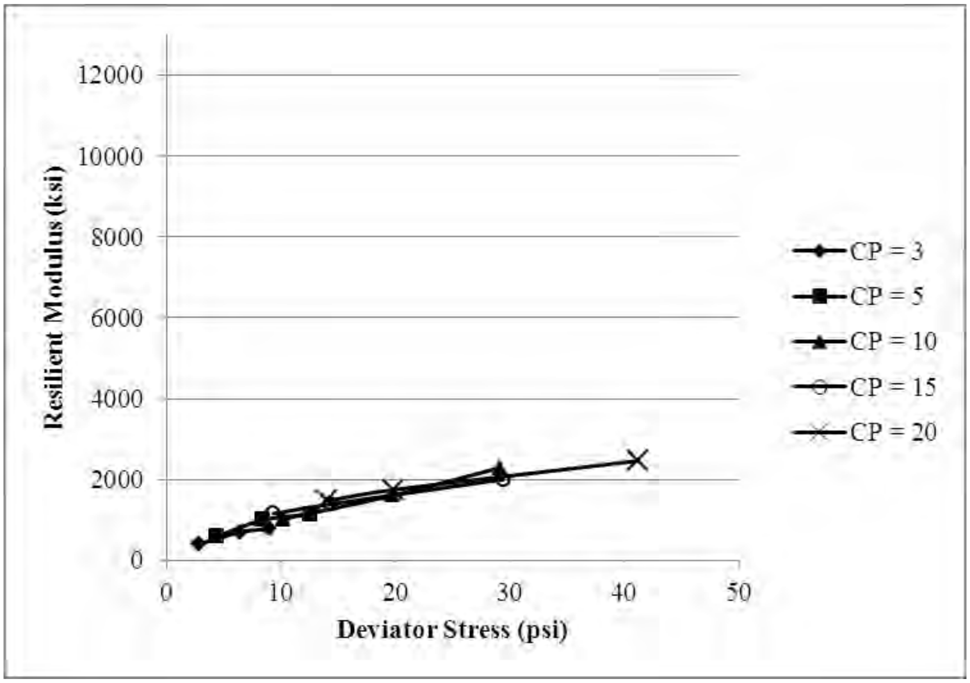

Figure H.1. M_R for FC = 6%, MC = 3.3%, Low Gradient, -5 °C

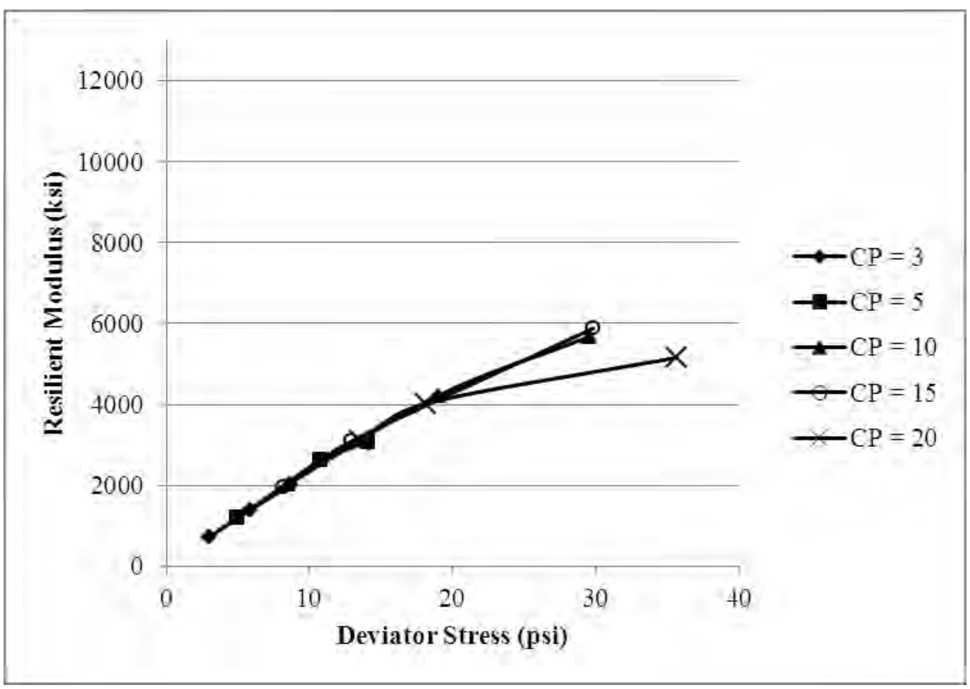

Figure H.2. M_R for FC = 12%, MC = 3.3%, Low Gradient, -5 °C

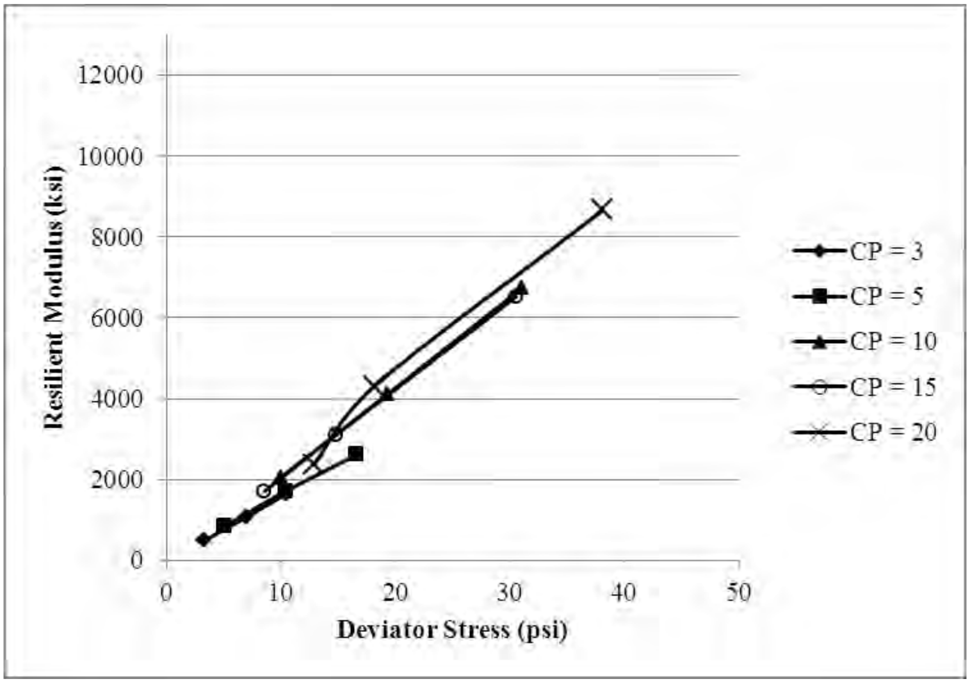

Figure H.3. M_R for FC = 6%, MC = 5.3%, Low Gradient, -5 °C

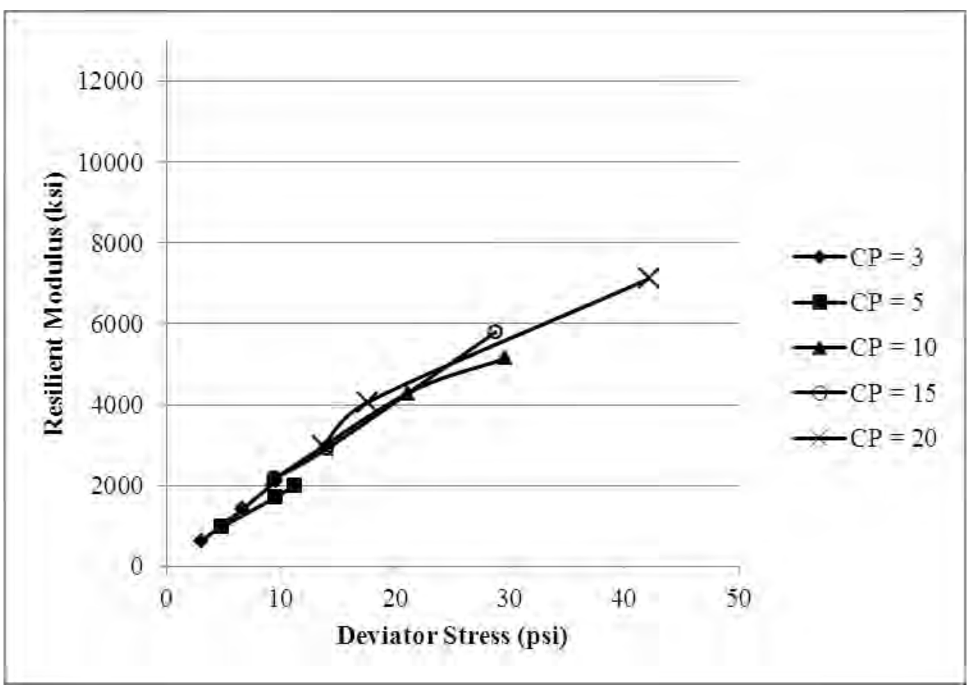

Figure H.4. M_R for FC = 12%, MC = 5.3%, Low Gradient, -5 °C

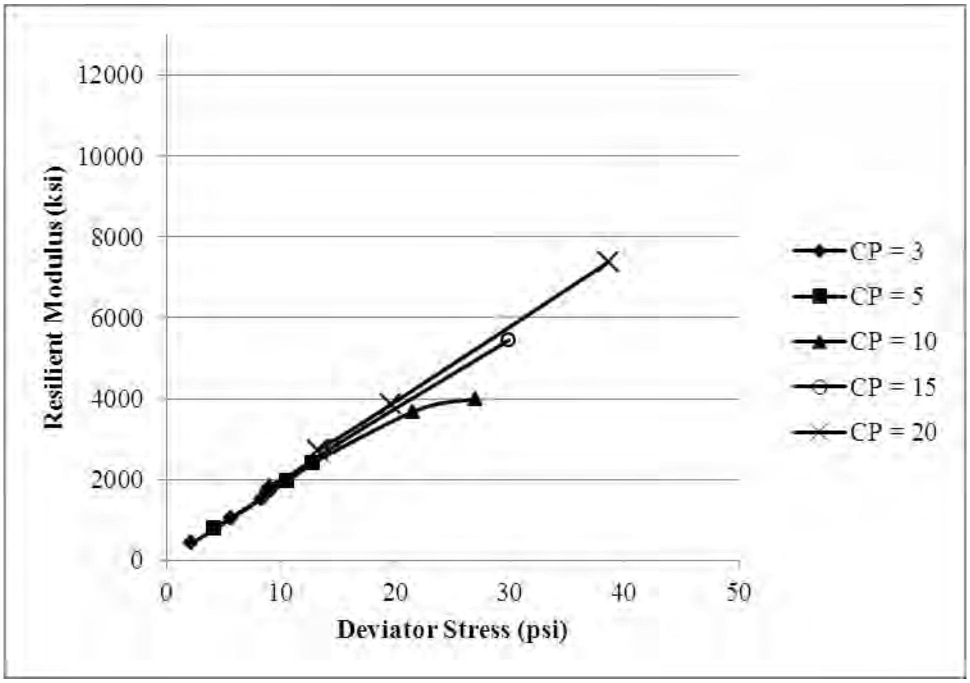

Figure H.5. M_R for FC = 6%, MC = 6%, Low Gradient, -5 °C

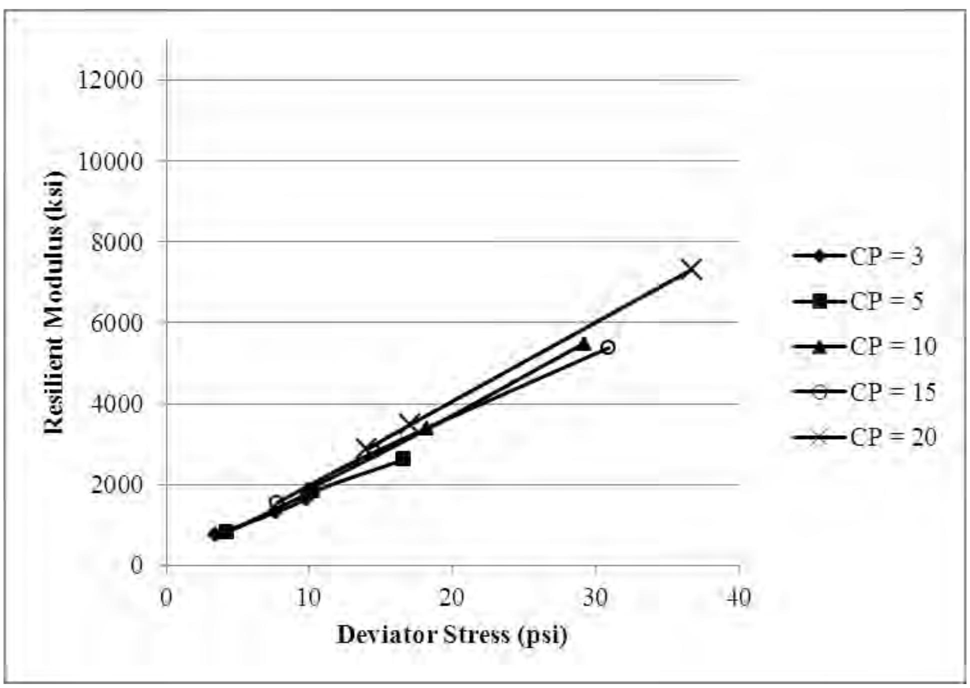

Figure H.6. M_R for FC = 12%, MC = 6%, Low Gradient, -5 °C

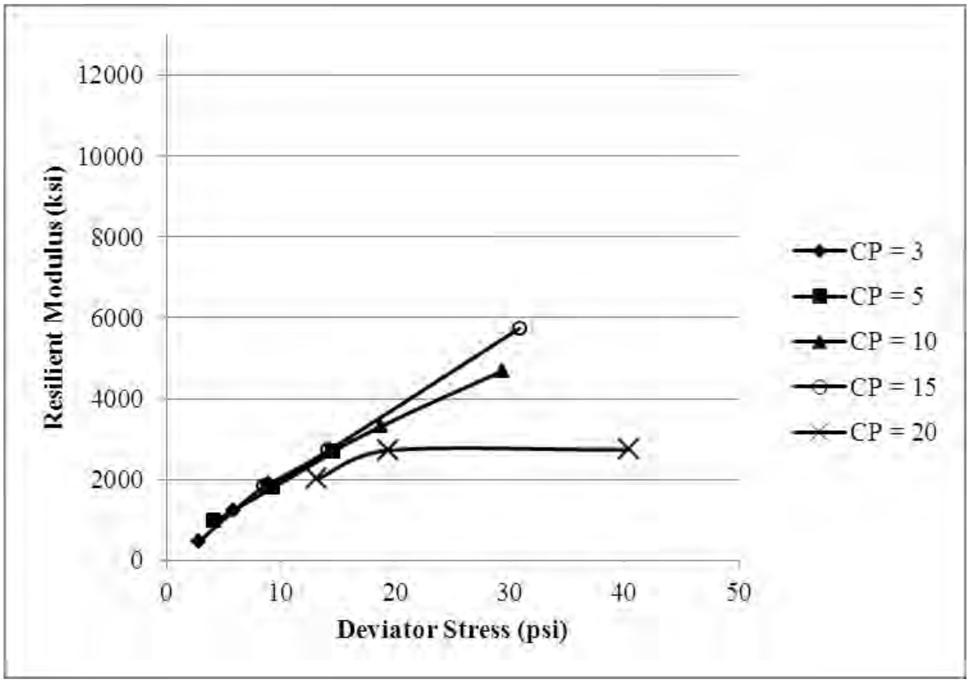

Figure H.7. M_R for FC = 6%, MC = 3.3%, Medium Gradient, -5 °C

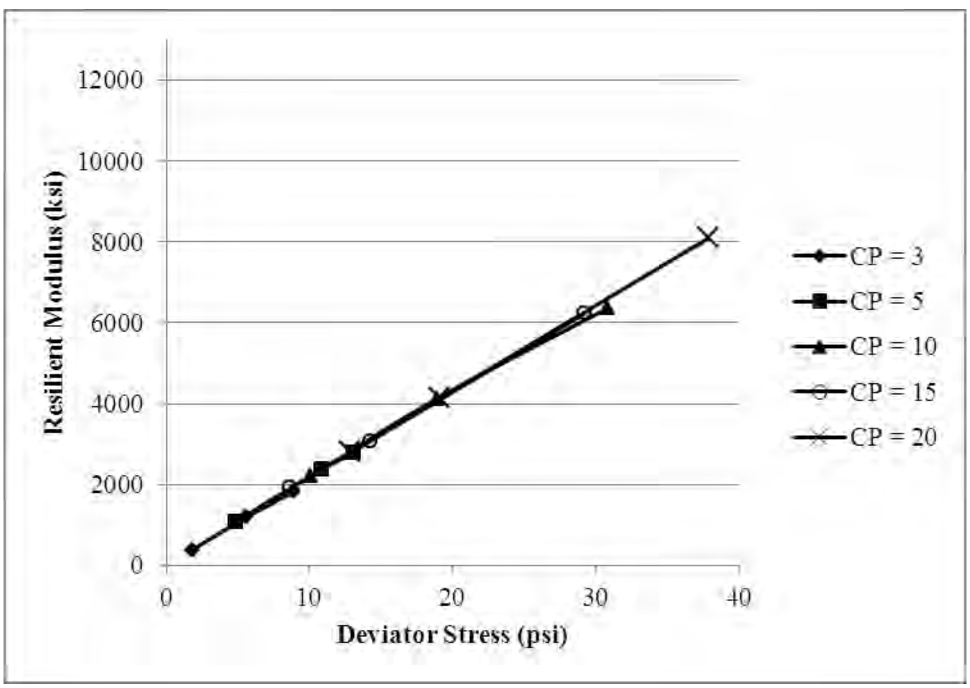

Figure H.8. M_R for FC = 12%, MC = 3.3%, Medium Gradient, -5 °C

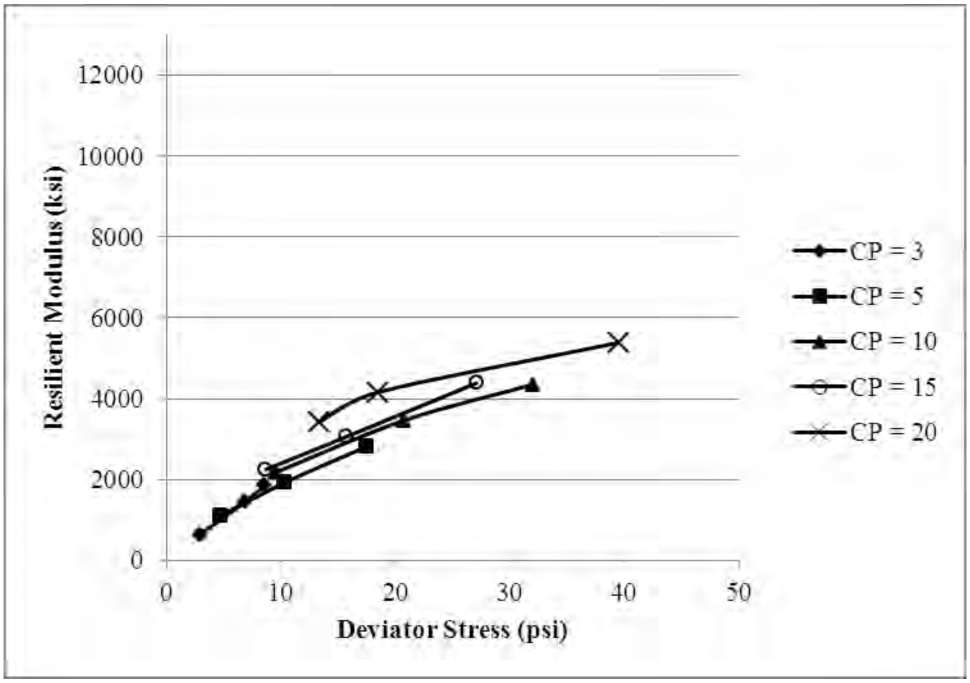

Figure H.9. M_R for FC = 6%, MC = 5.3%, Medium Gradient, -5 °C

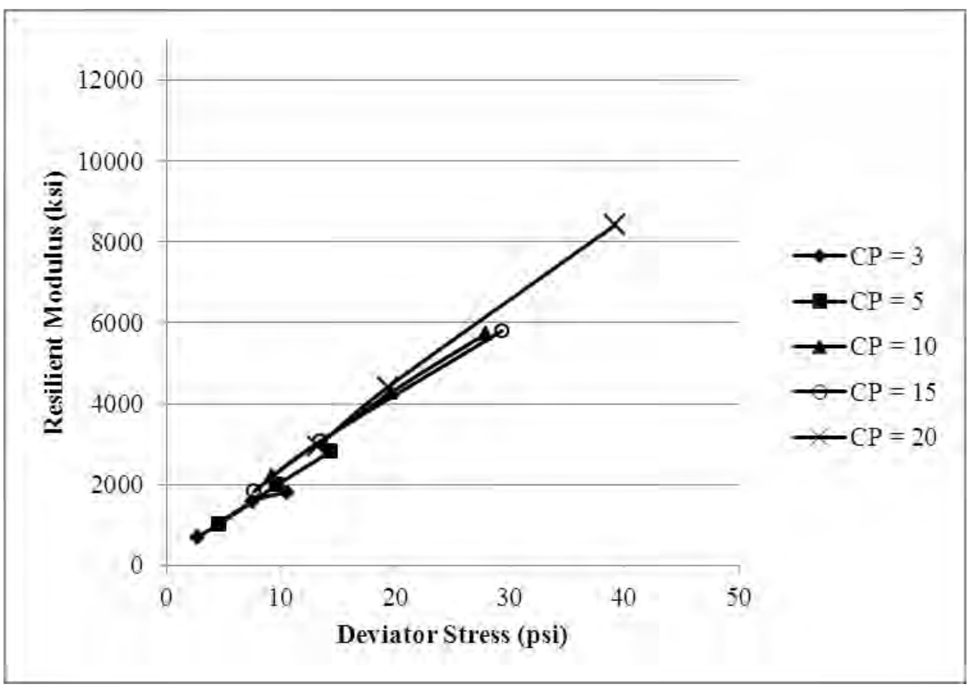

Figure H.10. M_R for FC = 12%, MC = 5.3%, Medium Gradient, -5 °C

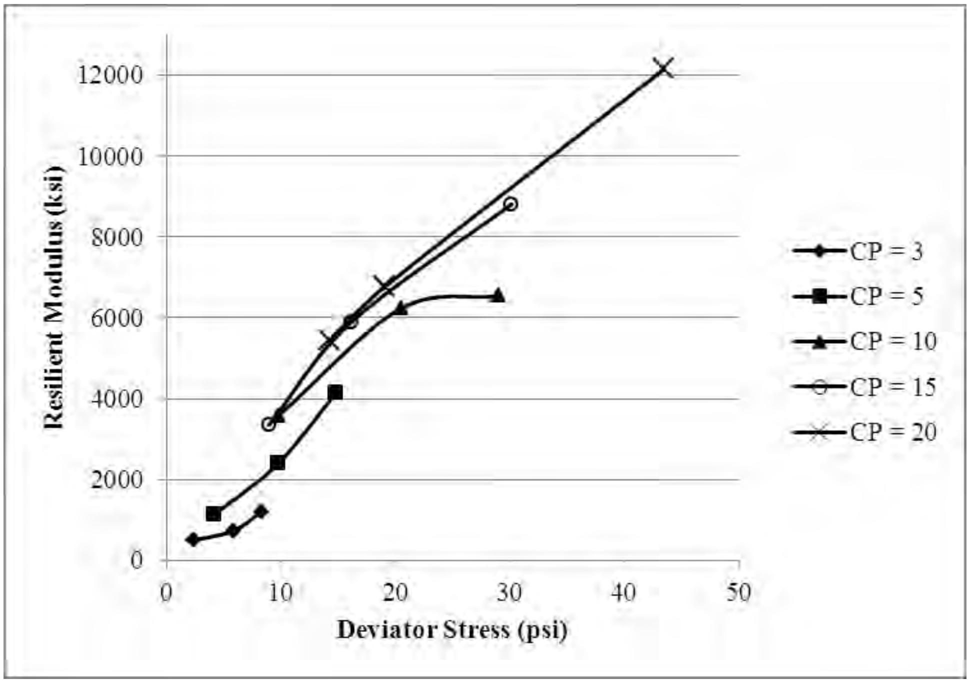

Figure H.11. M_R for FC = 6%, MC = 6%, Medium Gradient, -5 °C

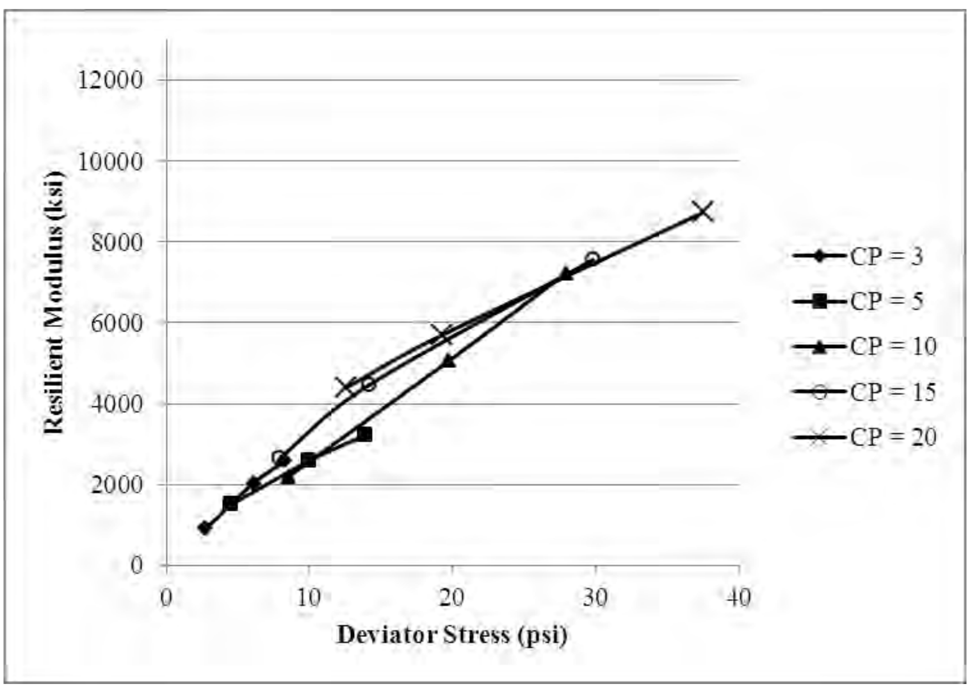

Figure H.12. M_R for FC = 12%, MC = 6%, Medium Gradient, -5 °C

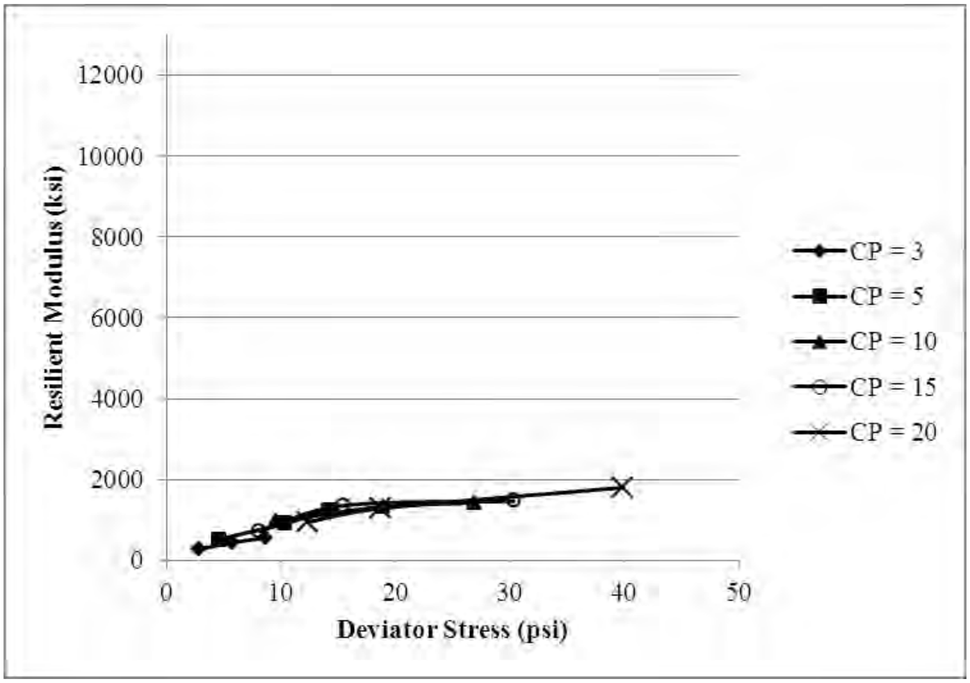

Figure H.13. M_R for FC = 6%, MC = 3.3%, High Gradient, -5 °C

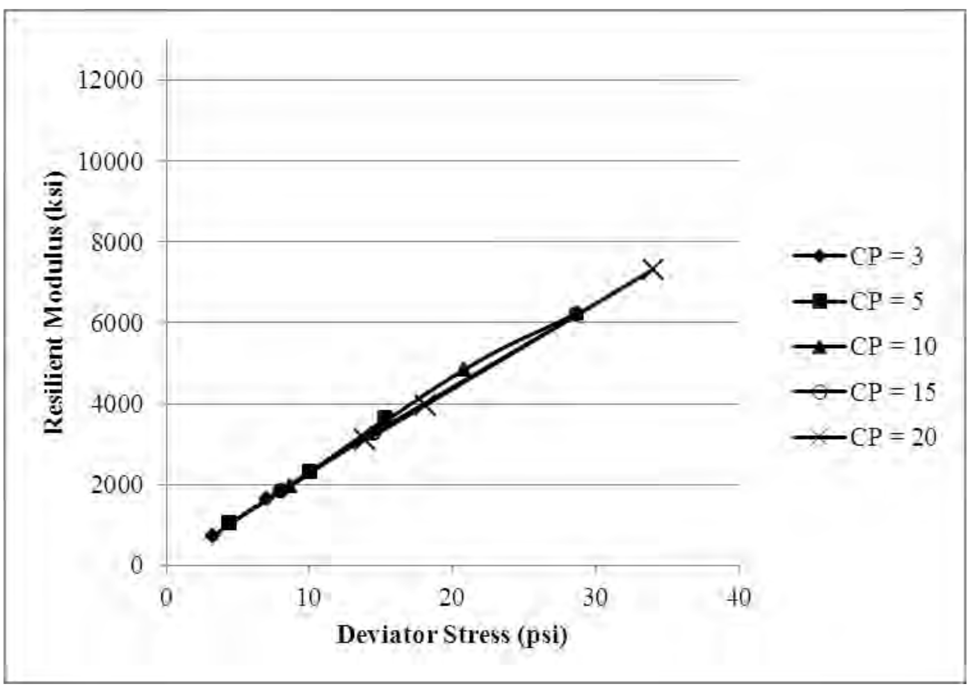

Figure H.14. M_R for FC = 12%, MC = 3.3%, High Gradient, -5 °C

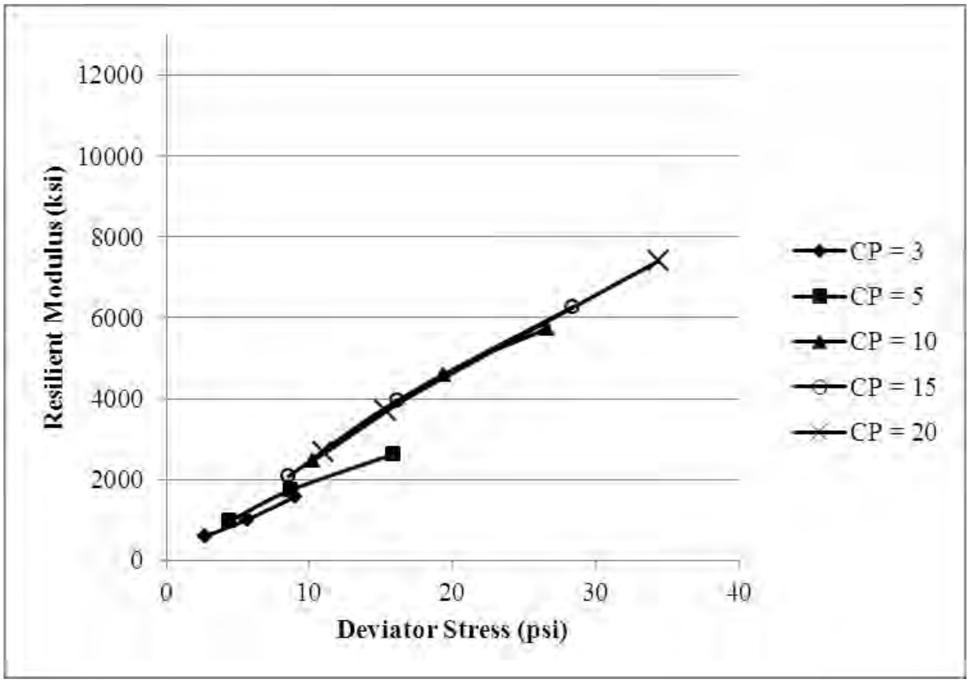

Figure H.15. M_R for FC = 6%, MC = 5.3%, High Gradient, -5 °C

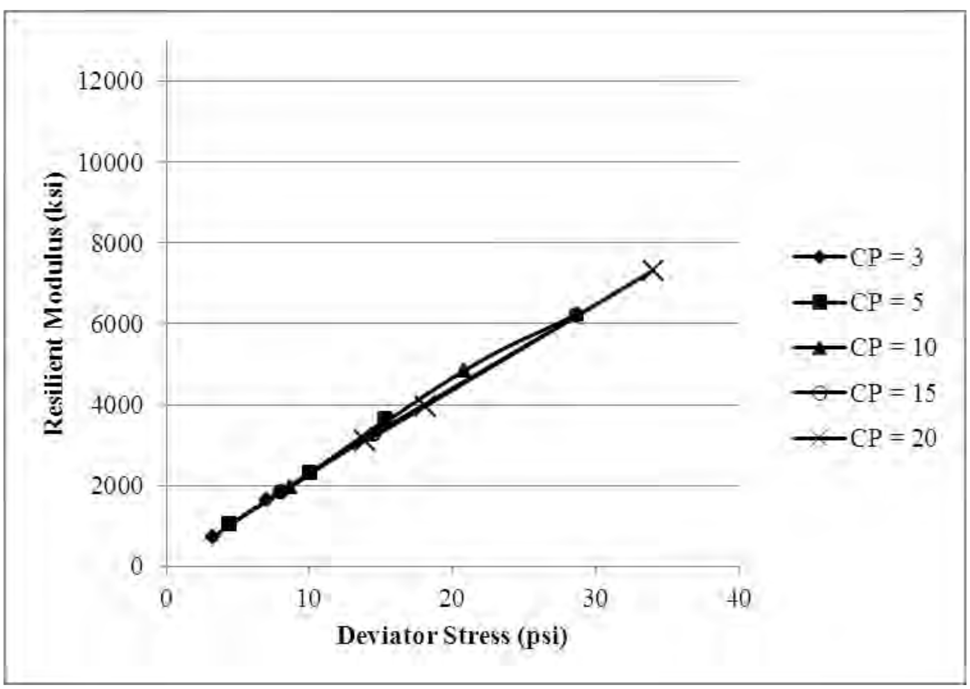

Figure H.16. M_R for FC = 12%, MC = 5.3%, High Gradient, -5 °C

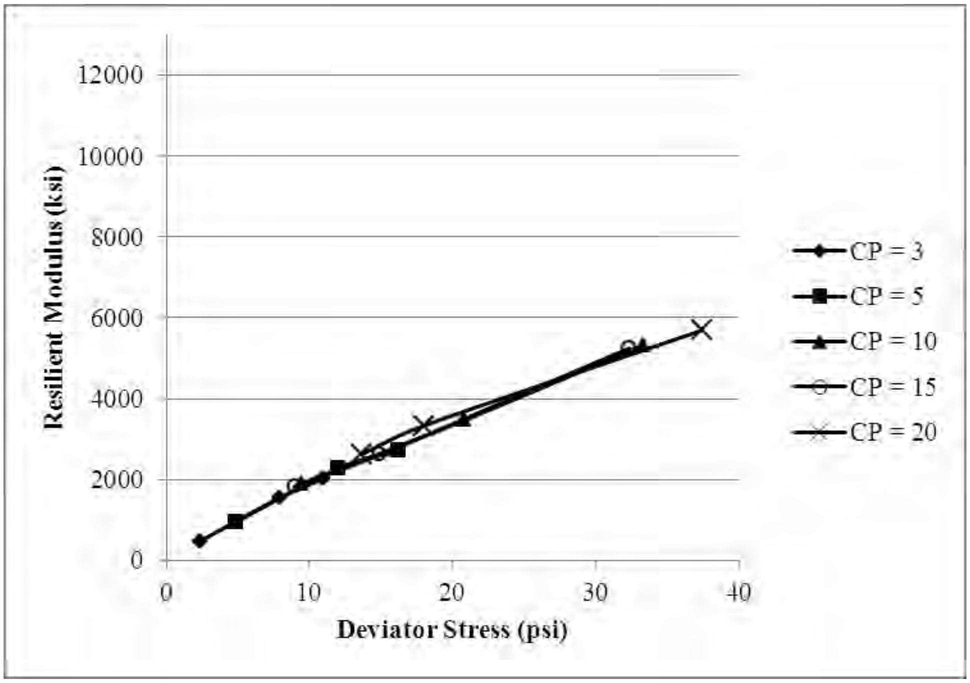

Figure H.17. M_R for FC = 6%, MC = 6%, High Gradient, -5 °C

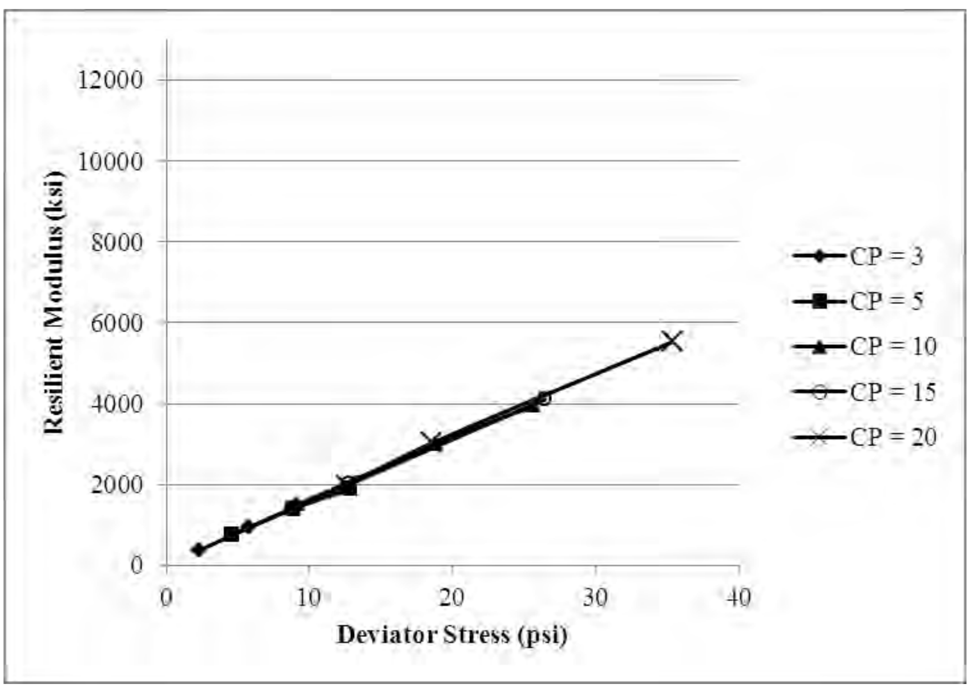

Figure H.18. M_R for FC = 12%, MC = 6%, High Gradient, -5 °C

APPENDIX I

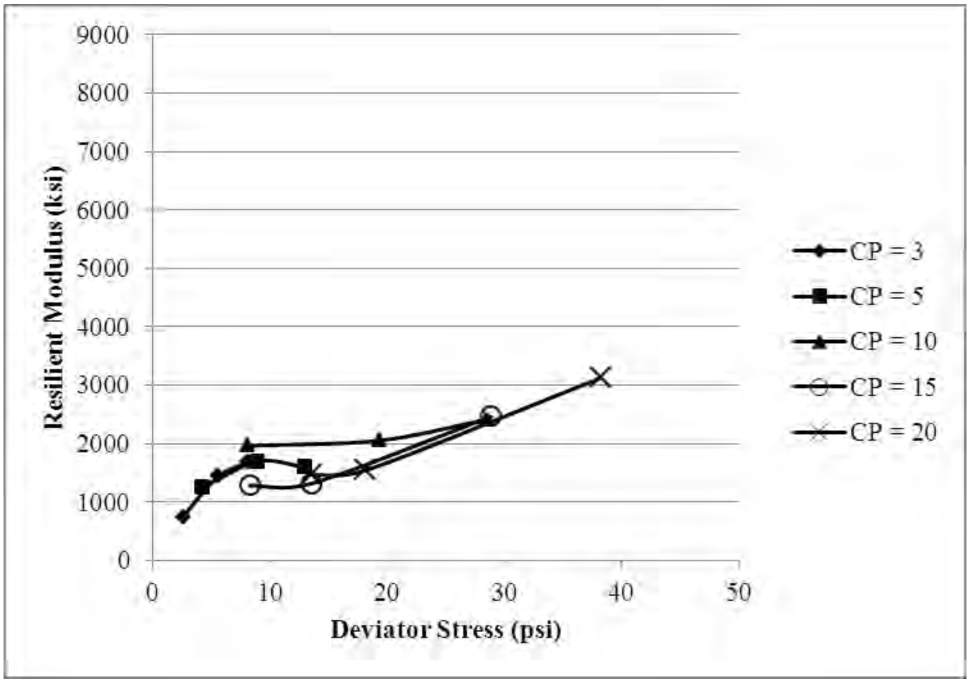

Figure I.1. M_R for FC = 6%, MC = 3.3%, Low Gradient, -1 °C

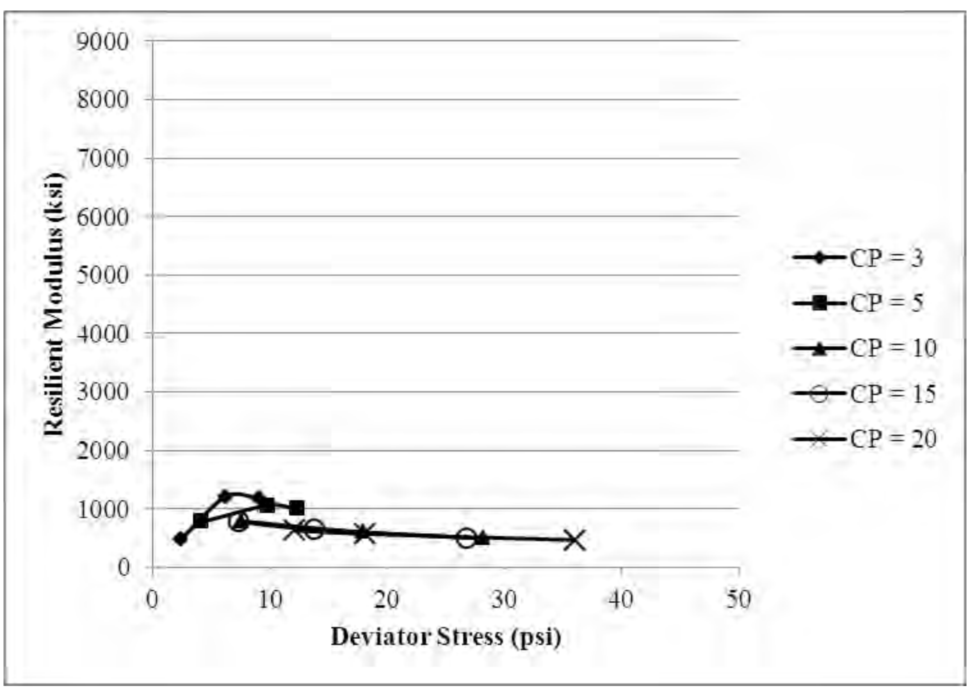

Figure I.2. M_R for FC = 12%, MC = 3.3%, Low Gradient, -1 °C

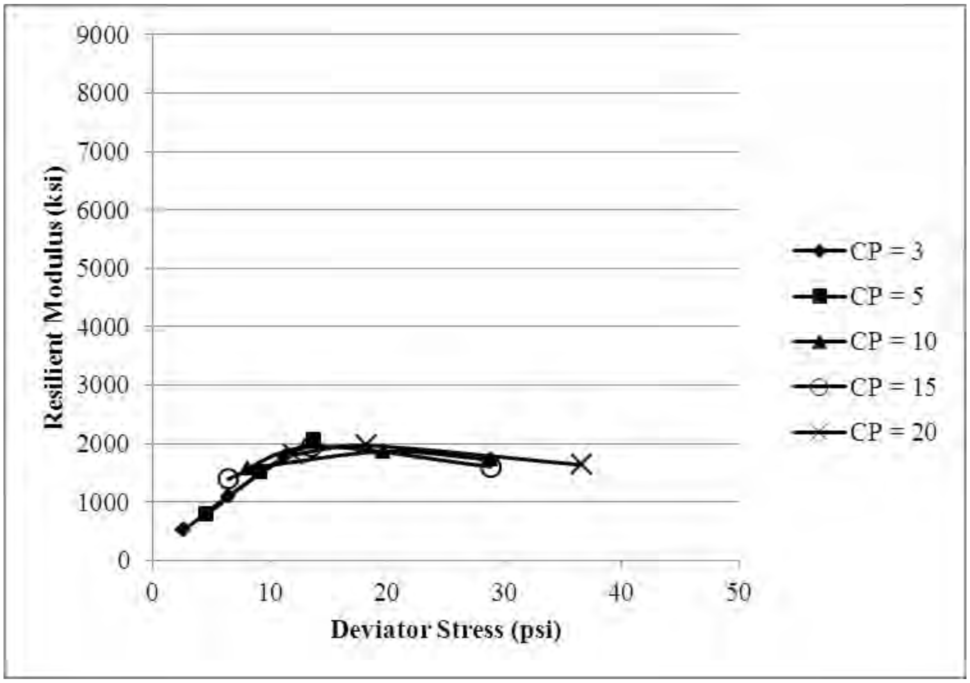

Figure I.3. M_R for FC = 6%, MC = 5.3%, Low Gradient, -1 °C

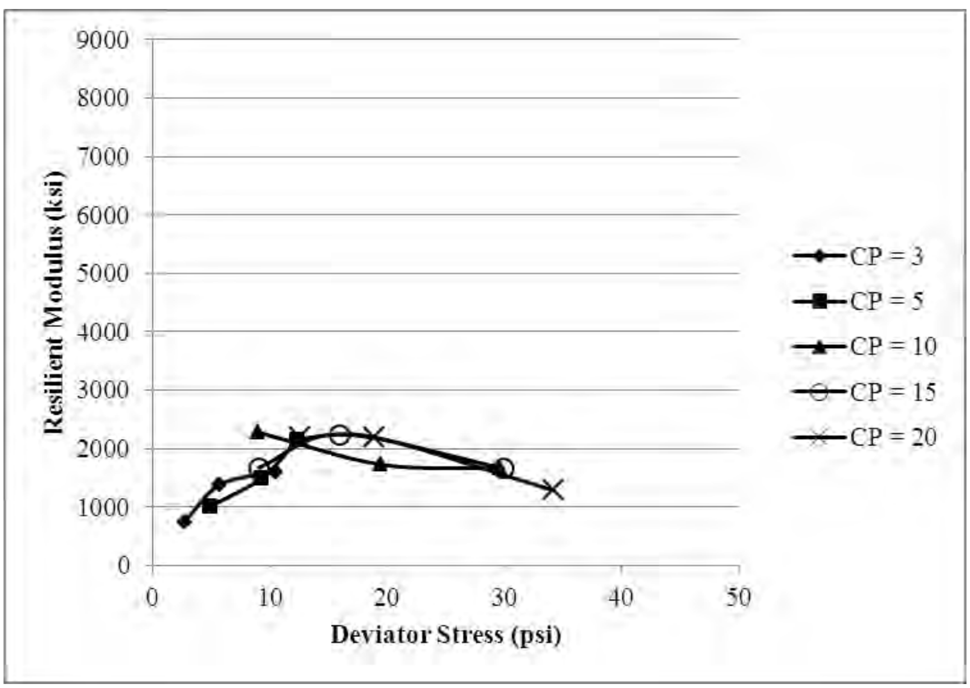

Figure I.4. M_R for FC = 12%, MC = 5.3%, Low Gradient, -1 °C

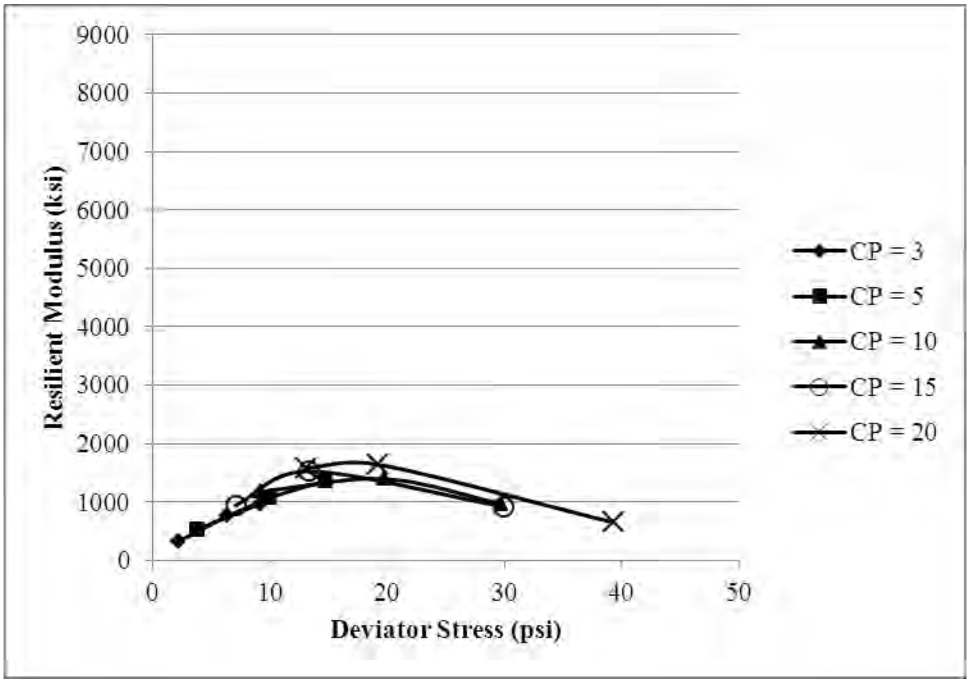

Figure I.5. M_R for FC = 6%, MC = 6%, Low Gradient, -1 °C

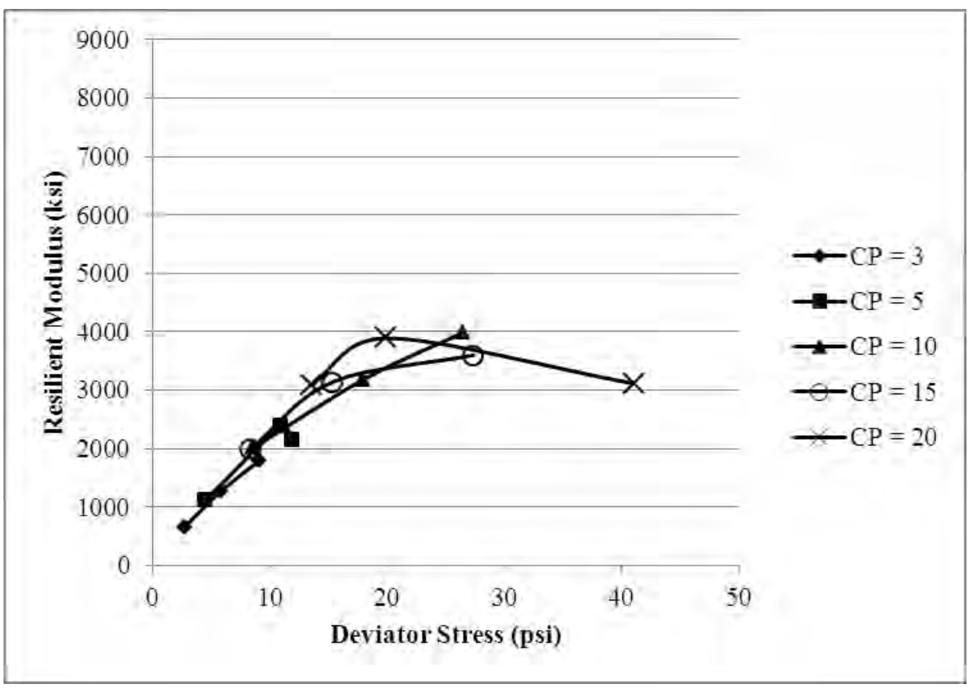

Figure I.6. M_R for FC = 12%, MC = 6%, Low Gradient, -1 °C

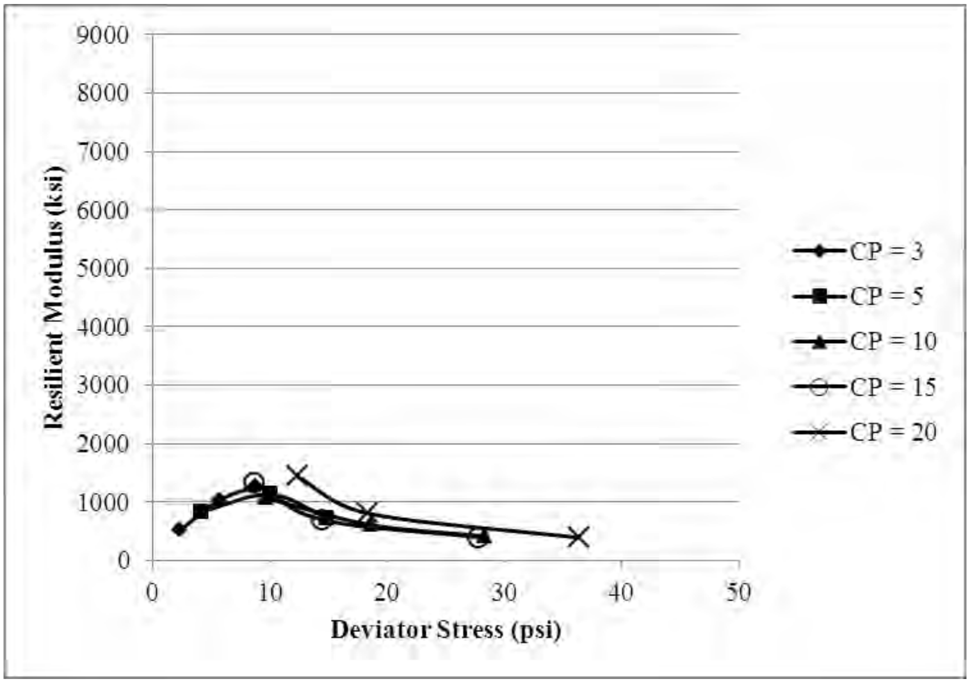

Figure I.7. M_R for FC = 6%, MC = 3.3%, Medium Gradient, -1 °C

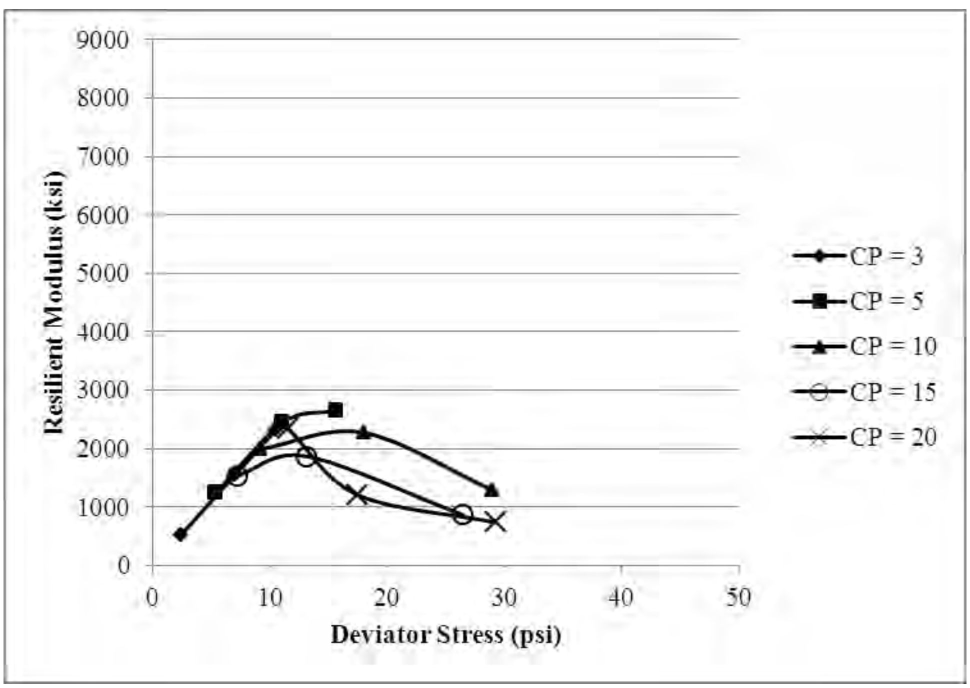

Figure I.8. M_R for FC = 12%, MC = 3.3%, Medium Gradient, -1 °C

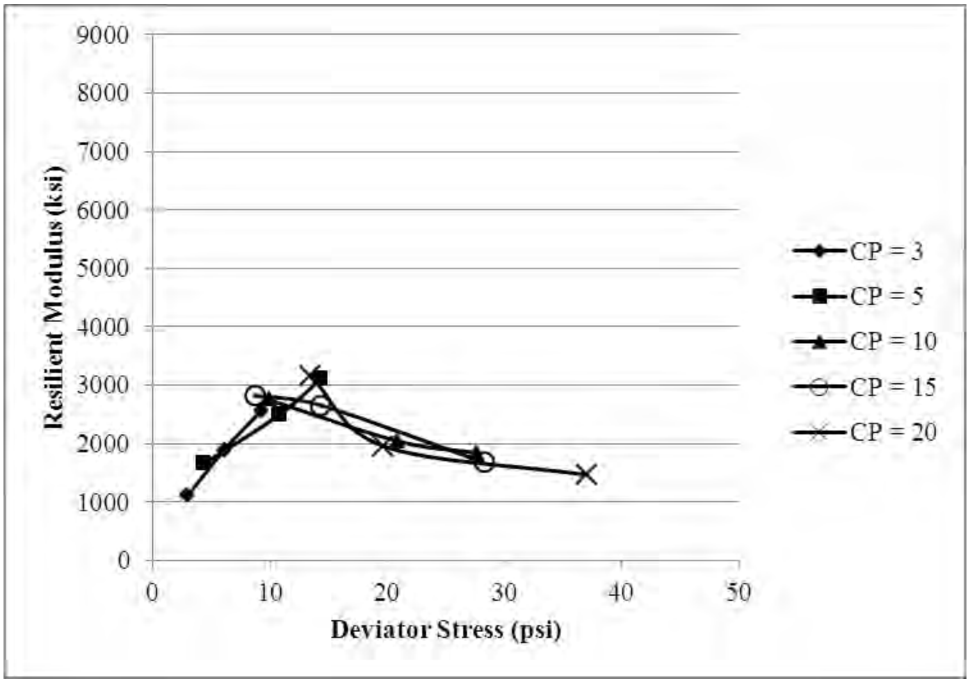

Figure I.9. M_R for FC = 6%, MC = 5.3%, Medium Gradient, -1 °C

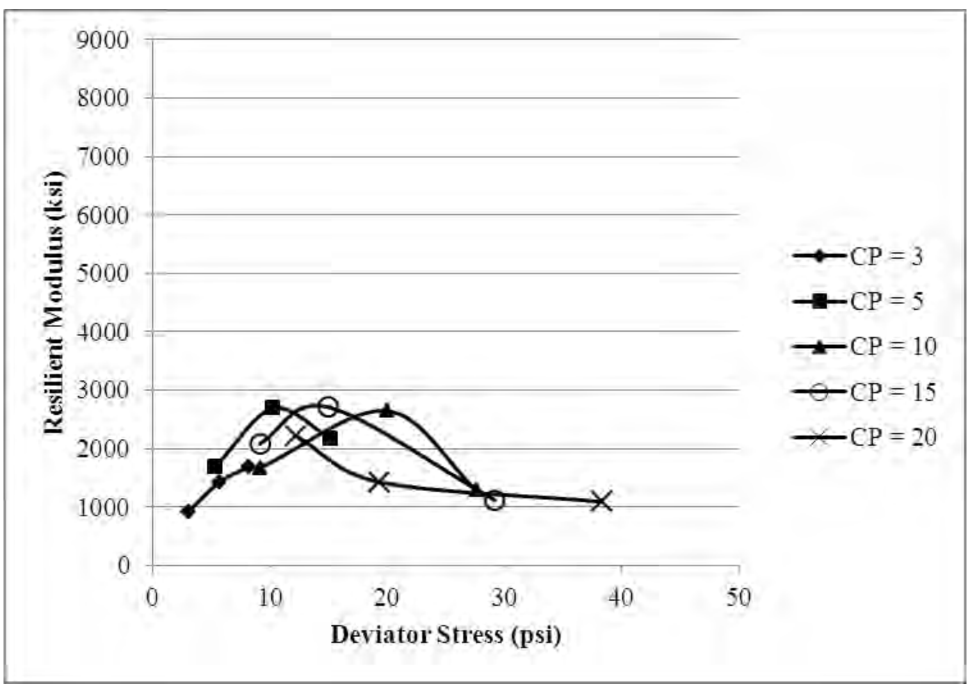

Figure I.10. M_R for FC = 12%, MC = 5.3%, Medium Gradient, -1 °C

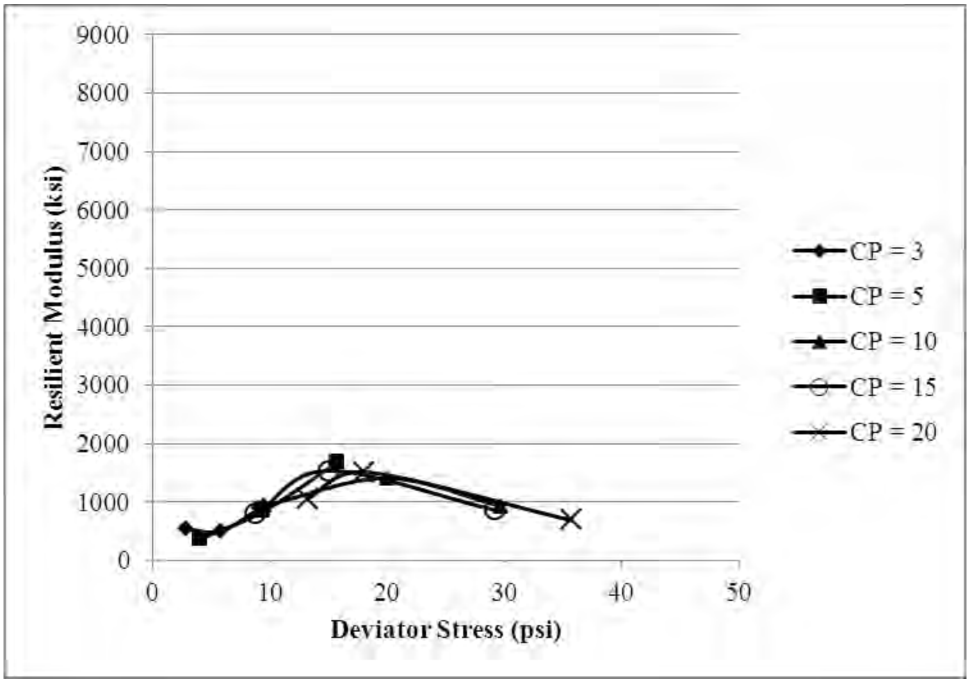

Figure I.11. M_R for FC = 6%, MC = 6%, Medium Gradient, -1 °C

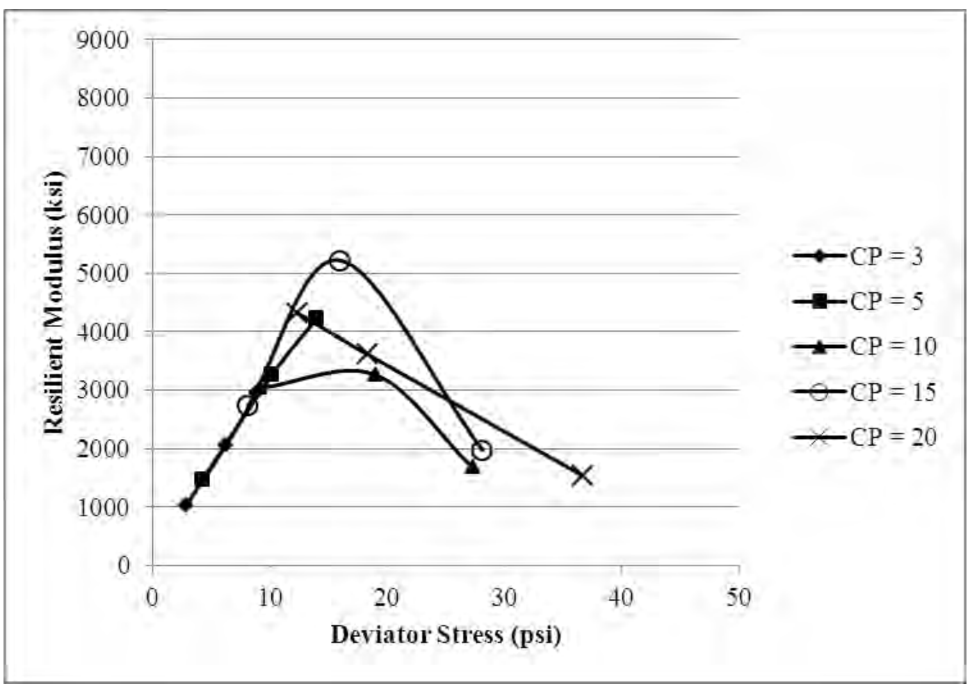

Figure I.12. M_R for FC = 12%, MC = 6%, Medium Gradient, -1 °C

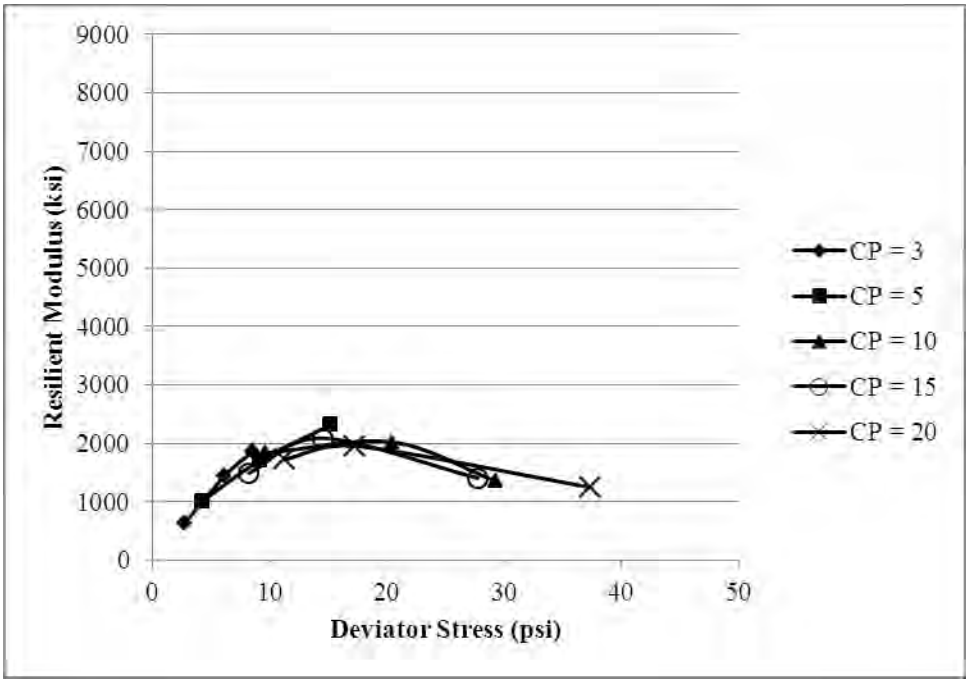

Figure I.13. M_R for FC = 6%, MC = 3.3%, High Gradient, -1 °C

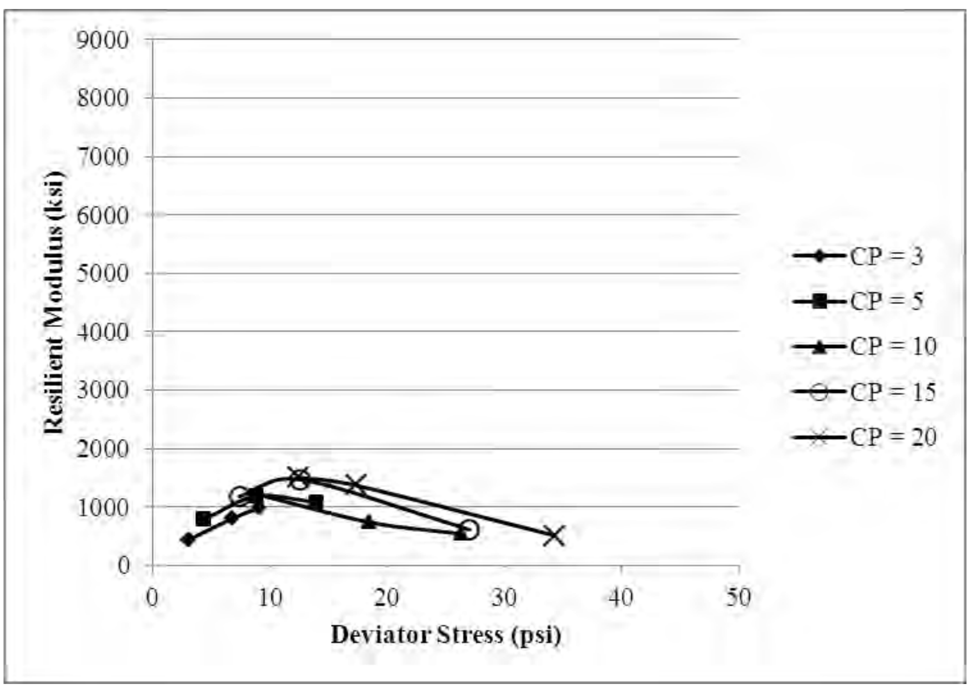

Figure I.14. M_R for FC = 12%, MC = 3.3%, High Gradient, -1 °C

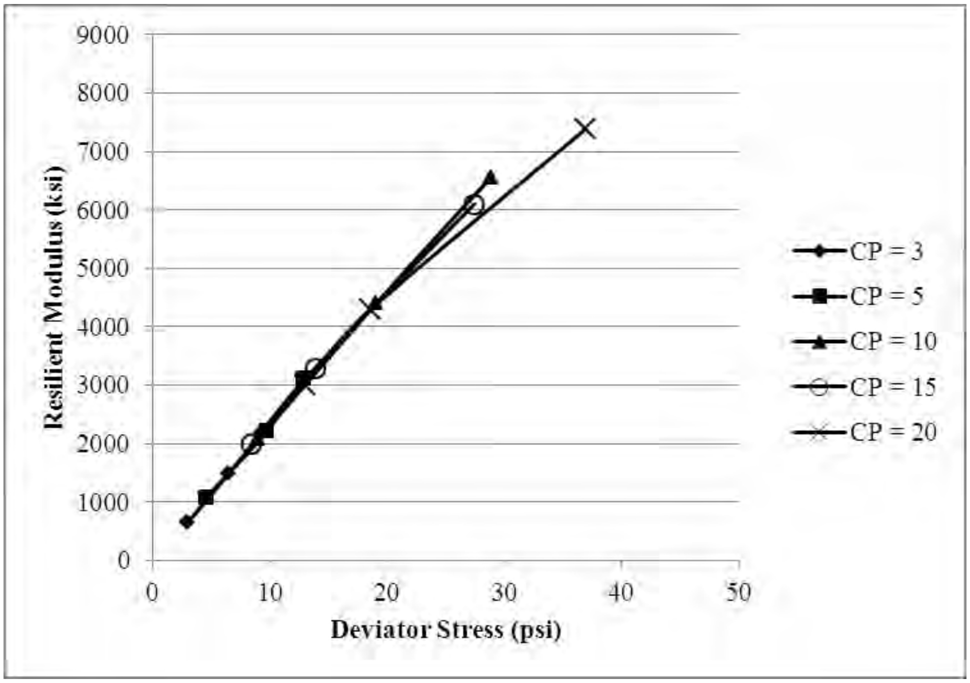

Figure I.15. M_R for FC = 6%, MC = 5.3%, High Gradient, -1 °C

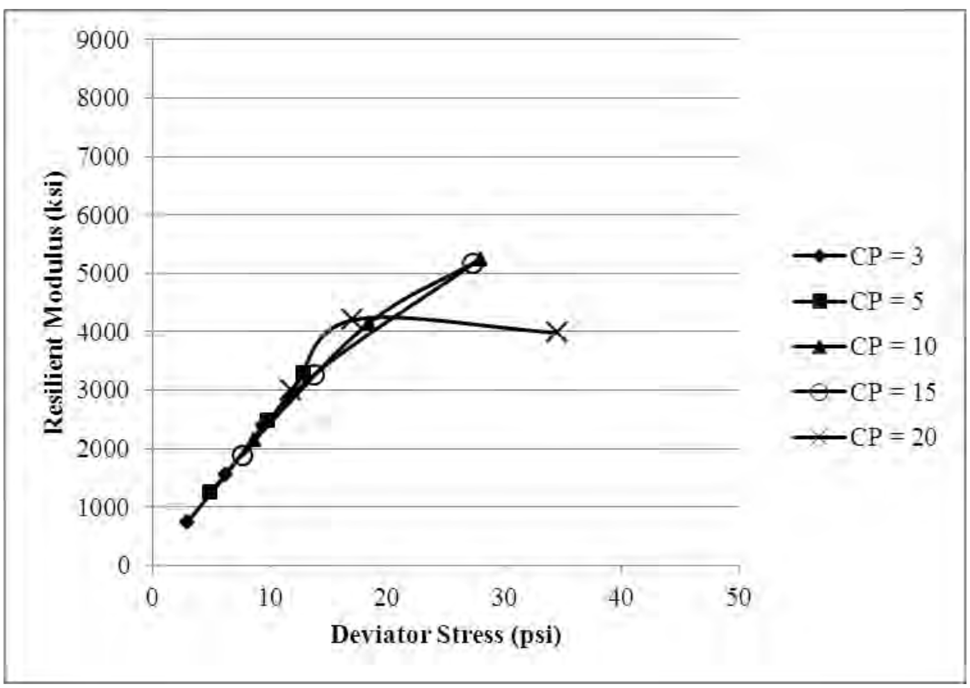

Figure I.16. M_R for FC = 12%, MC = 5.3%, High Gradient, -1 °C

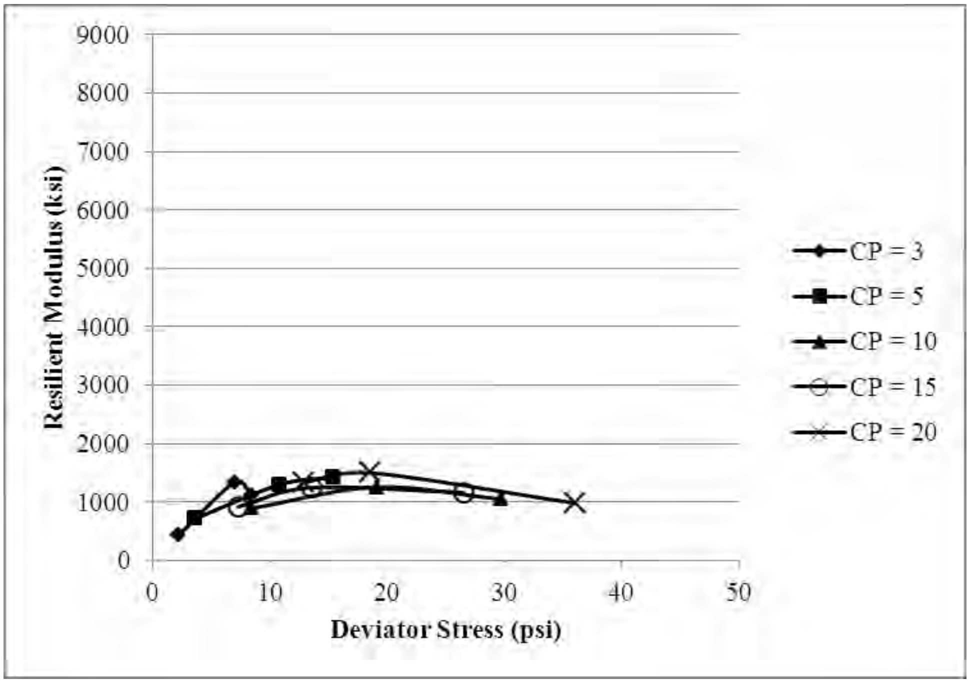

Figure I.17. M_R for FC = 6%, MC = 6%, High Gradient, -1 °C

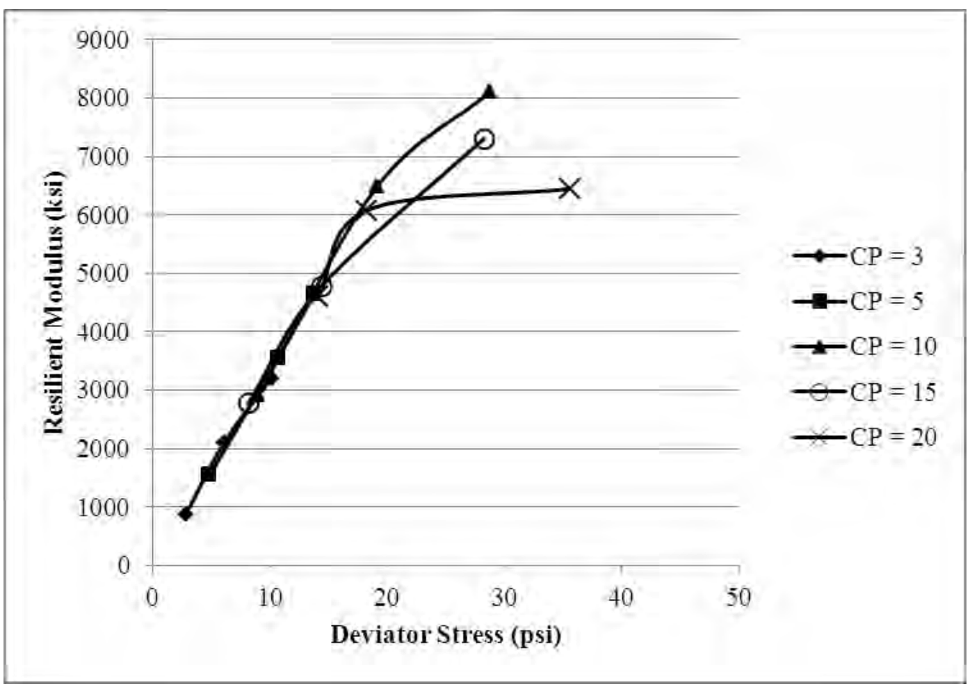

Figure I.18. M_R for FC = 12%, MC = 6%, High Gradient, -1 °C

APPENDIX J

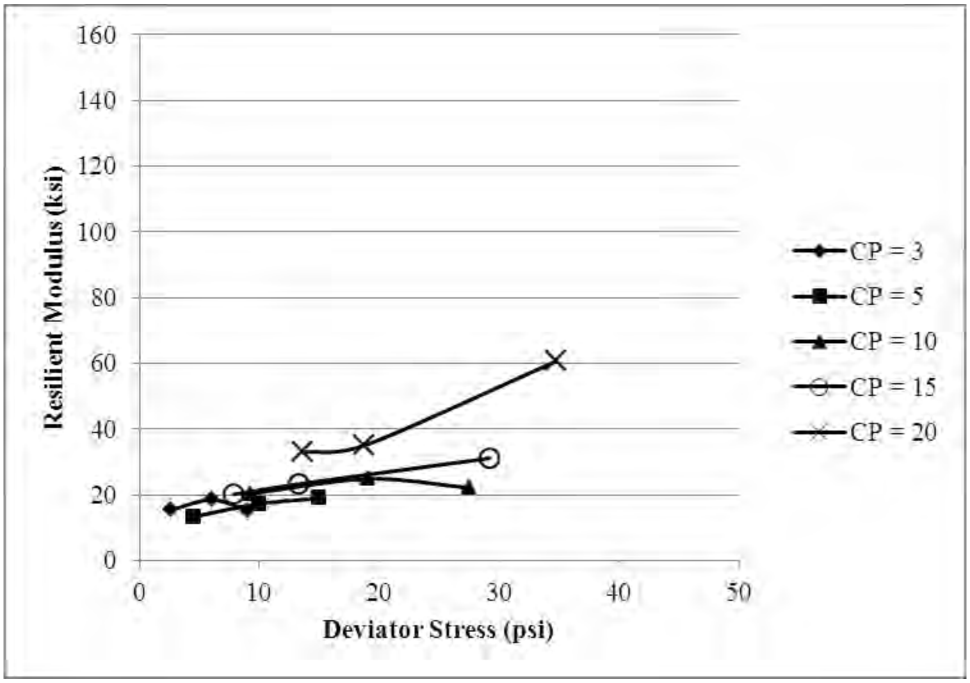

Figure J.1. M_R for FC = 6%, MC = 3.3%, Non-Frozen, 20 °C

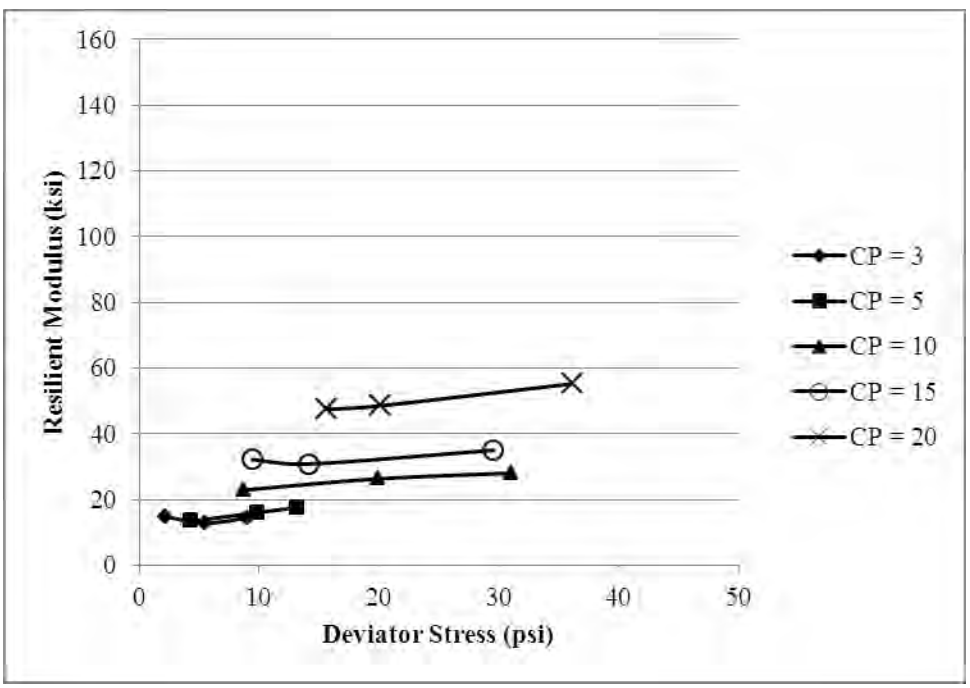

Figure J.2. M_R for FC = 6%, MC = 5.3%, Non-Frozen, 20 °C

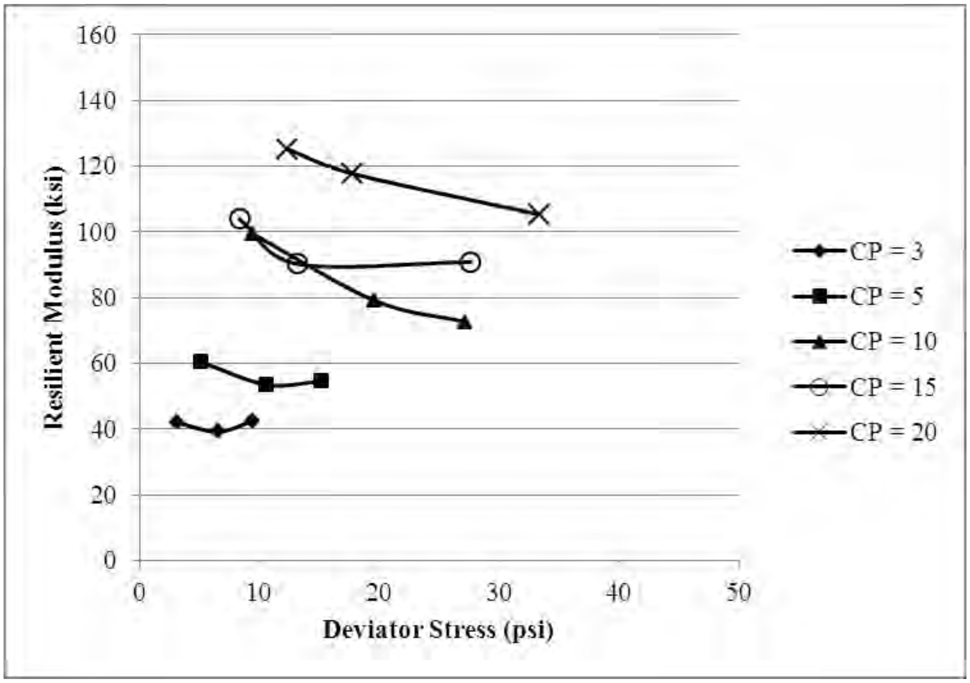

Figure J.3. M_R for FC = 8%, MC = 3.3%, Non-Frozen, 20 °C

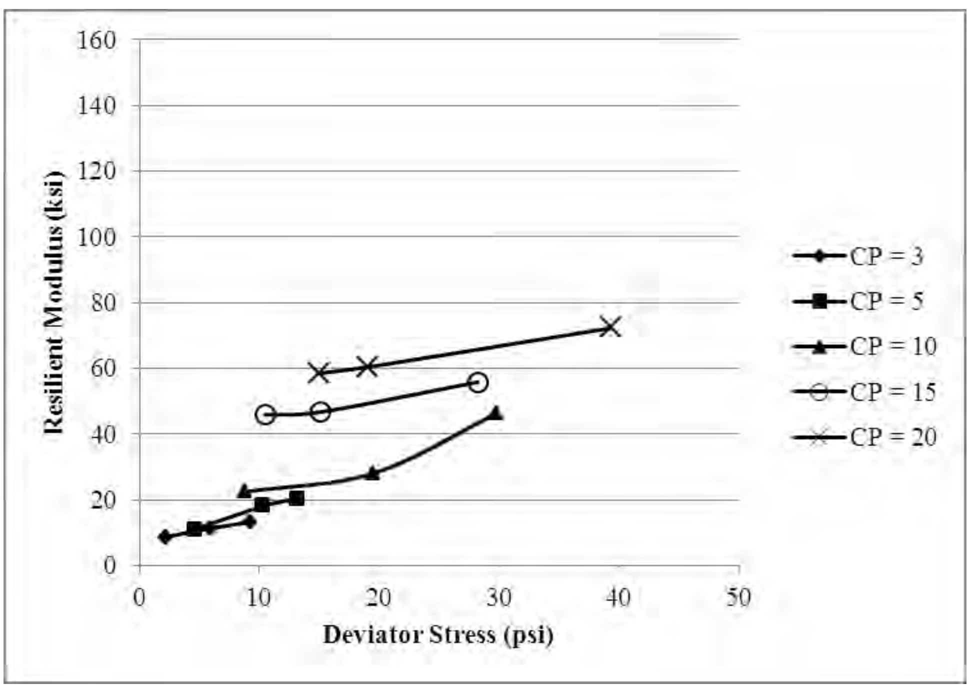

Figure J.4. M_R for FC = 8%, MC = 5.3%, Non-Frozen, 20 °C

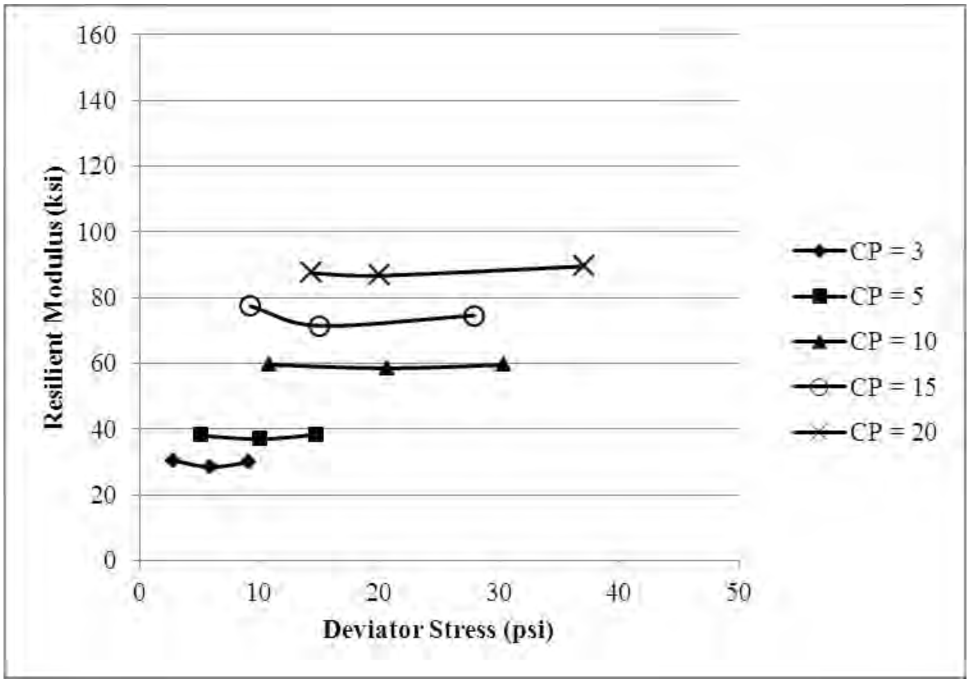

Figure J.5. MR for FC = 10%, MC = 3.3%, Non-Frozen, 20 °C

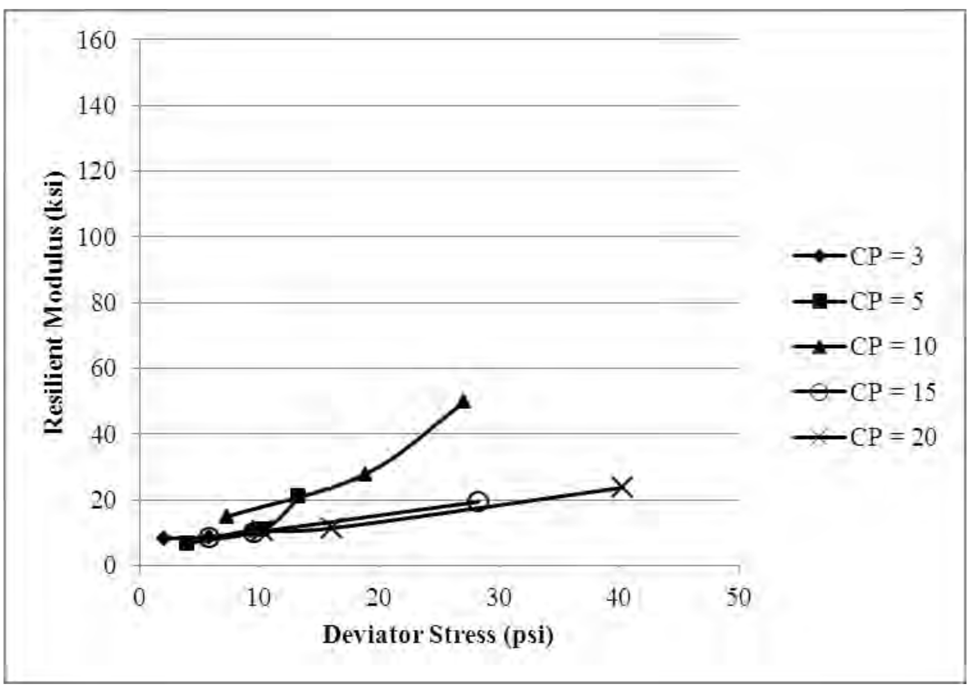

Figure J.6. MR for FC = 10%, MC = 5.3%, Non-Frozen, 20 °C

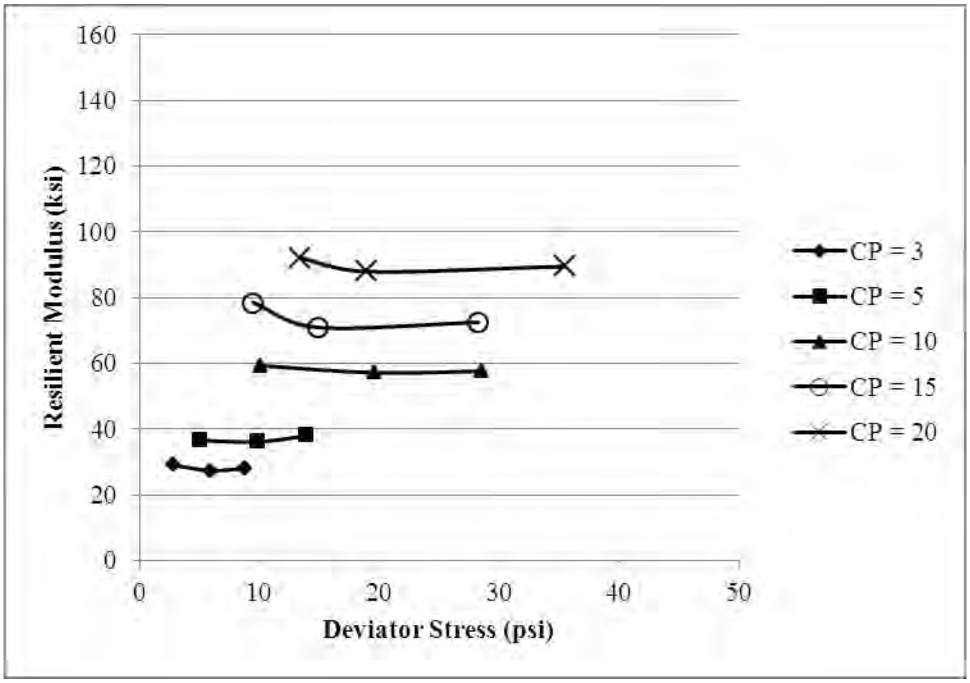

Figure J.7. M_R for FC = 12%, MC = 3.3%, Non-Frozen, 20 °C

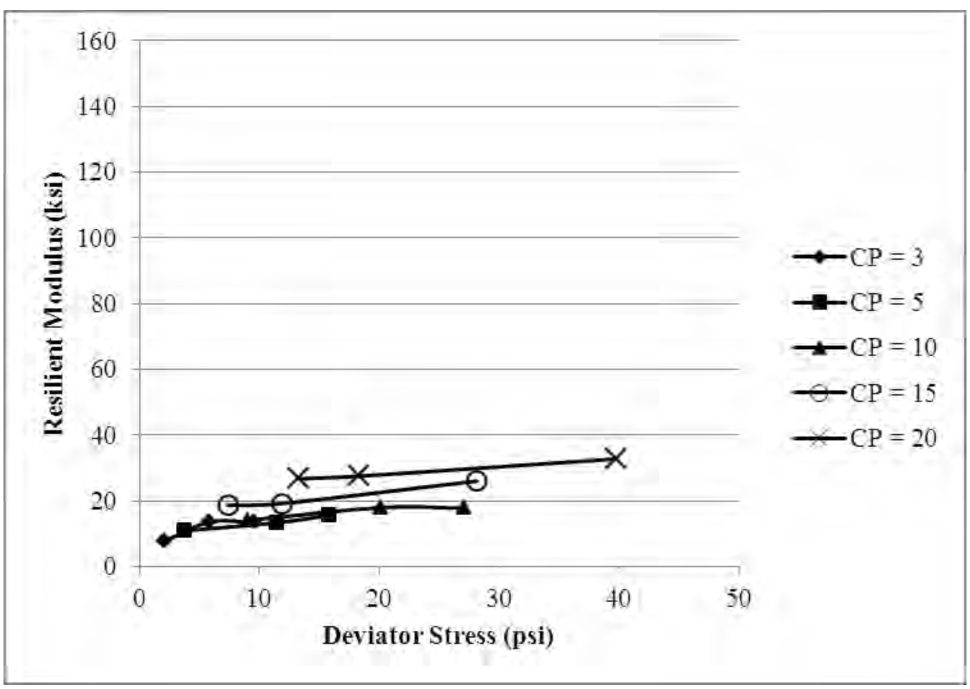

Figure J.8. M_R for FC = 12%, MC = 5.3%, Non-Frozen, 20 °C