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2009-05

Investigation of Stripping in Minnesota Class 7 (RAP) and Full-Depth Reclamation Base Materials

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16. Abstract (Limit: 200 words)

This research investigates the effect of RAP content, freeze-thaw and severe moisture conditions on the structural capacity of the pavement base layer. The investigated material included one source of 100% RAP, one source of virgin aggregate, and three full depth reclamation samples where RAP was mixed with virgin aggregate/soil and was in use as a base layer. RAP was blended in the lab with the virgin aggregate at 50% and 75% RAP content. RAP was coarser than virgin aggregate and it had a higher percentage loss in the Micro-Deval test. The resilient modulus (M_R) was measured following the National Cooperative Highway Research Program 1-28A test protocol. The M_R for all RAP material was higher than that of the virgin aggregate. The resilient modulus of RAP material was found to be dependent on confining pressure. There was no clear loss of the modulus due to freeze-thaw conditioning for the tested RAP. Decreasing the moisture content increased the resilient modulus for RAP material. Maximum deviator stress in the shear test was reduced after freeze-thaw (F-T) conditioning for RAP/aggregate blends at a low confining pressure, but the effect of F-T on the maximum deviator stress was not clear at a higher confining pressure.

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Executive Summary

The use of reclaimed asphalt pavement (RAP) as a pavement base material can reduce the amount of virgin aggregate needed, reduce construction cost, reduce lane closure time and eliminate disposal issues. Currently Mn/DOT allows the use of RAP as Class 7, which is an aggregate base course containing salvage/recycled aggregate material. This research investigates the effect of RAP on the structural capacity of the base layer, defined by resilient modulus (M_R) and shear strength. The effect of freeze-thaw (F-T) and severe moisture conditions on the structural capacity of RAP material as a base layer is investigated.

In the preliminary part of the project, data from test results on RAP material from Mn/ROAD cell 26 was collected from the Mn/DOT data base. Samples were collected from different highways in Minnesota. The investigated material included one source of 100% RAP produced by cold planning from Trunk Highway 10 (RAP TH 10), one source of virgin aggregate (Minnesota Class 5), and three Class 7 samples where RAP was mixed with virgin aggregate and is in use as a base layer. RAP TH 10 was blended with the virgin aggregate at 50% and 75% RAP content to investigate the effect of RAP content on base layer structural capacity.

The collected samples were evaluated in the laboratory by several testing methods, starting with aggregate gradation and asphalt extraction. Moisture density relations for the samples were determined using the standard Proctor test and the Superpave gyratory compactor. Aggregate/RAP resistance to abrasion and degradation was evaluated using the Micro-Deval test. The structural capacity of the RAP as compared to virgin aggregate was evaluated using the resilient modulus test following the National Cooperative Highway Research Program (NCHRP) 1-28A test protocol. Resilient modulus samples were compacted by the gyratory compactor to the objective dry density. Triaxial shear test was conducted on the resilient modulus samples, for samples compacted at optimum moisture content and maximum dry density, at two confining pressures to evaluate the shear strength of the tested samples. One set of samples was subject to two freeze-thaw cycles to evaluate the effect of freeze-thaw on the resilient modulus and the shear strength of RAP as compared to virgin aggregate.

RAP gradation was coarser than virgin aggregate and it fell within the Mn/DOT Class 5 gradation limits. RAP had a higher percentage loss in the Micro-Deval test as compared to virgin aggregate. Optimum moisture content (OMC) for RAP aggregate blend mixes were lower than OMC for Class 5 based on the gyratory compactor at 50 gyrations, however the OMC for RAP/aggregate blends were higher than Class 5 based on the standard Proctor test. The maximum dry densities (MDD) for RAP/aggregate blends and field samples were lower than MDD for Class 5. The resilient modulus for all RAP material was higher than that of Class 5. The resilient modulus of RAP material was found to be dependent on confining pressure. There was no clear loss of the modulus due to freeze-thaw conditioning for the tested RAP material. Decreasing the moisture content increased the resilient modulus for RAP material. The effect of dry density on M_R was dependent on the state of stress, material type and moisture content. There was no clear difference in friction angle and cohesion between RAP aggregate blend mixes, field samples and Class 5. There was no change in the internal friction angle for RAP due to freeze-thaw conditioning for the tested samples except RAP TH 19-101 material. Maximum deviator stress in the shear test was reduced after F-T conditioning for RAP aggregate blends at a

low confining pressure (4 psi) but the effect of F-T on maximum deviator stress was not clear at a higher confining pressure (8 psi).

Chapter 1

Introduction

1.1. Background

Over 100 million tons of recycled asphalt pavement (RAP) are produced by pavement rehabilitation activities each year in the USA (*1*). The Asphalt Recycling and Reclaiming Association (ARRA) defines Full Depth Reclamation (FDR) as "a pavement rehabilitation technique in which the full flexible pavement section and a pre-determined portion of the underlying materials are uniformly crushed, pulverized or blended, resulting in a stabilized base course (SBC); further stabilization may be obtained through the use of available additives" (2). Figure 1.1 shows a schematic of a typical FDR milling machine. The use of RAP as a base material can reduce the amount of virgin aggregate needed, reduce construction cost, reduce lane closure time and eliminate disposal issues. Currently Mn/DOT allows the use of RAP as Class 7, which is an aggregate base course containing salvage/recycled aggregate material (*8*).

The resilient modulus (M_R) is the basic property that defines the structural capacity of unbound layer strength in the pavement analysis and design process (3). The resilient modulus (M_R) test is a commonly conducted laboratory test to define stiffness of the base material (3, 4). Proper characterizations of the nonlinear stress-dependent behavior of pavement unbound layers have significant impact on the accuracy of prediction of pavement responses (5).

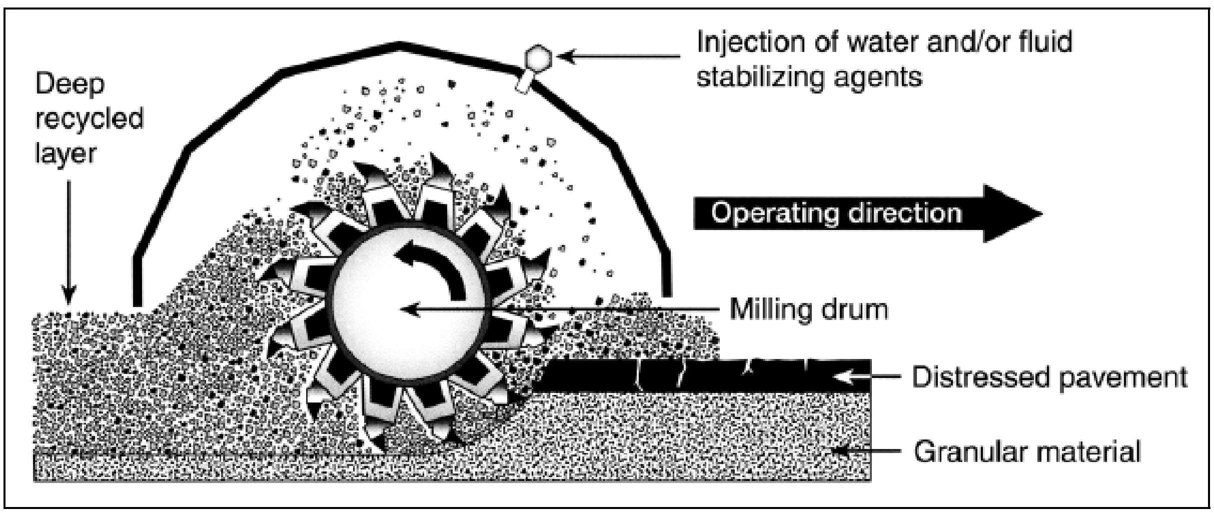


Figure 1.1 Schematic of milling machine operation in FDR process (6)

1.2. Problem Statement

The use of RAP as a base material can reduce the amount of virgin aggregate needed, reduce construction cost, reduce lane closure time and eliminate disposal issues. However, the long term change in the properties of RAP as a base material in service is a gap in the literature. The effect of RAP on the structural capacity of the base layer is not fully investigated. The effect of freeze-thaw (F-T) and severe moisture conditions on the behavior of RAP material as a base layer was not fully investigated.

1.3. Objectives

The research objectives are:

- Assess structure properties of RAP as a base layer.
- Evaluate the effect of freeze-thaw (F-T) cycles on the stiffness and strength of RAP material in Minnesota.

1.4. Implementation

The results of this research should help Mn/DOT in evaluating the suitability of using RAP as a base layer. Results will give data regarding the structural adequacy of RAP as a base layer in severe conditions where the pavement base is subject to several freeze-thaw cycles.

1.5. Report Organization

Chapter 2: presents a summarized literature review of the previous research conducted on using RAP as a base layer.
Chapter 3: contains descriptions of the data collected from Mn/DOT on RAP aggregate blends tested at Mn/DOT laboratories.
Chapter 4: contains descriptions of the tested material, experimental design, sample preparation procedures including gradation tests, Proctor and gyratory compaction tests, the Micro-Deval test, shear strength test and resilient modulus testing procedures.
Chapter 5: contains analysis and discussion of the collected data and the laboratory test results.
Chapter 6: summarizes and concludes the findings of the research.

Chapter 2

Literature Review

2.1. Introduction

Over 100 million tons of recycled asphalt pavement (RAP) are produced by pavement rehabilitation activities each year in the USA. RAP is the old asphalt pavement material that has been removed and/or reprocessed (*1*). It contains the aggregate and the aged asphalt cement. The two most common asphalt pavement removal processes are milling and full-depth reclamation. In first process, the pavement surface is removed using a milling machine, which can remove up to a 2 in. thickness in a single pass (*1*). Full-depth removal involves ripping and breaking the pavement using a rhino horn on a bulldozer and/or pneumatic pavement breakers.

When properly crushed and screened, RAP consists of high-quality, well-graded aggregates coated by asphalt. After collecting the RAP, material characterization is performed with respect to aggregate gradation and asphalt content *(1).*The old asphalt pavement is often recycled and processed in the same place to produce a granular pavement base. Hot in-place and cold in-place are the two methods of in-place recycling of asphalt pavement. Sometimes the recycling is performed by adding some additives, for example, cement or foamed asphalt to produce a stabilized base layer.

2.1.1. Application of RAP as Base Layer

It is reported that at least 13 state agencies (Arizona, Illinois, Louisiana, Maine, Nebraska, New Hampshire, North Dakota, Oregon, Rhode Island, South Dakota, Texas, Virginia, and Wisconsin) have used RAP as aggregate in the base course (*1*).

Through the literature review a full project was found in Illinois which consisted of the construction of the pavement base and then the observation of the performance of the roadway. In 1993 the Lincoln Avenue of Urbana, Illinois, was constructed with RAP base (*7*). The overall structural response and the field performance were monitored; in the conclusion the author mentioned that RAP can be successfully used as a conventional flexible pavement base material (*7*).

2.1.2. Examples of using RAP in base layers

The examples of the application of RAP in base layers in different state agencies are discussed here:

- Mn/DOT has adopted RAP as Class 7, which is an aggregate base mix containing salvage/recycle aggregate material (8).
- TXDOT allows 15%-20% RAP in the base layer but calls for a 100% RAP with a cement-stabilized base (9).
- FDOT allows 100% RAP only in paved shoulders, bike paths or other no traffic applications (10).
- NJDOT allows RAP in the HMA base layer. The maximum percentage of RAP is 25% (11).
- MHD's use of RAP in the base layer consists of recycling the existing pavement structure and a specified depth of acceptable sub-base material to produce a stabilized base (12).

Overall, the performance of RAP as a granular base, or as an additive to a granular base, has been described as satisfactory, good, very good, or excellent. Some of the positive features of RAP aggregates that have been properly incorporated into granular base applications include adequate bearing capacity, good drainage characteristics, and very good durability *(1)*.

2.2. Resilient Modulus

Resilient modulus is among the level two inputs for unbound layer strength in the current Mechanistic-Empirical Pavement Design Guide (MEPDG) (13). The resilient modulus (M_R) is the measure of the modulus of elasticity (E) under rapid loading (i.e. moving wheel load) where E is calculated under gradual loading applications. Resilient modulus is defined in Equation 2.1. The definition of M_R terms are explained in Figure 2.1.

$$M_R = \frac{\sigma_d}{\varepsilon_r} \quad (2.1)$$

M_R = Resilient modulus.
σ_d = Peak axial cyclic stress.
ε_r = Peak axial resilient strain.

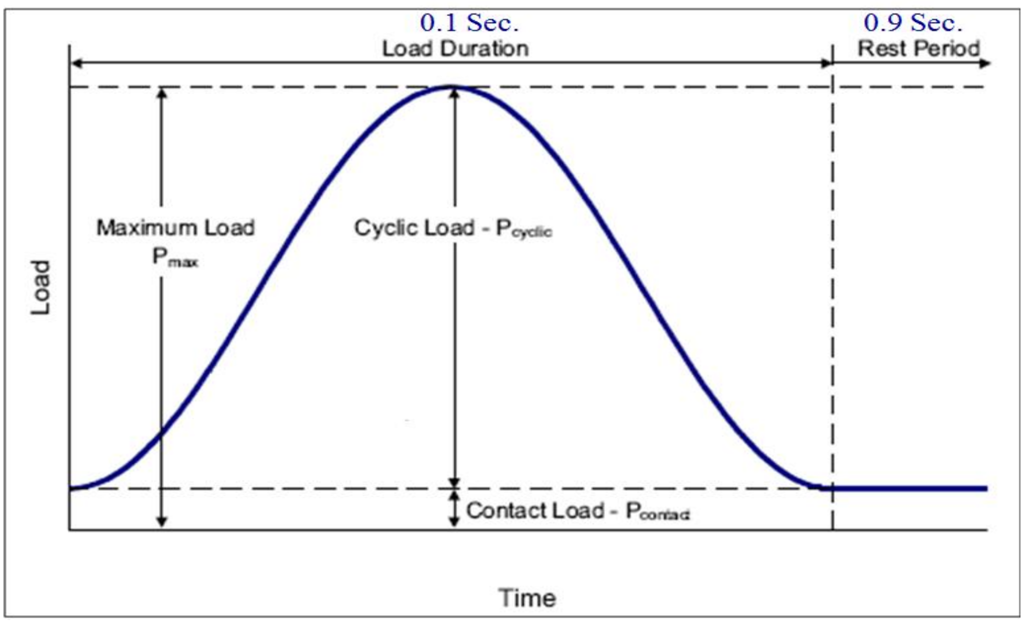


Figure 2.1 Definition of resilient modulus terms (14)

The loading type and duration used in the M_R testing simulates the actually occurring conditions in the field. When a wheel load is at a considerable distance from a given point in the pavement, the stress at that point is zero. When the load is directly above the given point, the stress at that point is the maximum (3). Resilient modulus values of material is obtained by applying a repeated axial cyclic stress of fixed magnitude, load duration, and cycle duration to a cylindrical test specimen. During testing, the specimen is subjected to a dynamic cyclic stress which simulates the stress from the vehicle and a static confining stress which simulates the stress from the surrounding material of a pavement section.

A number of factors affect the M_R of a material, some of which are moisture content, density, stress history, aggregate type, gradation, temperature, percent fines, and degree of saturation. There are a number of methods to perform the resilient modulus testing. The most common protocols for resilient modulus testing are: AASHTO T 292-91, AASHTO T 294-92, AASHTO T P46-94, LTPP Protocol P46 and NCHRP 1-28 (Appendix E).

The value of the M_R of these procedures is a measure of the elastic modulus of the unbound base, subbase materials and subgrade soils, recognizing its nonlinear variation with deviator stress and confining pressure. M_R values can be used with structural response analysis models to calculate the pavement structural response to wheel loads and with pavement design procedures to design pavement structures.

2.3. Past Studies on MR of RAP

This section summarizes previous studies related to the M_R of RAP. Bejarano (15) investigated the M_R of RAP. Resilient modulus testing was performed by following the protocol LTTP P-46. Three samples were used for this study. One was RAP, and the other two samples were two California aggregate Class 2 base materials. He found that RAP had the highest M_R value.

In a project done for Massachusetts Highway Department (MHD), MacGregor et al. *(16)* conducted M_R tests with different ratios of RAP and aggregate (crushed stone and gravel) mixtures. M_R test results showed an increase of M_R with the addition of RAP to the blend of RAP and aggregate. Kim and Labuz (5) did a study which showed that the M_R of 50% RAP mixed with 50% aggregate were similar to the M_R of 100% aggregate. Bennert and Maher (17) found that by adding RAP to a dense-graded aggregate base course, the M_R increased.

2.4. Investigation of Other Engineering Properties of RAP

To use RAP as a base layer, other engineering properties need to be investigated. In the next few sections, the literature on other properties is presented.

2.4.1. Particle Size Distribution

Gradation is a very important material property for a pavement base layer because it influences the base stability. Numerous factors are responsible for the variation of the particle size distribution of milled or crushed RAP. Those factors include: the type of equipment used to produce the RAP, the type of aggregate in the pavement, and whether any underlying base or subbase aggregate has been mixed in with the reclaimed asphalt pavement material during the pavement removal. In an aggregate plus RAP blend, the gradation also depends on the characteristics of the virgin aggregate. In a laboratory testing program for a research study in Montana *(18),* it was found that the addition of RAP to the virgin materials resulted in an increase in the amount of particles passing the upper sieves, and a decrease in the percentage of particles passing the lower sieves.

2.4.2. Specific Gravity

Based on laboratory testing conducted on the four materials examined in a research study done for the Montana Department of Transportation (18), it was found that the reclaimed asphalt had an average specific gravity of 2.49. This value is significantly lower than the specific gravities of any of the virgin aggregate, which ranged from 2.67 to 2.72. The researchers concluded that the effect of adding RAP to a granular aggregate would result in a reduction in the overall specific gravity of the blend.

2.4.3. Optimum Moisture Content and Maximum Dry Density

Guthrei et al. (*19*) showed that by increasing RAP content, optimum moisture content (OMC) and maximum dry density (MDD) decreased. They concluded that the reductions occurred because the RAP consisted of aggregate particles that were encased in asphalt, which led to reduced specific gravity values. The presence of the asphalt cement also led to reductions in the amount of water required to achieve MDD by reducing the amount of absorbed water and inter-particle friction *(19)*. Kim and Labuz 2007 (5) have shown that increasing the RAP content decreased the OMC and MDD using both standard Proctor test and the gyratory compactor. MacGregor et al. 1999 (16) evaluated the relation between the RAP content and OMC and MDD using one RAP source and two sources of virgin aggregate, but they did not find a clear relation between the RAP content and any of the OMC or MDD.

2.4.4. Moisture Susceptibility

Moisture susceptibility of a material can be defined as the potential to hold water by capillary rising. This property of a material causes the detrimental or unstable conditions of a pavement layer under traffic loading.

The moisture susceptibility testing on RAP was conducted by Guthrie et al. (19) using the tube suction test (TST). Guthrei et al. (*19*) have presented research using 25%, 50% and 75% RAP blended with other base materials. In TST, the dielectric value (DV) is a measure of the unbound water within the soil sample (*19*). Aggregates whose final dielectric values in the TST are less than 10 are expected to provide superior performance, while those with dielectric values above 16 are expected to provide poor performance as base materials. Aggregates having final dielectric values between 10 and 16 are expected to be marginally moisture susceptible (*19*). The authors of the study conclude that for materials having similar properties to those evaluated in their study, the use of high RAP contents can improve the moisture susceptibility of the base layer (20).

2.5. Methods of Evaluating Freeze Thaw Effect on Construction Materials

One objective of this project is to evaluate the effect of freeze-thaw on the resilient modulus/strength of RAP as a base layer. Table 2.1 summarizes the methods that are used to investigate the effect of freeze-thaw on hot mix asphalt, Portland cement concrete, soil cement mixture, and coarse aggregate and fine-grained clay.

Table 2.1 Summary of Freeze Thaw Testing for Basic Pavement Construction Material

Material tested	Freeze conditions	Thaw conditions	Number of F-T cycles	Reference
Compacted HMA	-18 ± 2° C (-0.04 ± 3.6° F) for at least 15 hours, sample warped in plastic bag	60 ± 1° C (140 ± 1.8° F) for 24 hours, sample immersed in water	1	ASTM D 4867 (21)
Portland Cement concrete	From 40° F to 0° F and back to 40° F within 2 to 5 hours, at least 20 to 25% of time shall be used for thawing		Less than 36 cycles	ASTM C 666 (22)
Soil-cement mixture	Less than -10° F (-32° C) for 24 hours	70° F (21° C) for 24 hours		ASTM D 560 (23)
Soil-cement mixture	20° F for 16 hours	77° F for 8 hours	10	George and Donald 1963 (24)
Portland Cement concrete	-17.8 ± 2.8° C at rate of 2.8 ± 0.6° C (by calculation it should take about 14 hours	Warm back to initial temperature while sample immersed in water	Record height each 10 cycles	California test No. 528-2001 (25)
Coarse Aggregate	-15° F (-26° C) for time enough for sample to freeze, 90 minutes is ok	30 minutes at 70 to 81° F (21 to 27° C)	16	AASHTO T 103-91 Nebraska modified (26)
Fine grained clay	20° F (-7° C) for 18 hours	57° F (14° C) for 6 hours	Up to 21 cycles	Da-Yan et al. 2007 (27)
Soil-cement mixture	8 hours at cooling rate < 10° F/hour	8 hours		Packard and Chapman 1963 (28)

Chapter 3
Data Collection

3.1. Introduction

This chapter presents the data collected from the Minnesota Department of Transportation (Mn/DOT) on the resilient modulus (M_R) testing on RAP/aggregate blends. The data served as the start for the analysis and experimental design presented in the following chapter.

3.2. Data Collection from Mn/DOT

Millings from a 2001 rehabilitation project on Mn/ROAD cell 26 constructed in 1994 provided the RAP source. The data collected from Mn/DOT included the following:

- M_R testing on various percentages of RAP blended with different materials. The aggregates blended with RAP are Taconite and Minnesota's CL6 material,
- M_R testing on samples with different combination of dry density and moisture content,
- Properties of the RAP which includes asphalt content, maximum dry density and optimum moisture content,
- Resilient modulus testing on different aggregate without RAP for comparison,
- Asphalt properties and the content of RAP samples.

3.2.1. The Resilient Modulus Data Collection

The M_R testing was conducted in Mn/DOT Office of Materials laboratory, by following a modified version of the LTPP P-46 (35). Mn/DOT measures the axial displacements using three internal linear variable differential transducers (LVDTs). Resilient modulus samples were compacted using a vibratory hammer in a split mold following LTPP P-46 protocol requirements. The height of the samples was 12 inches and the diameter was 6 inches. Optimum moisture content and maximum dry density was determined using the standard Proctor test (AASHTO T 99, Mn/DOT modified).The resilient modulus testing was performed at different combinations of moisture content and dry density. The moisture contents were 7% and 8%, and the dry densities of the samples were 125 pcf, 130 pcf, and 135 pcf. The testing was conducted on the following materials:

- 100% RAP
- RAP + CL6 material (granular material)
  RAP content = 0%, 30%, 50%, 70%
- RAP + Taconite
  RAP content = 50 %

Table 3.1 presents a list of M_R testing samples collected from Mn/DOT.

Table 3.1 List of M_R Testing Conducted by Mn/DOT

Sample	Dry density, pcf	Moisture content	Mn/DOT file name
30% RAP + 70% Class 6	130.35	6.59%	26GKR1
50% RAP + 50% Class 6 sample 1	130.24	6.66%	26GGR2
50% RAP + 50% Class 6 sample 2	125.31	6.71%	26GJR4
70% RAP + 30% Class 6	125.26	6.76%	26GJR5
100% RAP, sample1	124.68	6.83%	C26031A
100% RAP , sample2	124.56	6.86%	C26032A
100% RAP, sample3	124.14	7.28%	26036A
50% RAP+ 50% Taconite- sample 1	125.2	6.78%	26GNR1
50% RAP+ 50% Taconite- sample 2	124.54	6.63%	26GNR2
50% RAP+ 50% Taconite- sample 3	135.34	6.58%	26GPR1
50% RAP+ 50% Taconite- sample 4	123.82	8.26%	26HNR1
50% RAP+ 50% Taconite - sample 5	124.11	7.77%	26HNR2
50% RAP+ 50% Taconite- sample 6	129.53	7.65%	26HOR1

Chapter 4

Experimental Considerations

4.1. Introduction

This chapter presents details of the testing program that was established to investigate the physical and mechanical properties of collected field RAP/aggregate samples.

Resilient modulus testing and the triaxial shear test were conducted on the collected samples. Moisture related damage to RAP/aggregate combinations due to freeze-thaw (F-T) cycles was evaluated. Several other tests including Micro-Deval, standard Proctor, specific gravity and asphalt extraction were conducted.

4.2. General Description of Materials and Testing Procedures

This study was conducted on RAP and base materials that were collected by Mn/DOT from several rehabilitation projects in the state of Minnesota. A list of all tested materials is presented in Table 4.1. The dynamic cone penetration test was conducted on the field samples and results are presented in Appendix G. The test program was categorized into 2 phases. Phase 1, the original plan of the project, investigated the effect of the F-T cycles on materials compacted at optimum moisture content (OMC). Phase 2 contains more experiments on samples compacted at moisture content higher than OMC. Phase 2 was added to the project by the research team as we thought that its results could support the recommendations regarding the effect of F-T on RAP/aggregate blends. Figures 4.1 and 4.2 present the detailed testing matrix for the two phases.

Table 4.1 List of Tested RAP Samples

Material code	Description	Notes
C	Class 5	Base aggregate
R	RAP - TH 10 – Lake Park	100% RAP material
T	50 % Class 5 + 50 % RAP TH10	Laboratory blended material
S	25% Class 5 + 75 % RAP TH 10	Laboratory blended material
U	TH 19 - LT Sh 1d – MM 101.0 – CL 7B	Field blend
V	TH 19 - RT Sh 1d – MM 104.0 – CL 7B	Field blend
W	TH 22 – NBL - RT Sh 1d – CL 7 BG	Field blend
Notes: TH: Trunk highway MM: Refer to mile at which sample was collected		

The M_R samples were coded in the following manner: Litter 1-Litter 2-Number. The sample code meaning is presented in Table 4.2.

Table 4.2 M_R Samples Coding

	Litter 1	Litter 2	Number
	Represent tested material	Status of the sample with respect to freeze-thaw conditioning	Express material moisture content and replicate
Possible values	C, R, S, T, S, U, V or W (material symbols are defined in Table 1)	N = No freeze- thaw F= sample was subject to 2 freeze thaw cycles before testing	1= OMC 2=OMC (replicate) 3 = OMC + 1% 4= OMC + 2%
Examples	C-F-1: Class 5, subject to 2 freeze thaw cycles, compacted at OMC T-N-3: 50% Class 5 + 50% RAP TH-10, no freeze-thaw conditioning, compacted at (MC = OMC + 1%)		
MC: Moisture content at compaction time OMC: Optimum moisture content			

Detailed testing results will be presented in the following Sequence:

- Material index properties
  - Gradation
  - Asphalt extraction
  - Moisture – density relations
- Evaluation of material durability
  - Micro-Deval.
- Structure properties of RAP
  - Resilient modulus testing
  - Freeze thaw conditioning
  - Shear test

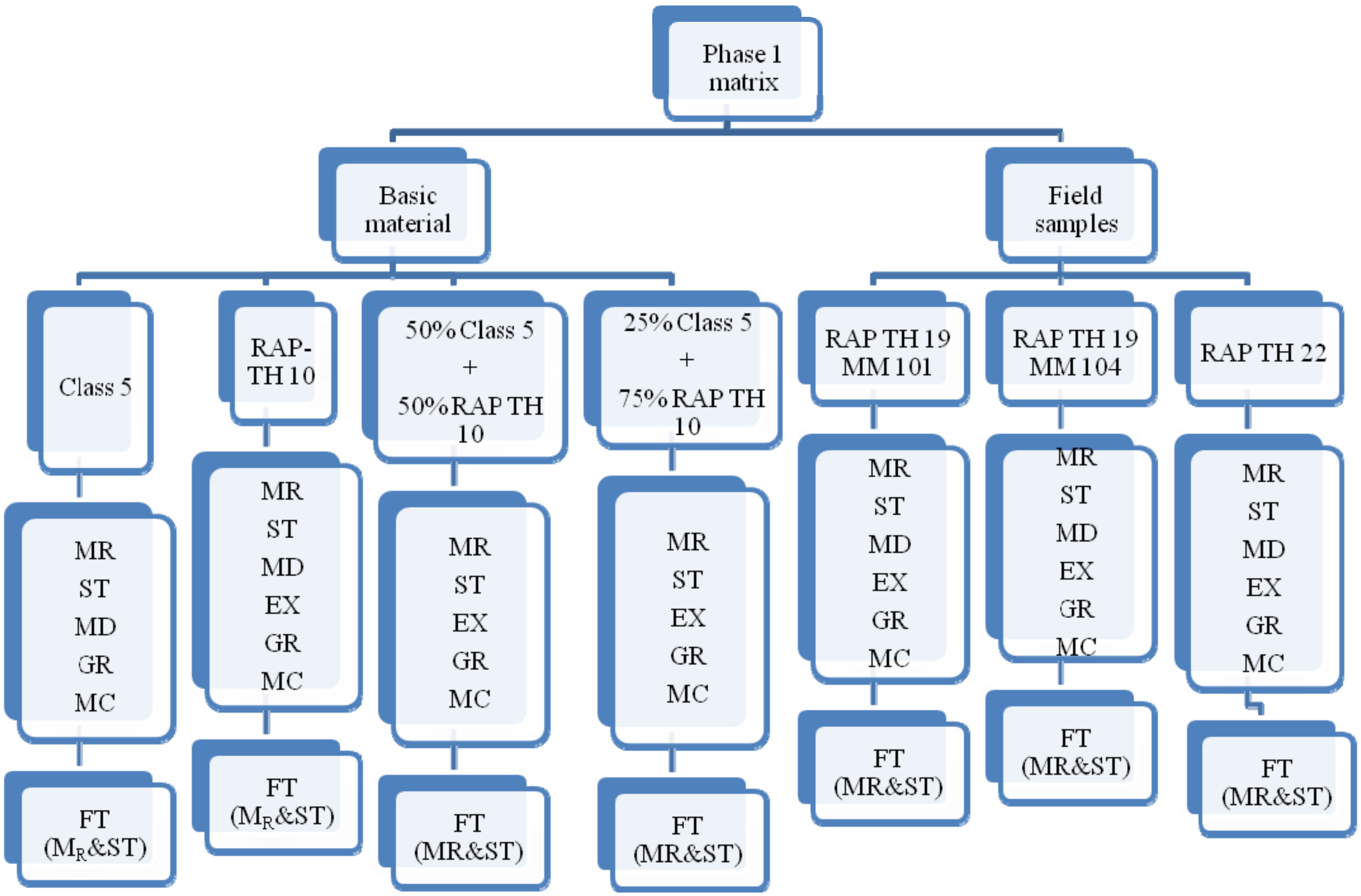


Figure 4.1 Phase 1 testing matrix (M_R at optimum moisture content)

MR: Resilient modulus testing (for 1 sample and a replicate) (at optimum moisture content)
ST: Shear test at 4 and 8 psi confining pressure
MD: Micro-Deval
MC: Moisture content and maximum dry density by gyratory compactor
EX: Asphalt extraction
GR: Aggregate gradation
FT (MR&ST): Resilient modulus and shear test for freeze-thaw conditioned sample (testing for 1 sample and a replicate at optimum moisture content)

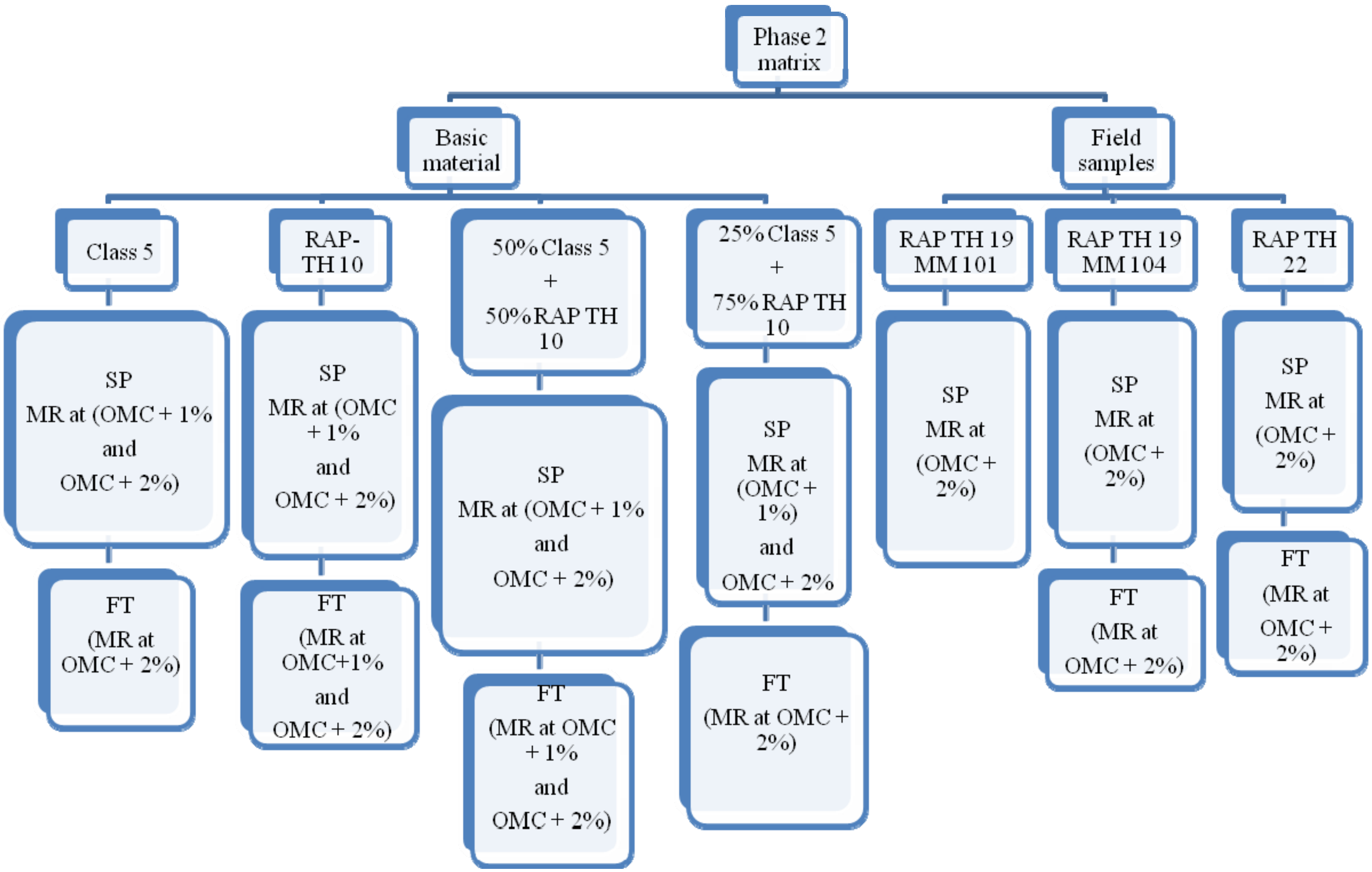


Figure 4.2 Phase 2 testing matrix (M_R at moisture content higher than the optimum)

SP: Standard Proctor
OMC: Optimum moisture content as determined by gyratory compactor
MR: Resilient modulus testing
FT (M_R): Resilient modulus test for freeze- thaw conditioned sample

4.3. Material Index Properties

This section presents the methods used to determine aggregate gradation, moisture density relationship and asphalt content for the investigated materials.

4.3.1. Aggregate Gradation

Gradation is a very important material property for the pavement base layer because it influences the base stability. Dry sieve analysis was done based on ASTM C136. Representative material of each sample was collected and oven dried at a temperature less than 140° F for 2 days. Then, the material of each sample was put into the soil sieve shaker; Figure 4.3; and the mass retained on each sieve was measured after 10 minutes of shaking.

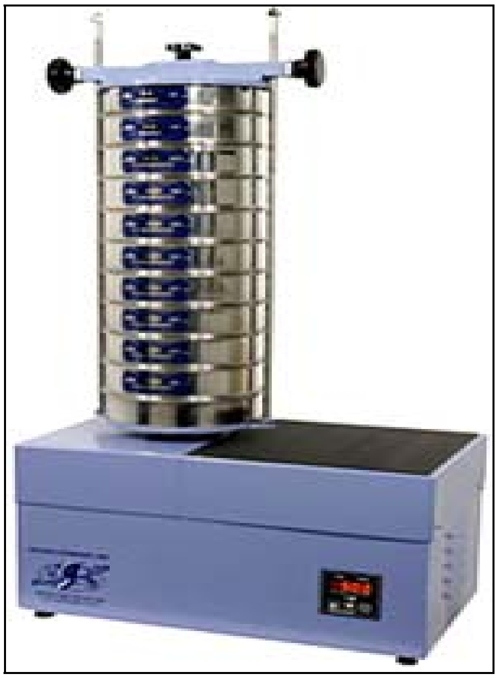


Figure 4.3 Sieve shaker

4.3.2. Asphalt Extraction

Asphalt content is one of the criteria that are normally considered by the highway agencies when trying to utilize RAP material. In this research, asphalt extraction was done by reflux extraction following ASTM D2172 (Method B). Figure 4 presents the asphalt extraction apparatus. A representative amount of the material was oven dried. The material was then placed in the 2 cones, 500 grams in each cone. Trichloroethylene (TCE) was used as an extraction solvent.

Figure 4.4 Asphalt extraction apparatus

4.3.3. Maximum Dry Density and Optimum Moisture Content

The relation between the dry density and moisture content was conducted by gyratory compactor (Figure 4.5) and standard Proctor tests. All material greater than 12.5 mm was replaced by material passing 12.5 mm and retained on sieve # 4 (5, 29). The optimum moisture content and maximum dry density are based on samples compacted by the gyratory compactor at a pressure equal to 600 Kpa, the number of gyrations equal to 50, the machine was set to conduct 30 revolutions per minute and the angle of gyration was set to 1.25 degrees. This setup was recommended in the literature as it is the best to simulate field conditions (5).

The standard Proctor test was conducted on all materials following the Mn/DOT procedure # 1305 in Mn/DOT procedure manual "The Moisture-Density Relations of Soils Using A 2.5kg (5.5 LB) Rammer and A 305mm (12 inch) Drop, AASHTO Designation T 99, Method "C" (Mn/DOT Modified)". All particles greater than 12.5 mm were replaced by particles passing 12.5 mm and retained on sieve # 4 to facilitate the comparison between the maximum dry density and optimum moisture content by the gyratory compactor and standard Proctor test.

Figure 4.5 Superpave gyratory compactor used

4.4. Evaluation of Material Durability

Durability is a very important property for the aggregate to be used in pavement applications. Aggregate and RAP durability was evaluated in this research using the Micro-Deval test.

4.4.1. Resistance to Abrasion and Degradation by Micro-Deval

The Micro-Deval test provides a measure of durability and abrasion resistance of mineral aggregates. The test depends on the actions of abrasion between aggregate particles and steel balls in the presence of water (30). The Micro-Deval test for fine aggregate was conducted based on Mn/DOT procedure # 1217 in Mn/DOT procedure manual “Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus”. The sample was sieved into separate sizes. The samples were oven dried then made up to F.M. of 2.8 using the weights presented in Table 4.3. The sample was then saturated in tap water for 24 ± 4 hours. The sample was placed in the Micro-Deval abrasion container with 1250 ± 5 gms of the stainless steel balls and 750 ± 25ml of tap water. The Micro-Deval machine (Figure 4.6) then runs at 100 ± 5 rpm for 15 minutes. The material was washed over # 200 sieves, oven dried and the new weight of the material was recorded.

The Micro-Deval test for coarse aggregate was done based on Mn/DOT procedure #1216 as listed in Mn/DOT procedure manual “Resistance of Abrasion of coarse aggregate to Degradation by Abrasion in the Micro-Deval Apparatus, Ontario Standard Test Method LS-618 (Mn/DOT Modified)”. 1500 gms of coarse aggregate were soaked in water for 2 hours. The sample was placed with water in the Micro-Deval abrasion container with 5000 ± 5 gms of the stainless steel balls and the container was placed on the Micro-Deval machine. After the test material retained on sieve # 4 was oven dried and the new weight is recorded.

Table 4.3 Fine Aggregate Weights for Micro-Deval Test

Passing Sieve #	Retained on Sieve #	Weight Retained, gm
#4	# 8	50
# 8	# 16	125
# 16	# 30	125
# 30	# 50	100
# 50	#100	75
#100	# 200	25
Total		**500**

Figure 4.6 Micro-Deval apparatus

4.5. Structural Properties of RAP

The structural capacity of the base layer is evaluated by its resilient modulus and shear strength. The effect of freeze thaw on structural capacity of RAP is evaluated. This section gives detailed procedures followed in the resilient modulus and shear strength testing.

4.5.1. Resilient Modulus Testing

The resilient modulus test was conducted based on NCHRP 1-28A (14) testing protocol and Mn/DOT requirements. The resilient modulus is the ratio of axial cyclic stress to the recoverable strain. In order to determine the resilient modulus of unbound materials, a cyclic stress of fixed magnitude for 0.1 second is applied to the specimen followed by a 0.9 second rest period. The specimen is subjected to a confining stress provided by means of a triaxial pressure chamber. The test loads that were applied are presented in Table 4.4. The system used to measure the resilient modulus is presented in Figures 4.7 and 4.8. A detailed description of the testing equipment and calibration process is provided in Appendix B.

Figure 4.7 Resilient modulus sample during testing on the MTS

Table 4.4 Test Sequence for Base/Subbbase Materials NCHRP1-28A-procedure 1A (14)

Sequence	Confining pressure	Contact stress	Cyclic stress	Maximum stress	Number of load repetitions
	psi	psi	psi	psi	
0	15	3	30	33	1000
1	3	0.6	1.5	2.1	100
2	6	1.2	3	4.2	100
3	10	2	5	7	100
4	15	3	7.5	10.5	100
5	20	4	10	14	100
6	3	0.6	3	3.6	100
7	6	1.2	6	7.2	100
8	10	2	10	12	100
9	15	3	15	18	100
10	20	4	20	24	100
11	3	0.6	6	6.6	100
12	6	1.2	12	13.2	100
13	10	2	20	22	100
14	15	3	30	33	100
15	20	4	40	44	100
16	3	0.6	9	9.6	100
17	6	1.2	18	19.2	100
18	10	2	30	32	100
19	15	3	45	48	100
20	20	4	60	64	100
21	3	0.6	15	15.6	100
22	6	1.2	30	31.2	100
23	10	2	50	52	100
24	15	3	75	78	100
25	20	4	100	104	100
26	3	0.6	21	21.6	100
27	6	1.2	42	43.2	100
28	10	2	70	72	100
29	15	3	105	108	100
30	20	4	140	144	100

Figure 4.8 Resilient modulus sample with the internal load cell and LVDTs connected around the sample

4.5.1.1. Resilient Modulus Sample Preparation

The following procedure was followed during sample preparation and testing:

- Dry the sample in the oven for 24 hours at 150° F.
- Mix the sample material until it is homogeneous.
- Mix the required amount of water and soil to achieve the predefined moisture content until the sample become homogeneous.
- Take 2 samples for moisture content from different locations from the sample.
- Seal the reminder of the sample in an airtight container.
- Check that the moisture content is within 0.5% of the objective moisture content.
- Calculate the target weight of the material to be molded in the gyratory compactor to achieve the required dry density.
- Compact the sample using the gyratory compactor.
- Prepare 2 molds with the same material, (No visual lateral movement was found between the top and bottom samples in any of the tested samples at the end of the testing, deformation shape reflected that the 2 molds behaved as one sample).
- Calculate the actual wet and dry density.
- Place the upper plate on top of the sample, seal with o-rings.
- Assemble the LVDTs around the sample, connect the internal load cell.

- Check to make sure that the LVDTs have a sufficient stroke range.
- Cover and close the triaxial cell.
- Connect the cell to the air line, adjust the confining pressure to 15 psi
- Resilient modulus testing is done on a MTS hydraulic testing machine, the software used to control the test is MultiPurpose TestWare from MTS systems.
- Load sequences are in accordance to NCHRP 1-28a testing protocol, procedure 1A.
- Collect 512 data point/sec for the last 5 seconds of each load sequence.

Tables 4.5 and 4.6 list all tested samples, objective moisture content and objective dry density. Tables 4.7 to 4.10 give information regarding moisture and density control for all resilient modulus samples. 100 % of the samples achieved the objective moisture content ±0.5% as required by the NCHRP 1-28a protocol. A few samples failed to achieve the objective dry density when compacted at moisture content higher than the optimum.

4.5.2. Quality Control of M_R testing Data

Mn/DOT quality control procedures (31) for the resilient modulus data were followed.

- The coefficient of variation (COV) between the M_R values collected during the last 5 seconds of the each sequence was calculated. The COV was controlled to be less than 10%. All cycles that failed to meet Mn/DOT requirements were canceled from the analysis.

$$COV = \frac{Sdev}{Average} \quad (4.1)$$

Where:
S_{dev} = Standard deviation of M_R values during the last five cycles in each loading sequence.
Average = Average M_R value of the last five cycles in each loading sequence.

- The signal to noise ratio (SNR) was calculated for both load and displacement. A SNR value of 3 is the minimum limit for each of the three LVDTs at each cycle as reported by Mn/DOT. A SNR value of 10 was used for each loading cycle. All cycles that failed to pass the limits were withdrawn. Figure 4.9 and Equation 4.2 present the SNR.

$$SNR = 3 * \frac{Peak}{Sdev\,(base\ line)} \quad (4.2)$$

Where:
Peak= Peak values of load or LVDT from time history data.
Sdev (baseline)= standard deviation of baseline values

- The uniformity of the deformation on the sample was evaluated using the angle of rotation (AR) following Mn/DOT procedures. The limit value for AR is determined by Mn/DOT to be 0.04 degrees. All cycles that failed to meet Mn/DOT requirements were canceled from the analysis.

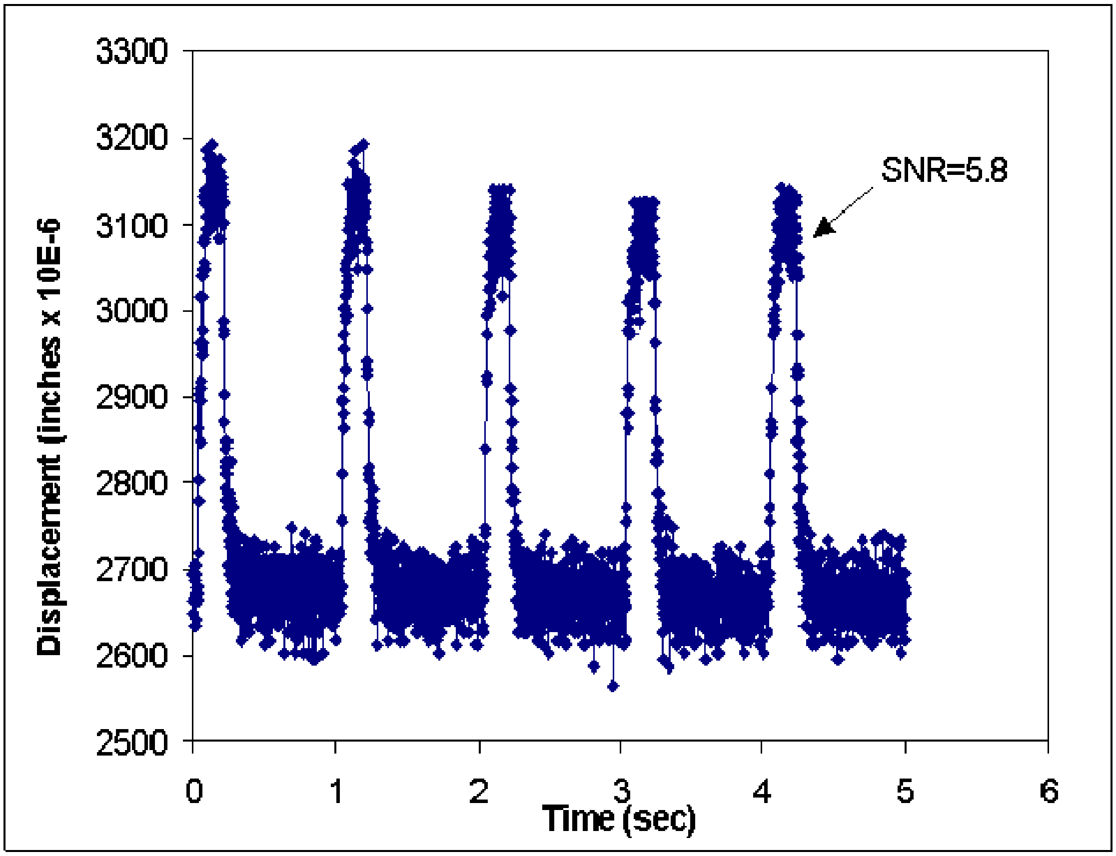


Figure 4.9 Example represent SNR concept (31)

4.5.3. Freeze Thaw Conditioning

One of the objectives of this researchh is to evaluate the effect of freeze-thaw on the stiffness /strength RAP material. To achieve this objective one set of the samples were tested for resilient modulus and shear strength immediately after compaction. The second set was subject to freeze-thaw conditioning before M_R testing.

The freeze thaw conditioning consisted of:

- Freezing time: 24 hours.
- Freezing temperature: temperature below -12° F.
- Thawing time: 24 hours.
- Thawing temperature and humidity level: Room temperature (75 ± 2° F).
- The sample was kept inside the latex membrane during the freeze-thaw process to keep its moisture content.
- The overall freeze-thaw conditioning consisted of 2 cycles (freeze, thaw, freeze and thaw then test for resilient modulus and shear strength).

4.5.4. Triaxial Shear Test

The triaxial shear test was conducted on the samples which were compacted at the optimum moisture content and maximum dry density. The shear test was conducted after the resilient modulus testing. The shear test was conducted in strain controlled mode, at a loading rate of 0.03 mm/sec and confining pressure of 4 and 8 psi. Figure 4.10 presents the basic concept for Mohr-Coulomb failure criteria which was used to calculate the friction angle and cohesion for the tested samples.

Table 4.5 List of Tested M_R Samples for Phase 1

Sample ID	Description	Target MC, %	Target dry density, Lb/ft^3
C-N-1	100% Class 5, OMC, no freeze	6.4	138.7
C-N- 2	100% Class 5, OMC, no freeze, replicate	6.4	138.7
CNOMC-3	100% Class 5, OMC, no freeze, 2nd replicate	6.4	138.7
C-F-1	100% Class 5, OMC, 2 freeze-thaw cycles	6.4	138.7
C-F-2	100% Class 5, OMC, 2 freeze-thaw cycles, replicate	6.4	138.7
T-N--1	50% Class 5- 50% RAP TH 10, OMC, no freeze	5.2	136.5
T-N-2	50% Class 5- 50% RAP TH 10, OMC, no freeze, replicate	5.2	136.5
T-F-1	50% Class 5- 50% RAP TH 10, OMC, 2 freeze-thaw cycles	5.2	136.5
T-F-2	50% Class 5- 50% RAP TH 10, OMC, 2 freeze-thaw cycles, replicate	5.2	136.5
S-N-1	25% Class 5- 75% RAP TH 10, OMC, no freeze	5.7	134.8
S-N-2	25% Class 5- 75% RAP TH 10, OMC, no freeze, replicate	5.7	134.8
S-F-1	25% Class 5- 75% RAP TH 10, OMC, 2 freeze-thaw cycles	5.7	134.8
S-F-2	25% Class 5- 75% RAP TH 10, OMC, 2 freeze-thaw cycles, replicate	5.7	134.8
R-N-1	100% RAP TH 10, OMC, no freeze	5.5	132.5
R-N-2	100% RAP TH 10, OMC, no freeze, replicate	5.5	132.5
R-F-1	100 % RAP TH 10, OMC, 2 freeze-thaw cycles	5.5	132.5
R-F-2	100% RAP TH 10, OMC, 2 freeze-thaw cycles, replicate	5.5	132.5
U-N-1	RAP TH 19-101, OMC, No freeze	5.9	122.5
U-N-2	RAP TH 19-101, OMC, No freeze, replicate	5.9	122.5
U-F-1	RAP TH 19-101, OMC, 2 freeze-thaw cycles	5.9	122.5
U-F-2	RAP TH 19-101, OMC, 2 freeze-thaw cycles, replicate	5.9	122.5
V-N-1	RAP TH 19-104, OMC, no freeze	7	129.3
V-N-2	RAP TH 19-104, OMC, no freeze, replicate	7	129.3
V-F-1	RAP TH 19-104, OMC, 2 freeze-thaw cycles	7	129.3
V-F-2	RAP TH 19-104, OMC, 2 freeze-thaw cycles, replicate	7	129.3
W-N-1	RAP TH 22, OMC, no freeze	5.25	133.74
W-N-2	RAP TH 22, OMC, no freeze, replicate	5.25	133.74
W-F-1	RAP TH 22, OMC, 2 freeze-thaw cycles	5.25	133.74
W-F-2	RAP TH 22, OMC, 2 freeze-thaw cycles, replicate	5.25	133.74

MC= Moisture content

Table 4.6 List of Tested Samples for Phase 2

Sample ID	Description	Target MC, %	Target dry density, Lb/ft^3
C-N-3	100% Class 5, OMC + 1%, no freeze	7.4	138.7
C-N-4	100% Class 5, OMC + 2%, no freeze	8.4	138.7
C-F- 4	100% Class 5, OMC + 2%, 2 freeze-thaw cycles	8.4	138.7
T-N- 3	50% Class 5 - 50% RAP TH 10, OMC +1%, no freeze	6.2	136.5
T-N- 4	50% Class 5 - 50% RAP TH 10, OMC + 2%, no freeze	7.2	136.5
T-F- 3	50% Class 5 - 50% RAP TH 10, OMC + 1%, 2 freeze-thaw cycles	6.2	136.5
T-F- 4	50% Class 5- 50% RAP TH 10, OMC+2%, 2 freeze-thaw cycles, replicate	7.2	136.5
S-N- 3	25% Class 5- 75% RAP TH 10, OMC+1%, no freeze	6.7	134.8
S-N-4	25% Class 5- 75% RAP TH 10, OMC+2%, no freeze	7.7	134.8
S-F-4	25% Class 5- 75% RAP TH 10, OMC+2%, 2 freeze-thaw cycles, replicate	7.7	134.8
R-N- 3	100% RAP TH 10, OMC + 1%, no freeze	6.5	132.5
R-N-4	100% RAP TH 10, OMC + 2%, no freeze, replicate	7.5	132.5
R-F- 3	100% RAP TH 10, OMC + 1%, 2 freeze-thaw cycles	6.5	132.5
R-F- 4	100% RAP TH 10, OMC + 2%, 2 freeze-thaw cycles, replicate	7.5	132.5
U-N- 4	RAP TH 19-101, OMC + 2%, no freeze, replicate	7.9	122.5
V-N- 4	RAP TH 19-104, OMC + 2%, no freeze	9	129.3
V-F- 4	RAP TH 19-104, OMC + 2%, 2 freeze-thaw cycles	9	129.3
W-N- 4	RAP TH 22, OMC + 2%, no freeze	7.25	133.74
W-F-2	RAP TH 22, OMC + 2%, 2 freeze-thaw cycles, replicate	7.25	133.74

MC= Moisture content

Table 4.7 Moisture Content Control for Phase 1

Sample ID	Description	Target MC, %	MC of sample before test, %	Δ MC, %
C-N-1	100% Class 5, OMC, no freeze	6.4	6.4	0
C-N-2	100% Class 5, OMC, no freeze, replicate	6.4	6.4	0
CNOMC-3	100% Class 5, OMC, no freeze, 2nd replicate	6.4	6.5	0.1
C-F-1	100% Class 5, OMC, 2 freeze-thaw cycles	6.4	6.4	0
C-F-2	100% Class 5, OMC, 2 freeze-thaw cycles, replicate	6.4	6.57	0.17
T-N-1	50% Class 5- 50% RAP TH 10, OMC, no freeze	5.2	5.15	-0.05
T-N-2	50% Class 5- 50% RAP TH 10, OMC, no freeze, replicate	5.2	4.87	-0.33
T-F-1	50% Class 5- 50% RAP TH 10, OMC, 2 freeze-thaw cycles	5.2	5.25	-0.05
T-F-2	50% Class 5- 50% RAP TH 10, OMC, 2 freeze-thaw cycles, replicate	5.2	5.22	0.02
S-N-1	25% Class 5- 75% RAP TH 10, OMC, no freeze	5.7	5.4	-0.3
S-N-2	25% Class 5- 75% RAP TH 10, OMC, no freeze, replicate	5.7	5.93	0.23
S-F-1	25% Class 5- 75% RAP TH 10, OMC, 2 freeze-thaw cycles	5.7	5.75	0
S-F-2	25% Class 5- 75% RAP TH 10, OMC, 2 freeze-thaw cycles, replicate	5.7	5.75	0
R-N-1	100% RAP TH 10, OMC, no freeze	5.5	5.4	0.1
R-N-2	100% RAP TH 10, OMC, no freeze, replicate	5.5	5.1	-0.4
R-F-1	100% RAP TH 10, OMC, 2 freeze-thaw cycles	5.5	5.42	-.08
R-F-2	100% RAP TH 10, OMC, 2 freeze-thaw cycles, replicate	5.5	5.5	0
U-N-1	RAP TH 19-101, OMC, no freeze	5.9	6.3	0.4
U-N-2	RAP TH 19-101, OMC, no freeze, replicate	5.9	6.08	0.18
U-F-1	RAP TH 19-101, OMC, 2 freeze-thaw cycles	5.9	5.8	-0.1
U-F-2	RAP TH 19-101, OMC, 2 freeze-thaw cycles, replicate	5.9	6.0	0.1
V-N-1	RAP TH 19-104, OMC, no freeze	7	7.1	0.1
V-N-2	RAP TH 19-104, OMC, no freeze, replicate	7	6.7	-0.30
V-F-1	RAP TH 19-104, OMC, 2 freeze-thaw cycles	7	6.6	-0.4
V-F-2	RAP TH 19-104, OMC, 2 freeze-thaw cycles, replicate	7	6.7	-0.30
W-N-1	RAP TH 22, OMC, no freeze	5.25	5.5	0.25
W-N-2	RAP TH 22, OMC, no freeze, replicate	5.25	5.45	0.20
W-F-1	RAP TH 22, OMC, 2 freeze-thaw cycles	5.25	5.5	0.25
W-F-2	RAP TH 22, OMC, 2 freeze-thaw cycles, replicate	5.25	5.45	0.20

MC= Moisture content

Table 4.8 Moisture Content Control for Phase 2

Sample ID	Description	Target MC, %	MC of sample before test, %	Δ MC, %
C-N-3	100% Class 5, OMC + 1%, no freeze	7.4	7.4	0
C-N-4	100% Class 5, OMC+ 2%, no freeze	8.4	8.65	0.25
C-F- 4	100% Class 5, OMC+2%, 2 freeze-thaw cycles	8.4	8.3	-0.1
T-N- 3	50% Class 5- 50% RAP TH 10, OMC + 1%, no freeze	6.2	5.95	-0.25
T-N- 4	50% Class 5- 50% RAP TH 10, OMC + 2%, no freeze	7.2	7	-0.20
T-F- 3	50% Class 5- 50% RAP TH 10, OMC + 1%, 2 freeze-thaw cycles	6.2	5.95	-0.25
T-F- 4	50% Class 5- 50% RAP TH 10, OMC + 2%, 2 freeze-thaw cycles, replicate	7.2	7.35	0.15
S-N- 3	25% Class 5- 75% RAP TH 10, OMC + 1%, no freeze	6.7	6.5	-0.20
S-N-4	25% Class 5- 75% RAP TH 10, OMC + 2%, no freeze	7.7	7.64	-0.06
S-F-4	25% Class 5- 75% RAP TH 10, OMC + 2%, 2 freeze-thaw cycles, replicate	7.7	7.84	0.14
R-N- 3	100% RAP TH 10, OMC + 1%, no freeze	6.5	6.3	-0.20
R-N-4	100% RAP TH 10, OMC + 2%, no freeze, replicate	7.5	7.5	0
R-F- 3	100% RAP TH 10, OMC + 1%, 2 freeze-thaw cycles	6.5	6.36	-0.14
R-F- 4	100% RAP TH 10, OMC + 2%, 2 freeze-thaw cycles, replicate	7.5	7.4	-0.10
U-N- 4	RAP TH 19-101, OMC + 2%, no freeze, replicate	7.9	8.4	0.50
U-N-OMC-97MDD	RAP TH 19-101, OMC, no freeze, replicate	5.9	6	0.1
V-N- 4	RAP TH 19-104, OMC + 2%, no freeze	9	9.5	0.50
V-F- 4	RAP TH 19-104, OMC + 2%, 2 freeze-thaw cycles	9	9.4	0.40
W-N- 4	RAP TH 22, OMC + 2%, no freeze	7.25	7.1	-0.15
W-F-4	RAP TH 22, OMC + 2%, 2 freeze-thaw cycles, replicate	7.25	7.50	0.25

MC= Moisture content

Table 4.9 Specimen Compaction Control for Phase 1

Sample ID	# of gyrations top	# of gyrations bottom	Total sample height, mm	ADD, lbf	ADD/MDD, %
C-N-1	57	46	293.14	139.27	100.34
C-N-2	49	47	293.4	139.25	100.33
C-F-1	55	59	293.4	139.6	100.6
C-F-2	69	77	293.05	138.9	100.1
T-N-1	73	66	301.7	136.88	100.27
T-N-2	61	48	303.3	136.2	99.8
T-F-1	45	40	301.4	136.7	100.16
T-F-2	48	50	301.46	136.8	100.2
S-N-1	40	35	305.1	135.1	100.2
S-N-2	51	55	302.7	135.3	100.4
S-F-1	54	57	303.4	135.3	100.3
S-F-2	42	35	303.4	135.2	100.3
R-N-1	140	136	305	132.34	99.88
R-N-2	115	101	304.4	132.5	100
R-F-1	50	45	302.2	132.56	100.05
R-F-2	59	58	305.2	132.55	100
U-N-1	120	97	305.2	123.5	100.8
U-N-2	104	130	293.6	123.09	100.5
U-F-1	150	150	311.4	121.8	99.4
U-F-2	150	150	314.3	121.44	99.4
V-N-1	134	96	305.1	129.9	100.47
V-N-2	83	83	306	129.96	100.5
V-F-1	120	50	307	129.56	100.2
V-F-2	50	50	306.5	129.62	100.25
W-N-1	119	81	306.75	134.16	100.31
W-N-2	102	98	306.96	134.25	100.38
W-F-1	66	66	305.2	133.83	100.06
W-F-2	73	67	305.4	133.93	100.14

ADD = Average dry density
MDD= Maximum dry density

Table 4.10 Specimen Compaction Control for Phase 2

Sample ID	# of gyrations top	# of gyrations bottom	Total Sample height, mm	ADD, lbf	ADD/MDD, %
C-N-3	150	150	299.74	137.6	99.11
C-N-4	150	150	301.8	134.8	97.12
C-F- 4	150	150	297	136.7	98.5
T-N- 3	150	50	305	136.9	100.29
T-N- 4	150	150	304.95	134.4	98.46
T-F- 3	57	40	302.2	136.6	100.1
T-F- 4	150	150	312	133.6	97.9
S-N- 3	150	150	306.2	131.6	97.63
S-N-4	150	150	307.7	130.45	96.77
S-F-4	150	150	306.4	130.65	96.92
R-N- 3	64	69	323.4	131.9	99.56
R-N-4	150	150	306.9	129.2	97.5
R-F- 3	82	130	302.2	132.4	99.92
R-F- 4	150	150	308	129.6	97.8
U-N- 4	150	150	307.4	123.8	101
U-N-OMC-97MDD	150	150	319.5	119.46	97.5
V-N- 4	150	150	312.6	124.48	96.27
V-F- 4	150*	150*	307.1	125	96.7
W-N- 4	150	150	306.9	131.2	98.1
W-F-4	150*	150*	303	130.9	97.9

*Gyratory pressure = 700 KPa

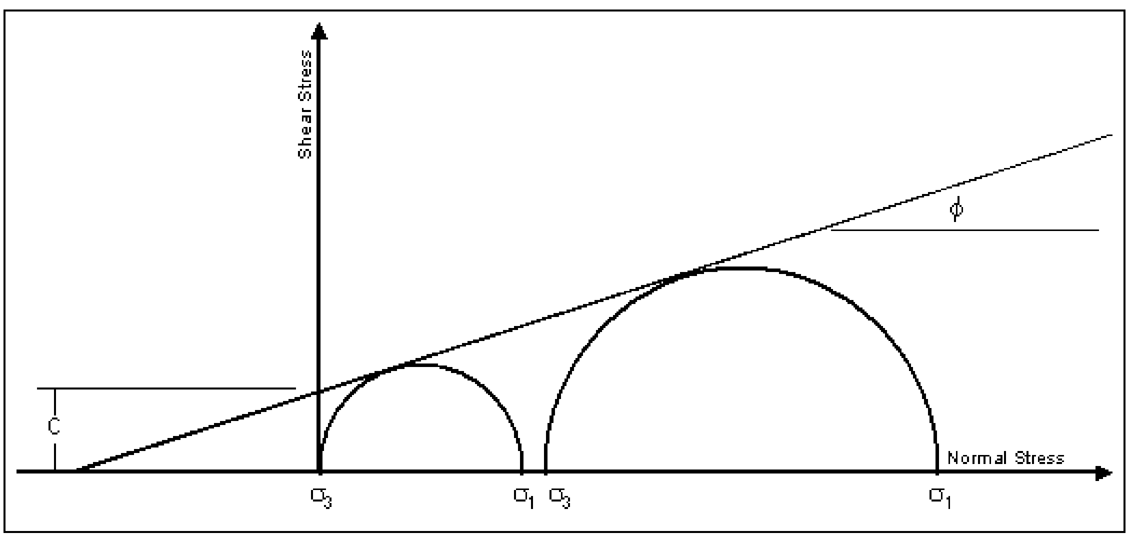


Figure 4.10 Graphical representation of the Mohr-Coulomb failure criteria (32)

Chapter 5

Data Analysis

5.1. Introduction

This chapter presents the analysis and discussion of the finding of the research. The difference in the physical and mechanical properties between RAP and typical base aggregate will be discussed based on testing conducted at North Dakota State University (NDSU) and data collected from the Minnesota Department of Transportation (Mn/DOT). The following relations are discussed:

- Effect of RAP on durability of base aggregate.
- Effect of RAP on maximum dry density and moisture content of base layer.
- The effect of freeze-thaw (F-T) on resilient modulus and shear strength of RAP as compared to a typical Minnesota base aggregate.
- Effect of different parameters, including moisture content, dry density, RAP content and state of stress, on the resilient modulus of base layer containing RAP.

The analysis included:

a. Material index properties
    a. RAP gradation vs. Class
    b. Effect of RAP content on maximum dry density and optimum moisture content
b. Evaluation of material durability
    a. Micro-Deval for RAP vs. Class 5.
c. Evaluation of structure properties of RAP
    a. Effect of freeze-thaw (F-T) conditioning on resilient modulus (M_R) of base layer containing RAP
    b. Effect of F-T conditioning and RAP content on shear strength of base layer containing RAP
    c. Effect of RAP content on M_R of base layer containing RAP
    d. Effect of moisture content on M_R of base layer containing RAP
    e. Effect of dry density on M_R of base layer containing RAP
    f. Effect of state of stress on M_R of base layer containing RAP

5.2. Material Index Properties

Material gradation and moisture density relation are investigated in this section. It is expected that adding RAP to virgin aggregate will alter the gradation, maximum dry density and optimum moisture content of the mixture.

5.2.1. Sieve Analysis

Sieve analysis was done based on ASTM C136. Results are presented in Figure 5.1. All tested materials were within the Mn/DOT aggregate specifications for Mn/DOT Class 5 material (33). Tested samples complied with Mn/DOT Class 7 material for particles finer than 2 mm, but did not meet specifications for coarser particles (tested materials were finer than Mn/DOT Class 7 specifications). The Mn/DOT specification states that "If Class 7 is substituted for Classes 1, 3, 4, 5, or 6, it shall meet the gradation requirements of the substituted class" (33). The RAP materials were considered to be useful as a substitute for Class 5 as a base layer based on the material gradation.

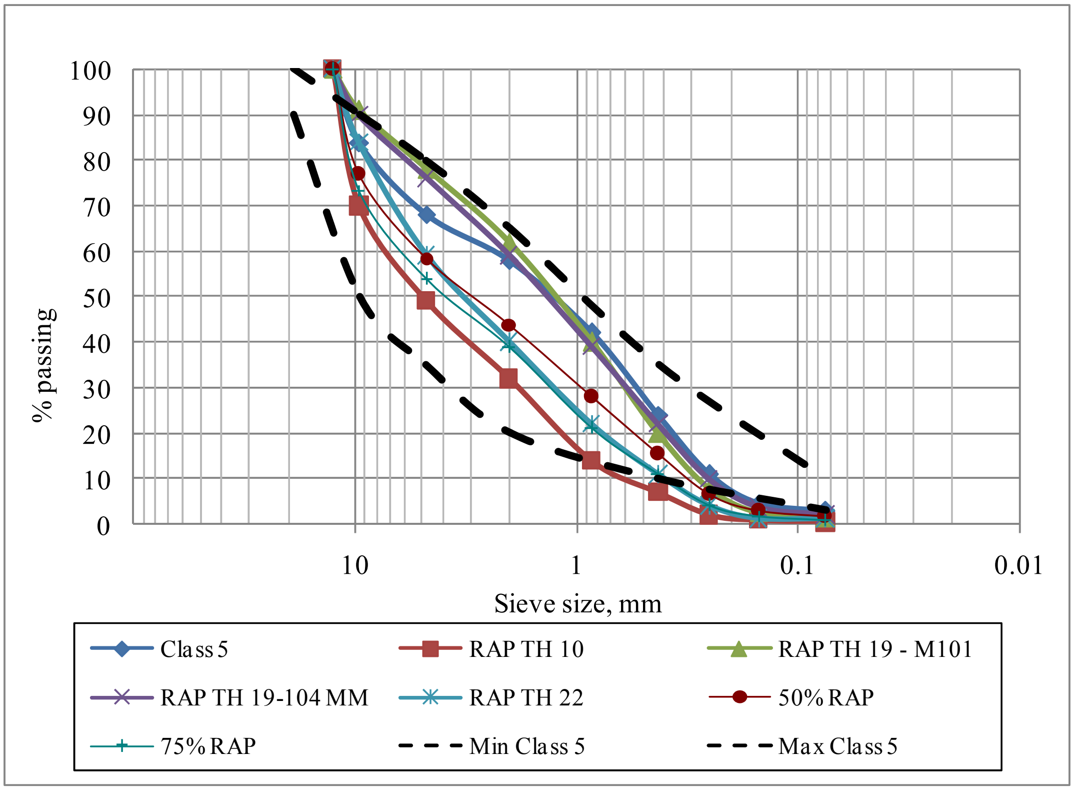


Figure 5.1 Gradation chart of all material after replacing material larger than 12.5 mm vs. Mn/DOT Class 5 specification

5.2.2. Effect of RAP Content on Maximum Dry Density and Optimum Moisture Content

The relation between the dry density and moisture content was established based on the gyratory compactor and the standard Proctor tests as presented in the experimental design. Detailed results are presented in Appendix A. Class 5 material had the highest dry density compared to all RAP sources. The gyratory compactor gave a lower dry density than the standard Proctor test for Class 5 material. For RAP/aggregate blends, the gyratory compactor gave a higher dry density than standard Proctor as presented in Figures 5.2 and 5.3.

Increasing RAP content decreased dry density as presented in Figure 5.4. Optimum moisture content (OMC) had different trends depending on the method of compaction. For the gyratory compactor, increasing RAP content decreased OMC. However, increasing RAP content decreased the OMC when the standard Proctor test was used, as presented in Figure 5.4. Literature reviews gave some mixed results. Data collected from a study done by Kim and Labuz (5) showed that RAP content did not have an effect on maximum dry density (MDD) when the gyratory compactor was used. However, using the standard Proctor procedures, increasing RAP content decreased MDD. In the same study by Kim and Labuz (5), analyzing the data showed that gyratory compactor samples had lower OMC than the standard Proctor test, and that increasing RAP content decreased the OMC, as presented in Figure 5.5. Data collected from earlier testing (19, 20) showed that increasing RAP content reduces both MDD and OMC, as presented in Figure 5.6.

Data collected from MnRoad cell 26 showed that the RAP had a lower maximum dry density (124 to 127 pcf) and higher optimum moisture content (8% to 9%) as compared to Class 6 material (136 pcf dry density and 7% OMC).

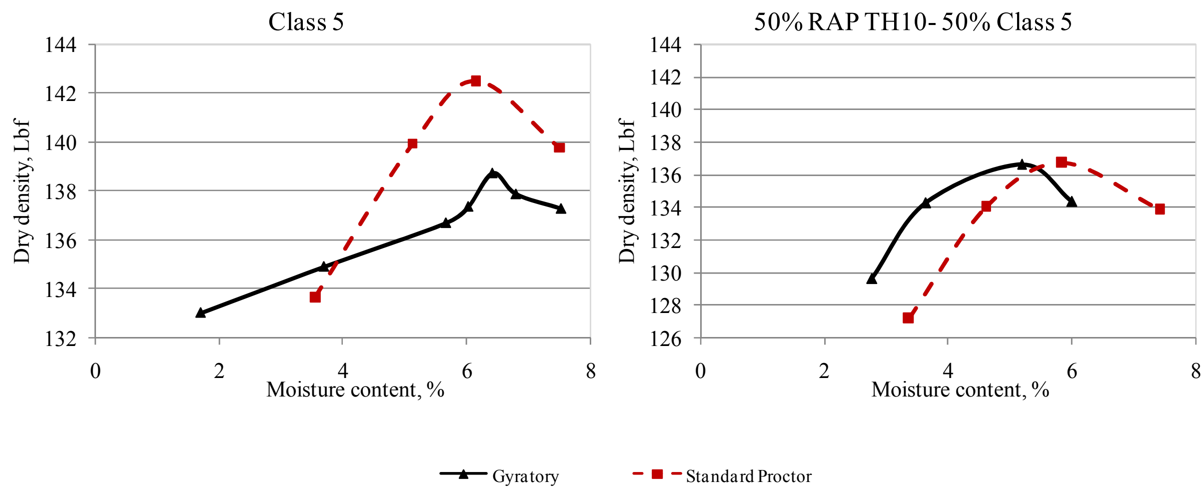


Figure 5.2 Moisture density relation for Class 5 and 50% RAP TH10 + 50% Class 5 using standard Proctor test and gyratory compactor at 50 gyrations

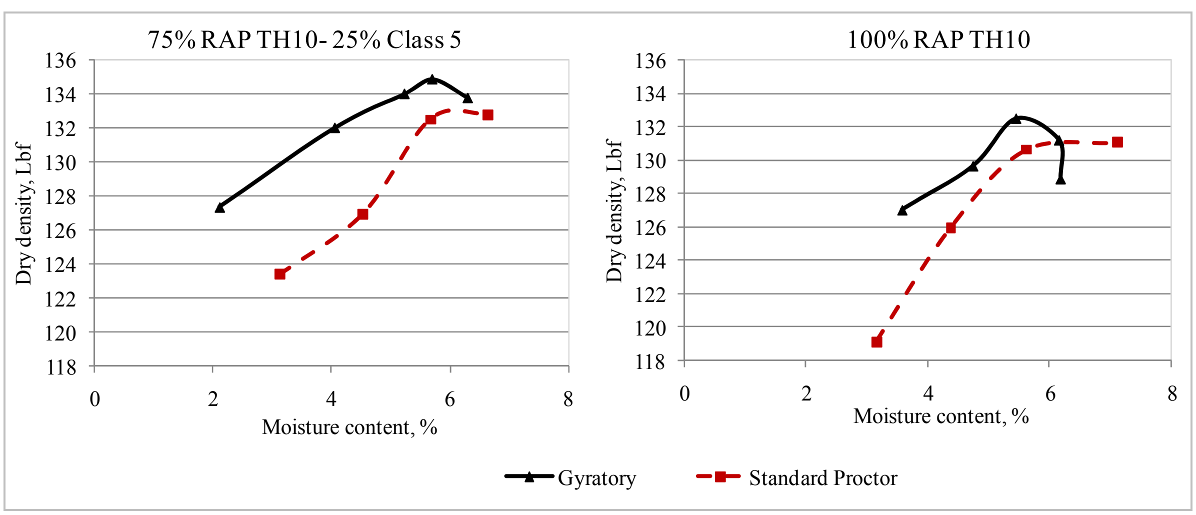


Figure 5.3 Moisture density relation for 75% RAP TH 10 +25% Class 5 and 100% RAP TH 10 using standard Proctor test and gyratory compactor at 50 gyrations

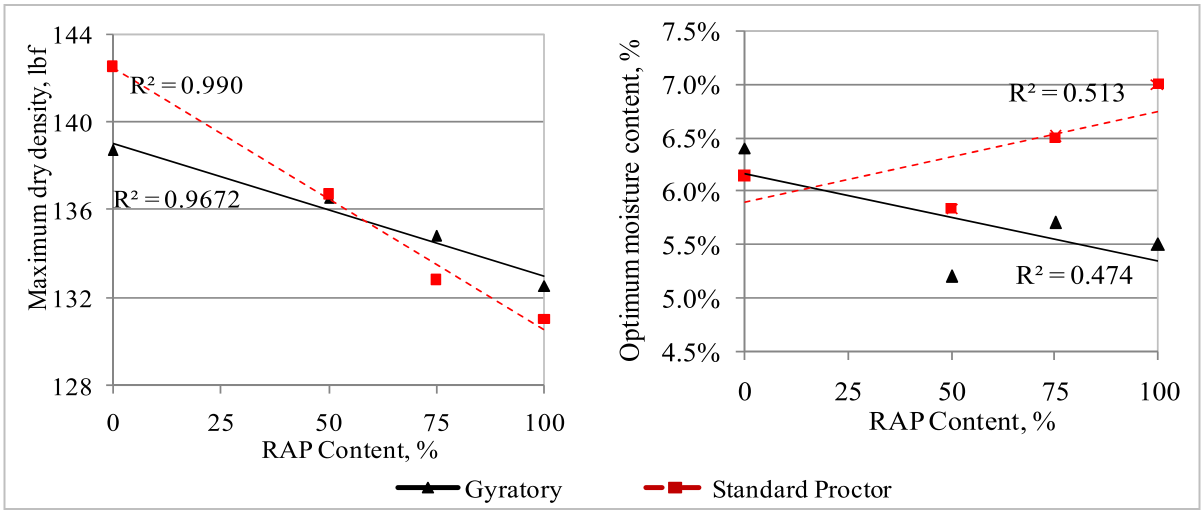


Figure 5.4 Relation between MDD, OMC and RAP content at 50 gyrations vs. standard Proctor

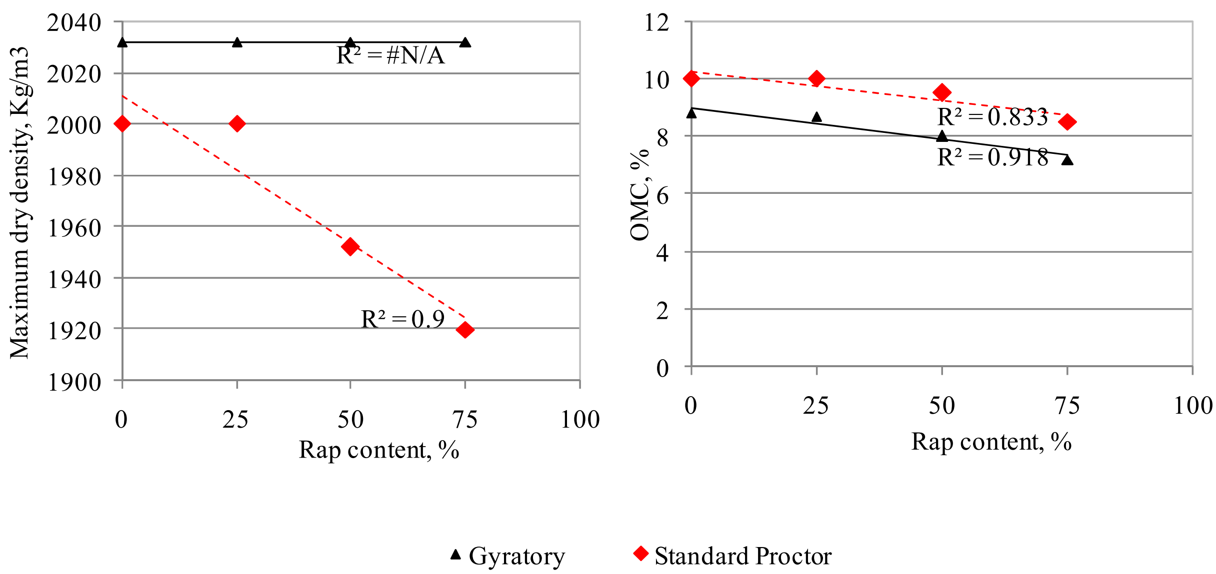


Figure 5.5 Relation between MDD, OMC and RAP content at 50 gyrations vs. standard Proctor, based on published data by Kim and Labuz (5)

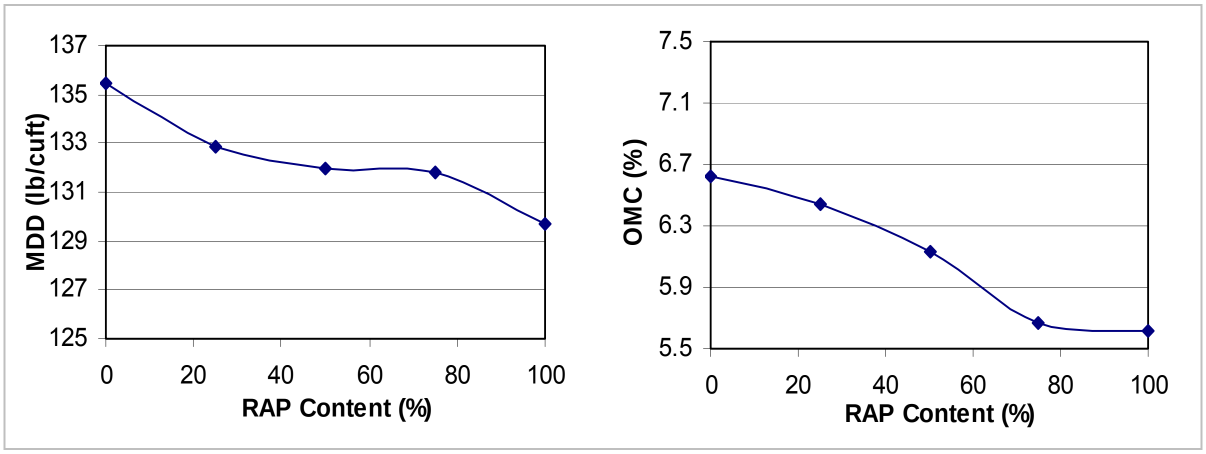


Figure 5.6 MDD and OMC for different RAP content using standard Proctor test (19, 20)

5.3. Evaluation of Material Durability

Material durability was evaluated using the Micro-Deval test. Results are presented in the following section.

5.3.1. Micro-Deval Test Results

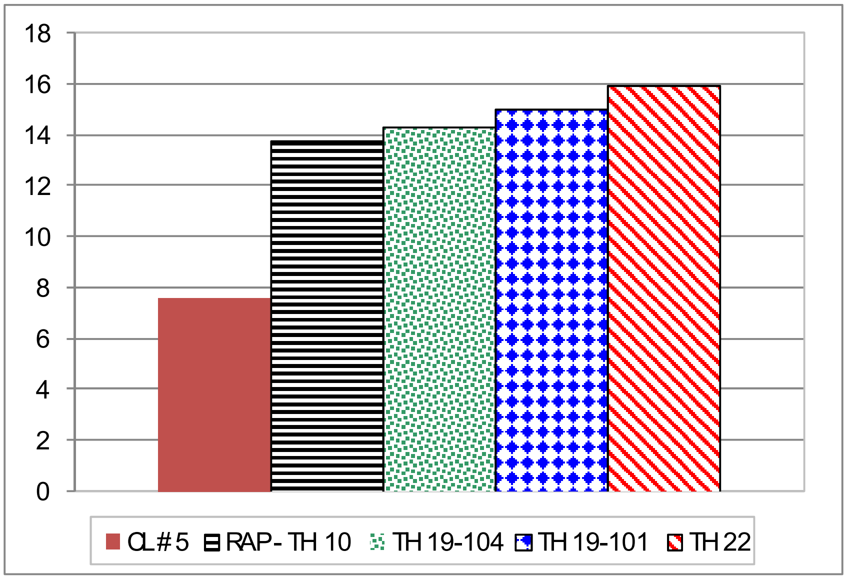
The Micro-Deval test results are presented in Tables 5.1 and 5.2. The test results show that the percentage loss for Class 5 material is much less than the loss in all received RAP material. The results also show that the loss of coarser particles was greater than the loss of fine particles for all tested samples. Results are presented in Figures 5.7 and 5.8.

Table 5.1 Micro-Deval Results for Fine Aggregate

Material	Percentage loss
Class 5	7.62
RAP TH 10	13.74
RAP TH 19-101	15.01
RAP TH 19-104	14.33
RAP TH 22	16.21

Table 5.2 Micro-Deval Results for Coarse Aggregate

Material	Percentage loss
Class 5	13.11
RAP TH 10	23.81
RAP TH 19-101	26.62
RAP TH 19-104	17.72
RAP TH 22	23.26



4.

Figure 5.7 Micro-Deval percentage loss for fine aggregate

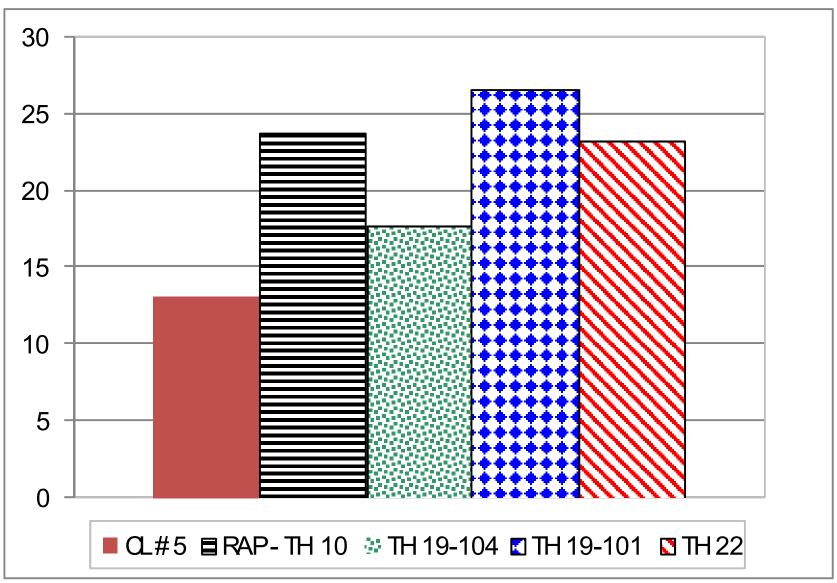


Figure 5.8 Micro-Deval percentage loss for coarse aggregate

5.4. Evaluation of Structure Properties of RAP as Base Layer

The structural capacity of the base layer is defined by its resilient modulus. The resilient modulus of the base layer is affected by several factors, including dry density, moisture content and environmental conditions. The effect of those factors on the base layer containing RAP is investigated in the following sections. Detailed resilient modulus testing results for all samples are presented in Appendix C.

5.4.1. Effect of Freeze-Thaw on M_R of Base Layer

Only the testing conducted at NDSU is considered in the analysis of this section. No data was collected from Mn/DOT regarding the effect of F-T on the base layer containing RAP. For Class 5 material, samples compacted at OMC did not show loss of strength due to freeze-thaw conditioning. For samples compacted at a moisture content higher than the OMC, there was an increase in M_R after freeze-thaw conditioning. The MC for both CN4 and CF4 samples were the same immediately before compaction, but the MC values after the M_R test were found to be different (6.5% and 5% respectively). This indicates loss of water during testing. After the thaw period the lower portion of the sample had a lot of water, and some water was lost from the base of the sample during the triaxial test. This indicates that the material does not have the ability to retain extra moisture which was drained during the 24 hour thawing period. The lower moisture content can be a reason for higher M_R for the sample after F-T cycles. Class 5 results are presented in Figures 5.9 and 5.10. The changes in moisture content before and after M_R test are presented in Tables 5.3 and 5.4.

For 50% RAP + 50% Class 5, samples compacted at OMC did not show loss of strength due to freeze-thaw conditioning, as presented in Figure 5.11. For samples compacted at a higher moisture content (OMC + 1%, OMC + 2%) there was an increase in M_R after freeze-thaw conditioning. This increase was apparent at higher confining pressures in the case of OMC + 1%, as presented in Figure 5.12, and at all confining pressures in the case of OMC + 2%. For 25% Class 5 + 75% RAP material, samples compacted at OMC did not show loss of strength due to freeze-thaw conditioning. For samples compacted at higher moisture content (OMC + 2%) there was an increase in M_R after freeze-thaw conditioning. This increase was apparent at higher confining pressures. Comparing the MC for SN4 and SF4 showed that after M_R testing the MC became 6.5% and 5.5% respectively. This can explain the increase in the M_R for the sample after freeze-thaw.

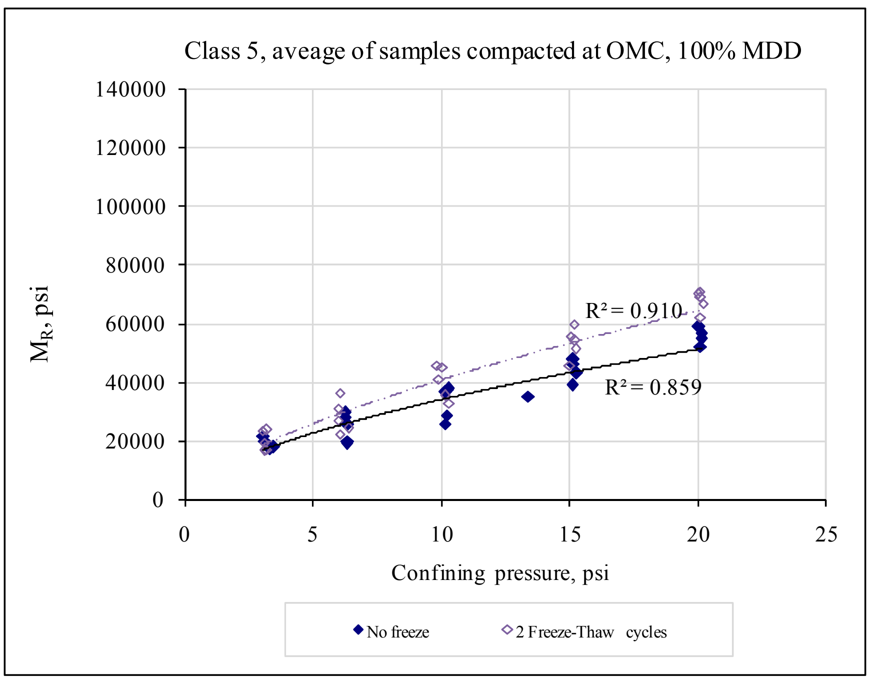


Figure 5.9 Effect of freeze-thaw on M_R for Class 5

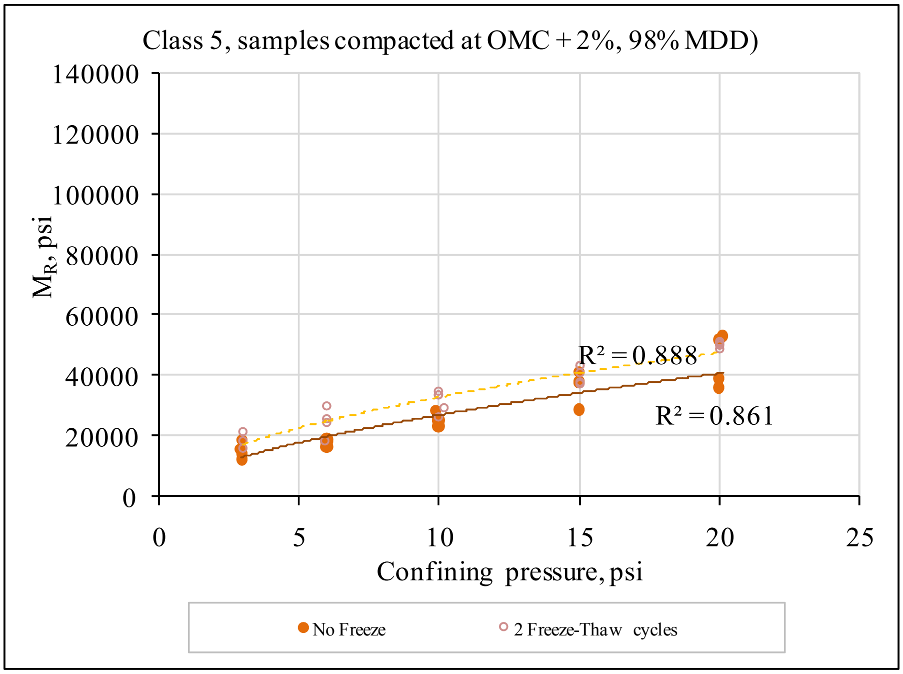


Figure 5.10 Effect of freeze-thaw on M_R of Class 5 for samples compacted OMC + 2%

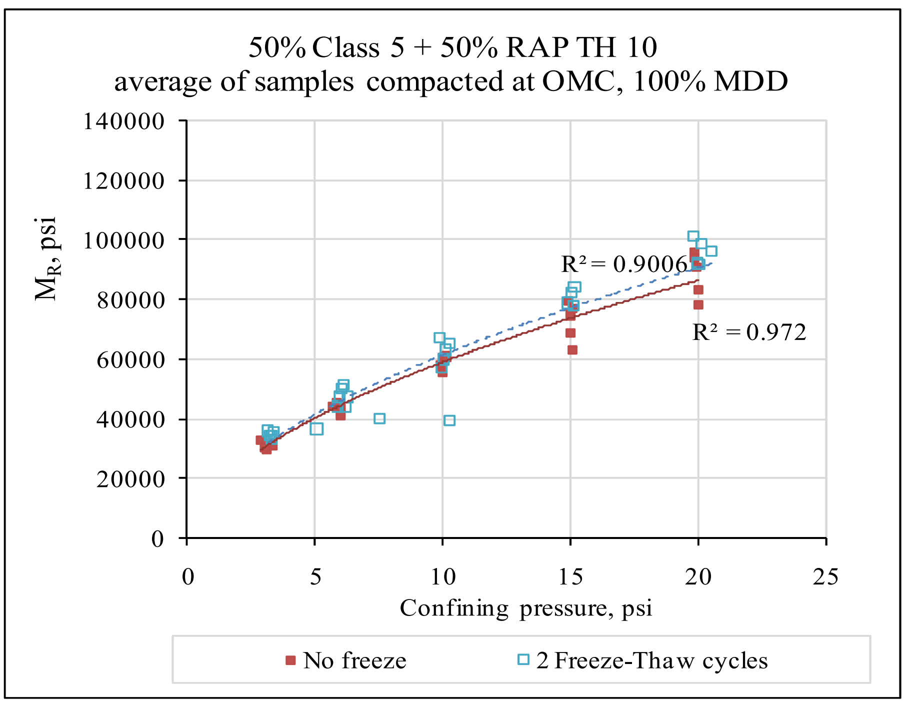


Figure 5.11 Effect of freeze-thaw on M_R for 50% Class 5 + 50% RAP TH 10

For 100% RAP material, samples compacted at OMC did not show loss of strength due to freeze-thaw conditioning. For samples compacted at a higher moisture content (OMC + 1%, OMC + 2%) there is an increase in M_R after freeze-thaw conditioning. This increase was apparent at higher confining pressure in the case of OMC + 1% and at all confining pressure in the case of OMC + 2%. Samples RN4 and RF4 were compacted at OMC +2 % (MC= 7.5 %), but checking MC after the M_R test showed that MC became 6.0% and 4.26% respectively. This can explain the increase in the M_R for the sample after freeze-thaw conditioning. A similar trend was found for the field RAP samples. The only exception was in RAP TH-19-101 material, as presented in Figure 5.13. The sample retained the moisture and showed loss of strength after F-T cycles.

As the tested materials did not hold the extra water, this indicates that they will not have extra moisture raised inside the base layer. Lack of fines could be the basic reason the materials did not hold extra moisture. For all tested materials the percent material passing # 200 sieve was less than 3%. RAP TH19-101 material kept its moisture content through the F-T cycles and in testing. A considerable loss of strength due to F-T cycles was found in RAP TH 19-101 material.

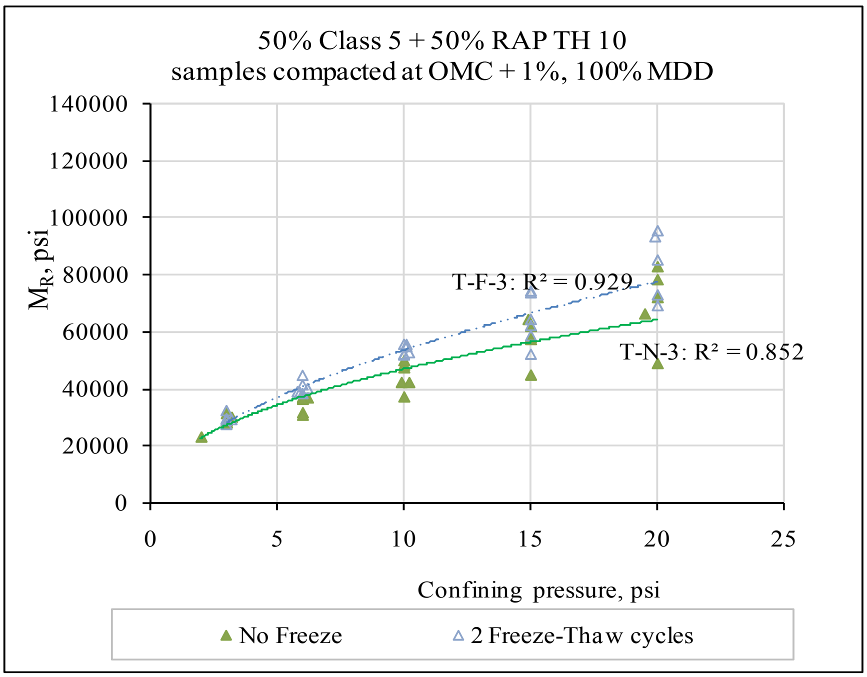


Figure 5.12 Effect of freeze-thaw on M_R for 50% Class 5 + 50% RAP TH 10, samples compacted at OMC+ 1%

Table 5.3 Comparing Moisture Content before and after M_R testing for Phase 1

Sample ID	Description	Target MC, %	MC of sample before test, %	MC of sample After test, %	ADD/MDD, %
C-N-1	100% Class 5, OMC, 100% MDD, no freeze	6.4	6.4		100.34
C-N-2	100% Class 5, OMC, no freeze, replicate	6.4	6.4	5.8	100.33
CNOMC-3	100% Class 5, OMC, no freeze, 2nd replicate	6.4	6.5	5.2	100.14
C-F-1	100% Class 5, OMC, 2 freeze-thaw cycles	6.4	6.4	5.3	100.6
C-F-2	100% Class 5, OMC, 2 freeze-thaw cycles, replicate	6.4	6.57	5.37	100.1
T-N-1	50% Class 5- 50% RAP TH 10, OMC, no freeze	5.2	5.15	5	100.27
T-N-2	50% Class 5- 50% RAP TH 10, OMC, no freeze, replicate	5.2	4.87	4.75	99.8
T-F-1	50% Class 5- 50% RAP TH 10, OMC, 2 freeze-thaw cycles	5.2	5.25	4.8	100.16
T-F-2	50% Class 5- 50% RAP TH 10, OMC, 2 freeze-thaw cycles, replicate	5.2	5.22	4.7	100.2
S-N-1	25% Class 5- 75% RAP TH 10, OMC, no freeze	5.7	5.4	5	100.2
S-N-2	25% Class 5- 75% RAP TH 10, OMC, no freeze, replicate	5.7	5.93	5.5	100.4
S-F-1	25% Class 5- 75% RAP TH 10, OMC, 2 freeze-thaw cycles	5.7	5.75	5.1	100.3
S-F-2	25% Class 5- 75% RAP TH 10, OMC, 2 freeze-thaw cycles, replicate	5.7	5.75	4.95	100.3
R-N-1	100% RAP TH 10, OMC, no freeze	5.5	5.4	4.7	99.88
R-N-2	100% RAP TH 10, OMC, no freeze, replicate	5.5	5.1	4.5	100
R-F-1	100% RAP TH 10, OMC, 2 freeze-thaw cycles	5.5	5.42	4.9	100.05
R-F-2	100% RAP TH 10, OMC, 2 freeze-thaw cycles, replicate	5.5	5.5	4.55	100
U-N-1	RAP TH 19-101, OMC, no freeze	5.9	6.3	5.9	100.8
U-N-2	RAP TH 19-101, OMC, no freeze, replicate	5.9	6	6	100
U-F-1	RAP TH 19-101, OMC, 2 freeze-thaw cycles	5.9	5.8	6	99.4
U-F-2	RAP TH 19-101, OMC, 2 freeze-thaw cycles, replicate	5.9	6.0	5.5	99.4
V-N-1	RAP TH 19-104, OMC, no freeze	7	7.1	6.5	100.47
V-N-2	RAP TH 19-104, OMC, no freeze, replicate	7	6.7	6.35	100.5
V-F-1	RAP TH 19-104, OMC, 2 freeze-thaw cycles	7	6.6	6.22	100.2
V-F-2	RAP TH 19-104, OMC, 2 freeze-thaw cycles, replicate	7	6.7	6.67	100.25
W-N-1	RAP TH 22, OMC, no freeze	5.25	5.5	5.23	100.31
W-N-2	RAP TH 22, OMC, no freeze, replicate	5.25	5.45	4.9	100.38
W-F-1	RAP TH 22, OMC, 2 freeze-thaw cycles	5.25	5.5	5	100.06
W-F-2	RAP TH 22, OMC, 2 freeze-thaw cycles, replicate	5.25	5.45	5	100.14

MC: Moisture content, MDD: Maximum dry density, ADD: Actual dry density

Table 5.4 Comparing Moisture Content before and after M_R testing for Phase 2

Sample ID	Description	Target MC, %	MC of sample before test, %	MC of sample After test, %	ADD/MDD, %
C-N-3	100% Class 5, OMC + 1%, no freeze	7.4	7.4	6	99.11
C-N-4	100% Class 5, OMC + 2%, no freeze	8.4	8.65	6.5	97.12
C-F- 4	100% Class 5, OMC + 2%, 2 freeze-thaw cycles	8.4	8.3	5	98.5
T-N- 3	50% Class 5- 50% RAP TH 10, OMC + 1%, no freeze	6.2	5.95	5.1	100.29
T-N- 4	50% Class 5- 50% RAP TH 10, OMC + 2%, no freeze	7.2	7	6	98.46
T-F- 3	50% Class 5- 50% RAP TH 10, OMC+ 1%, 2 freeze-thaw cycles	6.2	5.95	4.9	100.1
T-F- 4	50 % Class 5- 50% RAP TH 10, OMC+2%, 2 freeze-thaw cycles, replicate	7.2	7.35	5.5	97.9
S-N- 3	25% Class 5- 75% RAP TH 10, OMC + 1%, no freeze	6.7	6.5	5.7	97.63
S-N-4	25% Class 5- 75% RAP TH 10, OMC + 2%, no freeze	7.7	7.64	6.5	96.77
S-F-4	25% Class 5- 75% RAP TH 10, OMC+2%, 2 freeze-thaw cycles, replicate	7.7	7.84	5.5	96.92
R-N- 3	100% RAP TH 10, OMC + 1%, no freeze	6.5	6.3	5.23	99.56
R-N-4	100% RAP TH 10, OMC + 2%, no freeze, replicate	7.5	7.5	6.1	97.5
R-F- 3	100% RAP TH 10, OMC + 1%, 2 freeze-thaw cycles	6.5	6.36	5	99.92
R-F- 4	100% RAP TH 10, OMC + 2%, 2 freeze-thaw cycles, replicate	7.5	7.4	4.26	97.8
U-N- 4	RAP TH 19-101, OMC + 2%, no freeze, replicate	7.9	8.4	7.6	101
U-N-OMC-97MDD	RAP TH 19-101, OMC, no freeze, replicate	5.9	6.08	5.3	97.5
V-N- 4	RAP TH 19-104, OMC + 2%, no freeze	9	9.5	8.6	96.27
V-F- 4	RAP TH 19-104, OMC + 2%, 2 freeze-thaw cycles	9	9.4		96.7
W-N- 4	RAP TH 22, OMC + 2%, no freeze	7.25	7.1	6.35	98.1
W-F-4	RAP TH 22, OMC + 2%, 2 freeze-thaw cycles, replicate	7.25	7.50	6	97.9

MC: Moisture content, MDD: Maximum dry density, ADD: Actual dry density

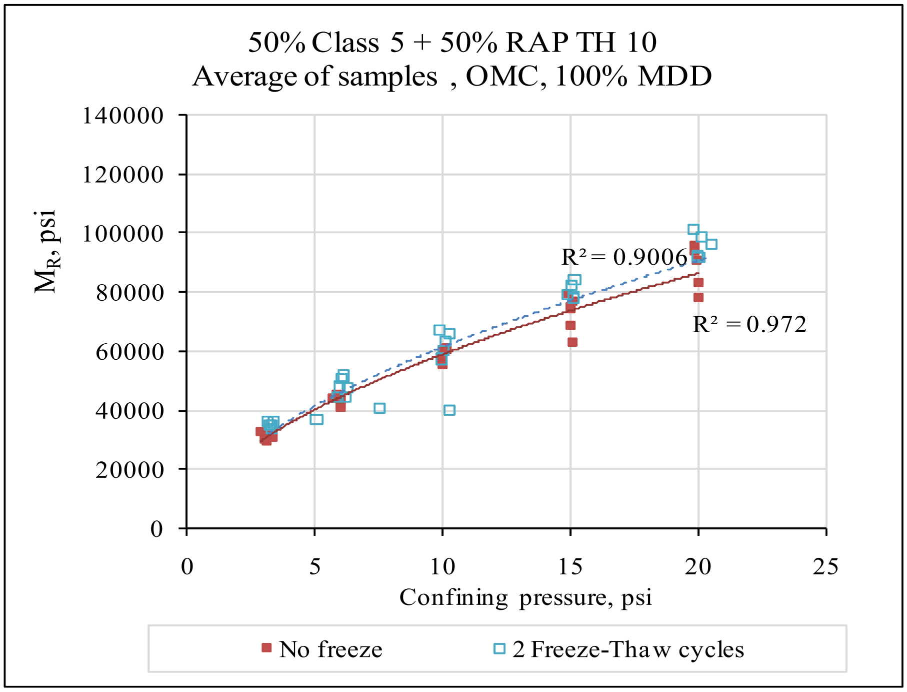


Figure 5.13 Effect of freeze-thaw on M_R for 50% Class 5 + 50% RAP TH 10, samples compacted at OMC+ 1%

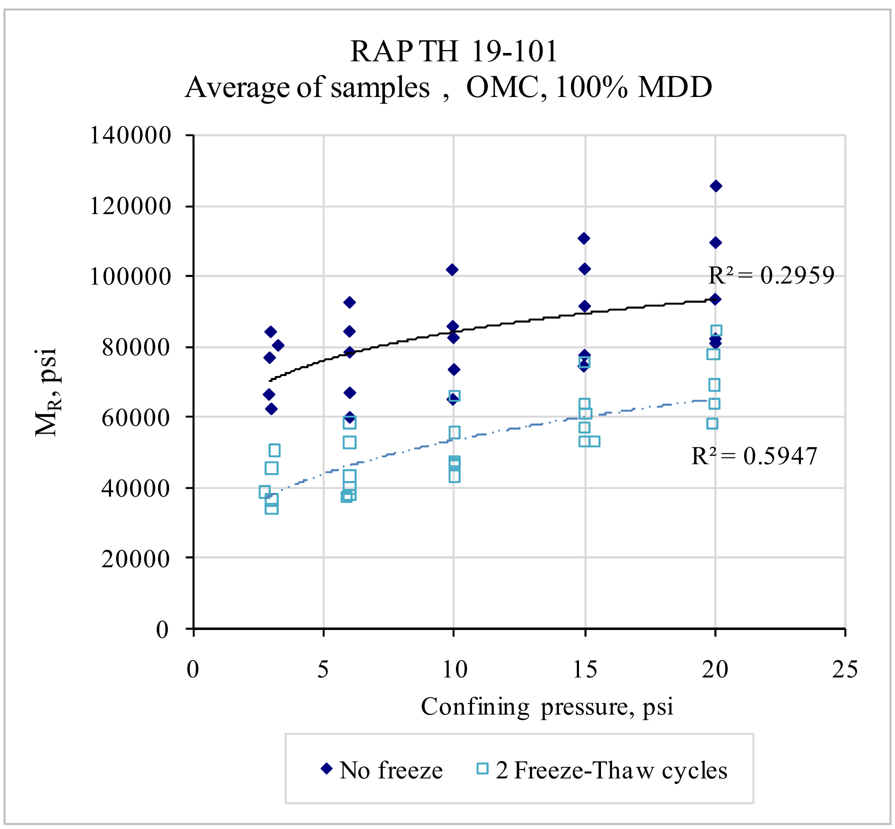


Figure 5.14 Effect of freeze-thaw on M_R for RAP TH 19-101

5.4.2. Effect of Freeze-Thaw conditioning and RAP Content on Shear Resistance of Base Layer Containing RAP

Analysis for this part will be based on testing conducted at NDSU. No data was collected from Mn/DOT regarding the effect of F-T on shear strength of the base layer containing RAP. The triaxial shear test was conducted on the samples which were compacted at the optimum moisture content and maximum dry density. The shear test was conducted after the resilient modulus testing. The shear test was conducted in strain controlled mode, at a loading rate of 0.03 mm/sec and a confining pressure of 4 and 8 psi. The maximum deviator stress from each confining pressure was used to construct the Mohr-Circle diagram for the determination of the friction angle (φ) and cohesion (C). The equation used to determine the final shear strength of the material is in the form of Equation 5.1.

$$\tau = C + \sigma_n \tan(\varphi) \quad (5.1)$$

Where,

τ = shear strength

C = cohesion

σ_n = normal stress

φ = friction angle (degrees)

Figure 5.14 presents the effect of F-T on the friction angle of RAP TH-10 and its blends with Class 5. It indicates that RAP mixes had a similar or lower friction angle compared to the Class 5 base material. For all RAP blends, an increase in the friction angle is shown after F-T cycles. Figure 5.15 presents the effect of F-T on cohesion of RAP/aggregate blends. F-T caused a reduction in the cohesion of RAP/aggregate blends. Increasing RAP content either did not have an effect or increased the cohesion of the material compared to Class 5. Figures 5.16 and 5.17 present the maximum deviator stress that was carried by the RAP/aggregate blends sample at 4 and 8 psi confining pressure. At low confining pressure, loss of strength was found for samples at 75% and 100% RAP after two F-T cycles, as presented in Figure 5.16. At high confining pressure, Figure 5.17 indicates that the failure load after F-T was almost equal to that of samples before conditioning.

Testing on field samples showed that there was no change in friction angle due to F-T for two field samples (RAP TH 19-104 and RAP TH 22), while there was considerable loss of friction between particles for RAP TH 19-101, as presented in Figure 5.18. However, examining the cohesion indicates that RAP TH 19-101 had higher cohesion after F-T, as presented in Figure 5.19.

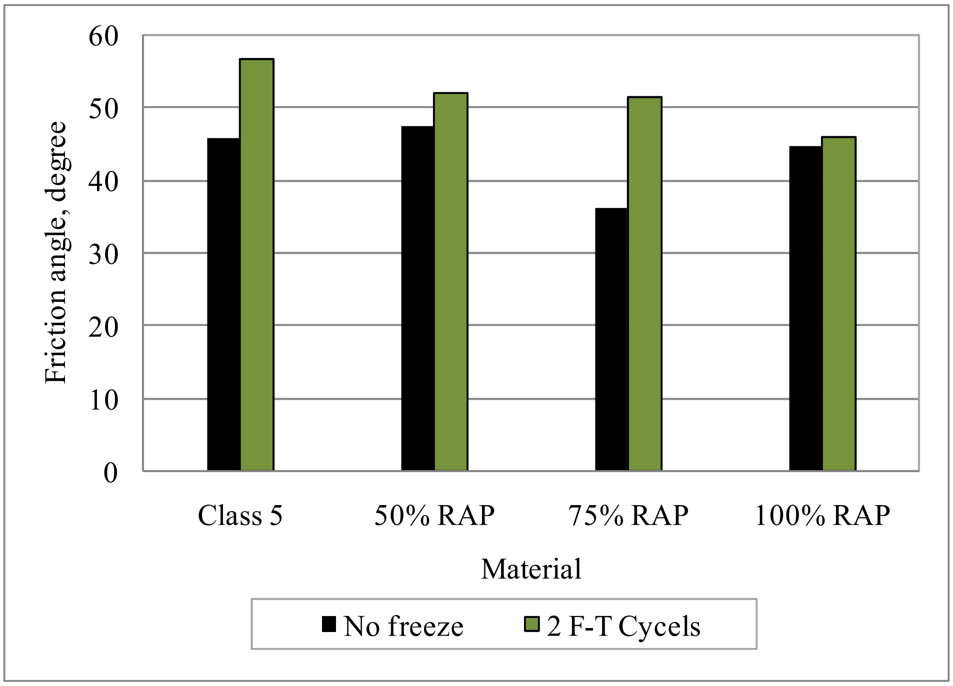


Figure 5.15 Effect of F-T on friction angle of base layer

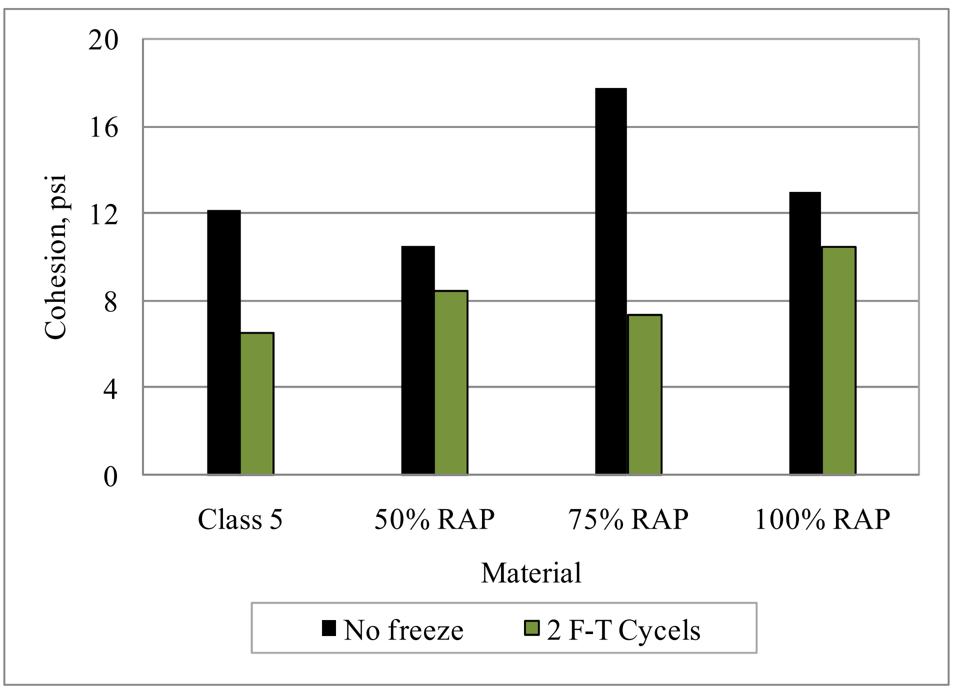


Figure 5.16 Effect of F-T on cohesion of base layer

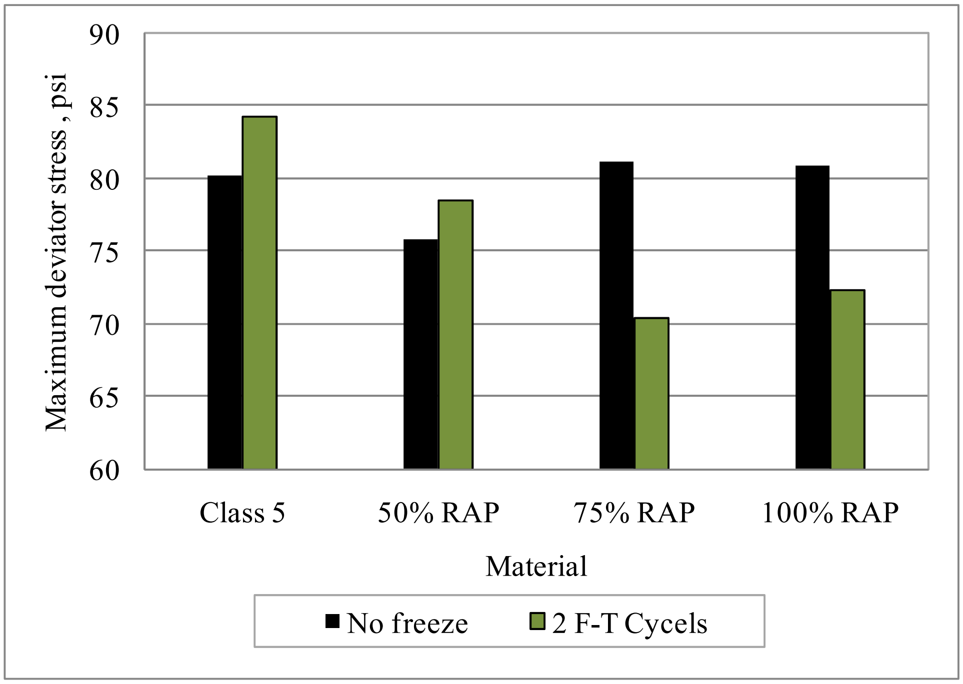


Figure 5.17 Effect of F-T on maximum deviator stress at confining pressure = 4 psi

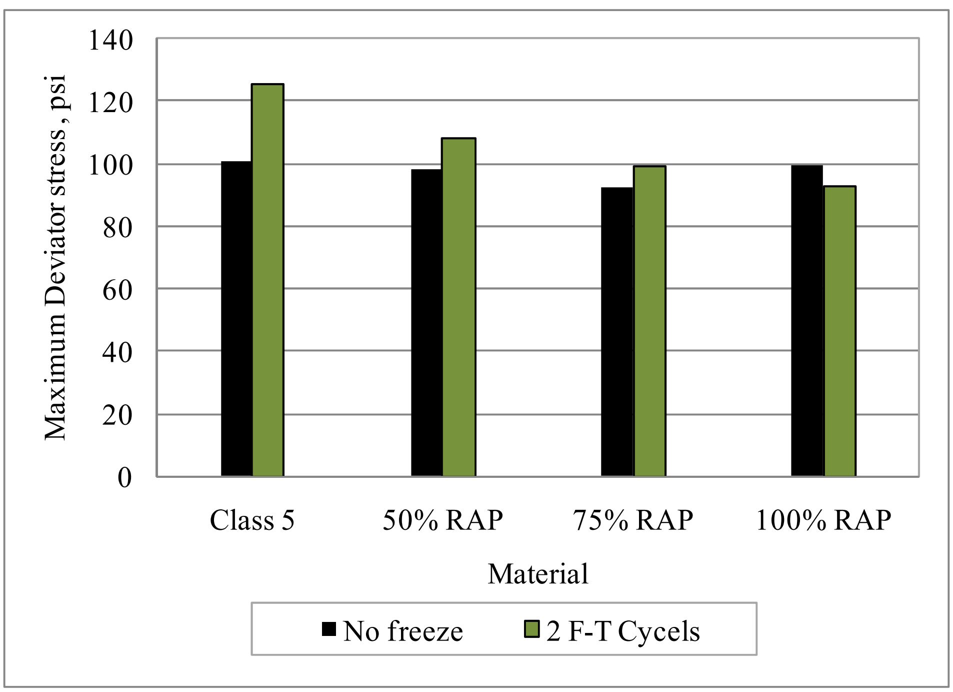


Figure 5.18 Effect of F-T on maximum deviator stress at confining pressure = 8 psi

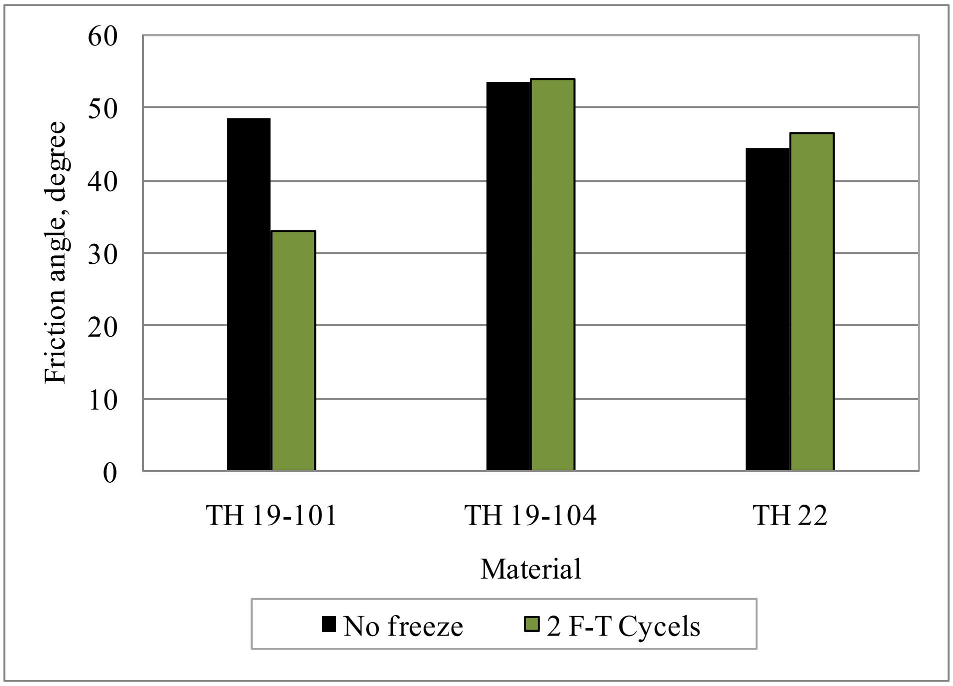


Figure 5.19 Effect of F-T on friction angle of base layer for field samples

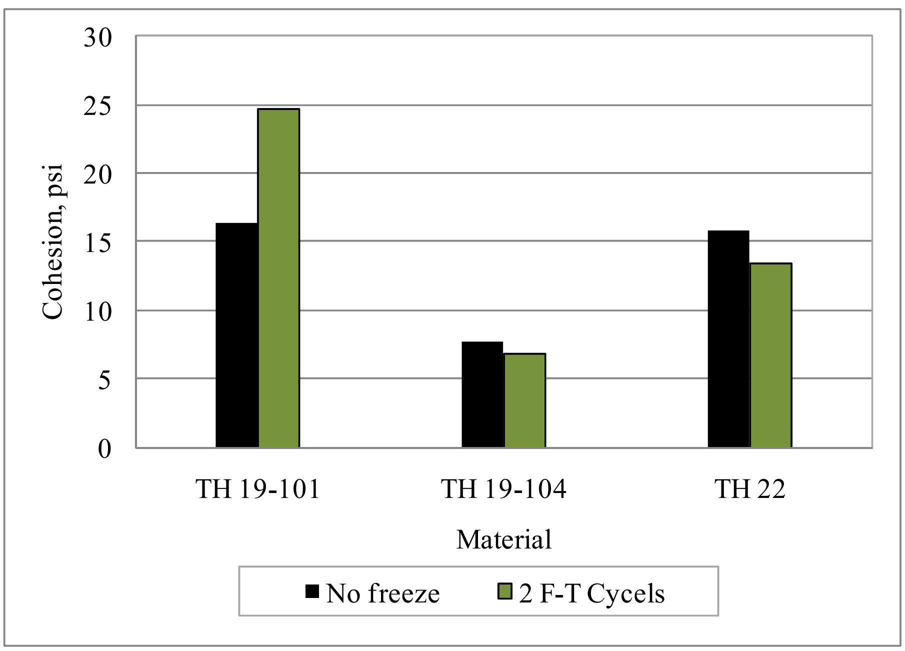


Figure 5.20 Effect of F-T on cohesion of base layer for field samples

Table 5.5 Summery of Shear Test Results

Sample ID	Sample Description	Conf. pressure	Deviator stress	Total stress	Friction angle (φ)	Cohesion
		psi	psi	psi	degree	psi
C-N-1	Class 5, OMC, no freeze	8	100.51	108.51	45.78	12.18
C-N-2	Class 5, OMC, No freeze, replicate	4	80.25	84.25		
C-F-1	Class 5, OMC, 2 freeze-thaw cycles	8	125.01	133.01	56.70	6.49
C-F-2	Class 5, OMC, 2 freeze-thaw cycles, replicate	4	84.21	88.21		
T-N-1	50% Class 5- 50% RAP TH 10, OMC, no freeze	8	98.03	106.03	47.30	10.47
T-N-2	50% Class 5- 50% RAP TH 10, OMC, no freeze, replicate	4	75.82	79.82		
T-F-1	50% Class 5- 50% RAP TH 10, OMC, 2 freeze-thaw cycles	8	108.11	116.11	51.93	8.42
T-F-2	50% Class5- 50% RAP TH 10, OMC, 2 freeze-thaw cycles, replicate	4	78.46	82.46		
S-N-1	25% Class 5- 75% RAP TH 10, OMC, no freeze	8	92.78	100.78	36.18	17.69
S-N-2	25% Class 5- 75% RAP TH 10, OMC, no freeze, replicate	4	81.24	85.24		
S-F-1	25% Class 5- 75% RAP TH 10, OMC, 2 FTC	8	99.03	107.03	51.38	7.31
S-F-2	25 % Class5- 75% RAP TH 10, OMC, 2 FTC, replicate	4	70.40	74.40		
R-N-1	100% RAP TH 10, OMC, no freeze	8	99.85	107.85	44.62	12.96
R-N-2	100% RAP TH 10, OMC, no freeze, replicate	4	80.95	84.95		
R-F-1	100% RAP TH 10, OMC, 2 freeze-thaw cycles	8	92.80	100.80	45.98	10.46
R-F-2	100% RAP TH 10, OMC, 2 freeze-thaw cycles, replicate	4	72.30	76.30		
U-N-1	RAP TH 19-101, OMC, no freeze	8	133.94	141.94	50.26	14.56
U-N-2	RAP TH 19-101, OMC, no freeze, replicate	4	107.28	111.28		
U-F-1	RAP TH 19-101, OMC, 2 freeze-thaw cycles	8	110.27	118.27	33.07	24.68
U-F-2	RAP TH 19-101, OMC, 2 freeze-thaw cycles, replicate	4	100.66	104.66		
V-N-1	RAP TH 19-104, OMC, no freeze	8	112.65	120.65	53.54	7.70
V-N-2	RAP TH 19-104, OMC, no freeze, replicate	4	79.73	83.73		
V-F-1	RAP TH 19-104, OMC, 2 freeze-thaw cycles	8	110.70	118.70	54.06	6.90
V-F-2	RAP TH 19-104, OMC, 2 freeze-thaw cycles, replicate	4	76.64	80.64		
W-N-1	RAP TH 22, OMC, no freeze	8	113.22	121.22	44.50	15.86
W-N-2	RAP TH 22, OMC, no freeze, replicate	4	94.45	98.45		
W-F-1	RAP TH 22, OMC, 2 freeze-thaw cycles	8	109.92	117.92	46.64	13.36
W-F-2	RAP TH 22, OMC, 2 freeze-thaw cycles, replicate	4	88.59	92.59		

5.4.3. Effect of RAP Content on M_R of Base Layer

Data for this section is based on samples tested at NDSU and data collected from Mn/DOT. Figures 5.20 and 5.21 present the effect of RAP content on M_R of base layer based on data collected from Mn/DOT. M_R results indicate an increase of strength as the percent RAP increases in the base layer. For testing conducted at NDSU, all RAP samples had higher resilient modulus than Class 5, as presented in Figure 5.22. This indicates that RAP/aggregate blends are a valuable alternative as a base layer, and are structurally sound.

5.4.4. Effect of Moisture Content on Resilient Modulus (M_R)

Investigating moisture sensitivity of the RAP is based on data collected from Mn/DOT and testing conducted at NDSU. Four samples composed of 50% RAP + 50% Taconite were compacted at the same dry density, at different moisture contents, and then tested for M_R. The results, presented in Figure 5.23, showed mixed effects of moisture content. While samples at the lowest moisture content (6.7%) had the highest resilient modulus, samples at the highest moisture content (8.2%) gave similar or higher resilient modulus values as compared to samples at 7.7% moisture content. Testing conducted by Kim and Labuz (5) showed that samples compacted at 65% of OMC always had a higher resilient modulus than samples compacted at OMC (5).

For testing conducted at NDSU, Class 5 samples tested at OMC had higher M_R than samples compacted at OMC + 1% or OMC + 2%, as presented in Figure 5.24. For samples containing 50% RAP + 50% Class 5 testing was conducted at OMC, OMC + 1%, OMC + 2%, OMC - 1% and OMC - 2%. The testing results are presented in Figures 5.25 and 5.26. The data showed a trend of increasing resilient modulus with decreasing the moisture content as long as it was possible to achieve the maximum dry density. For 75% RAP, samples compacted at moisture higher than the optimum had lower resilient modulus as compared to samples compacted at OMC, data are presented in Figure 5.27. Field RAP samples showed reduction in M_R with increasing moisture content for 2 materials; RAP TH19-101 and RAP TH19-104. Figure 5.28 represents RAP TH 19-101. RAP TH 22 did not show change in M_R due to 2% change in moisture content at low confining pressure, but there was reduction in M_R at high confining pressure, as presented in Figure 5.29.

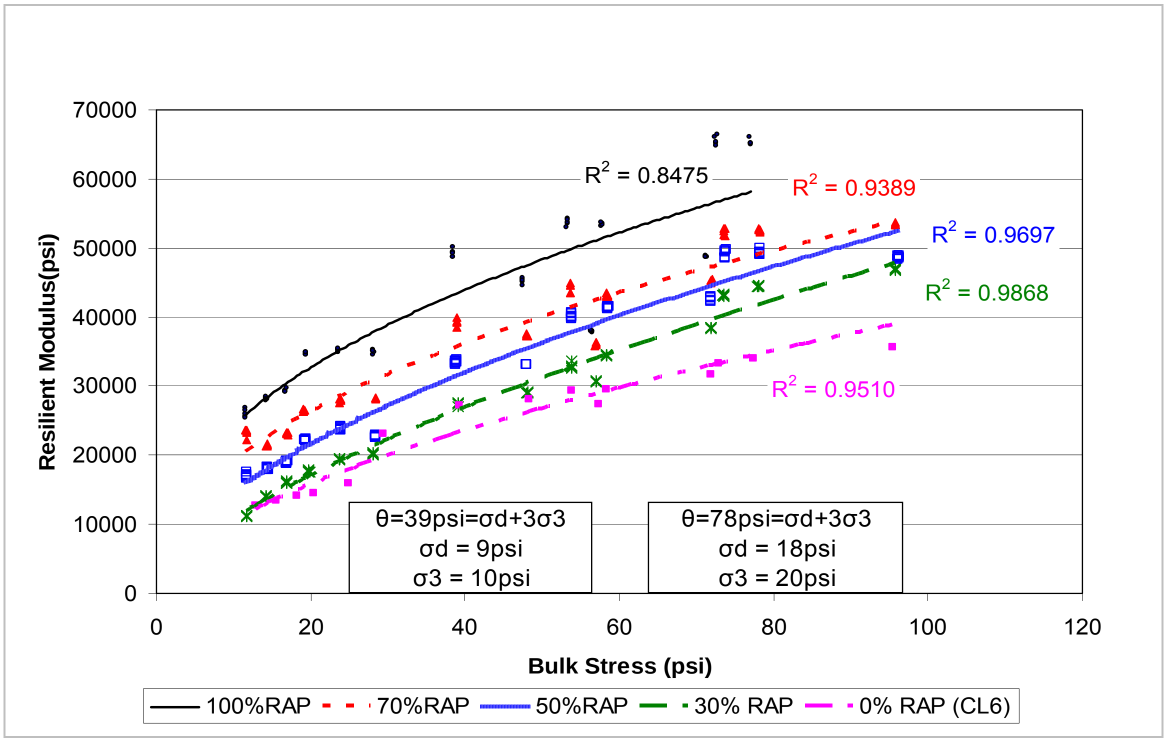


Figure 5.21 Effect of RAP content on M_R of base layer, Mn/DOT data (20)

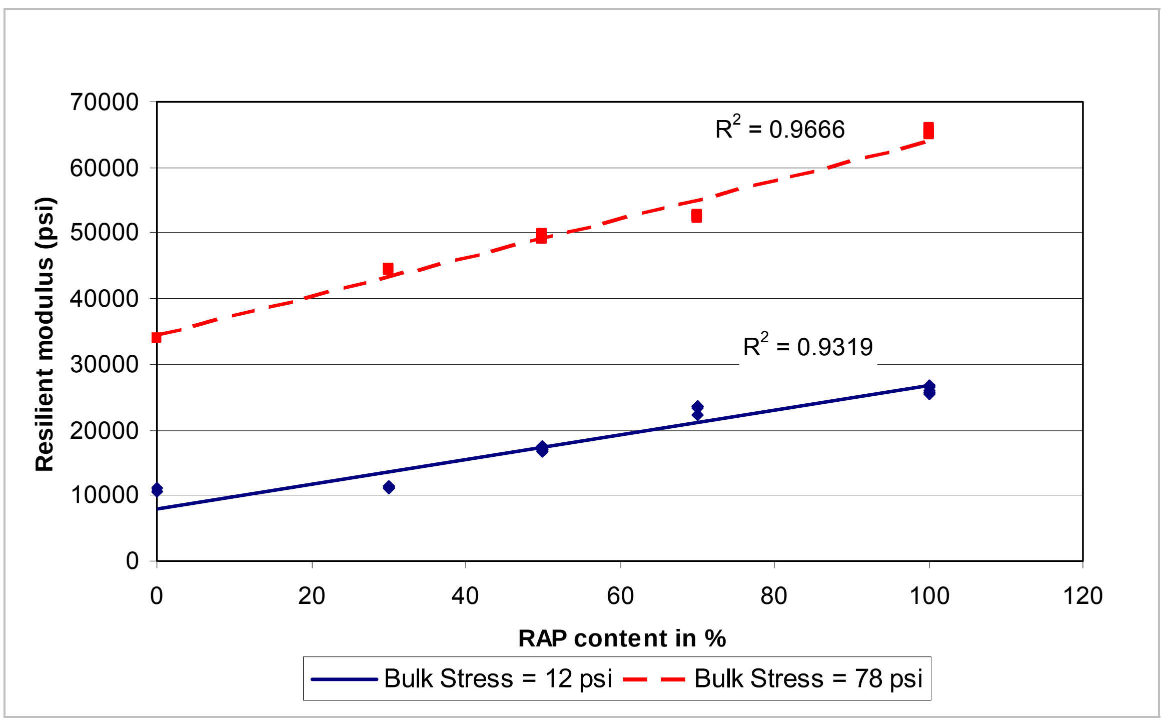


Figure 5.22 Effect of RAP content on M_R of base layer at selected states of stress, Mn/DOT data (20)

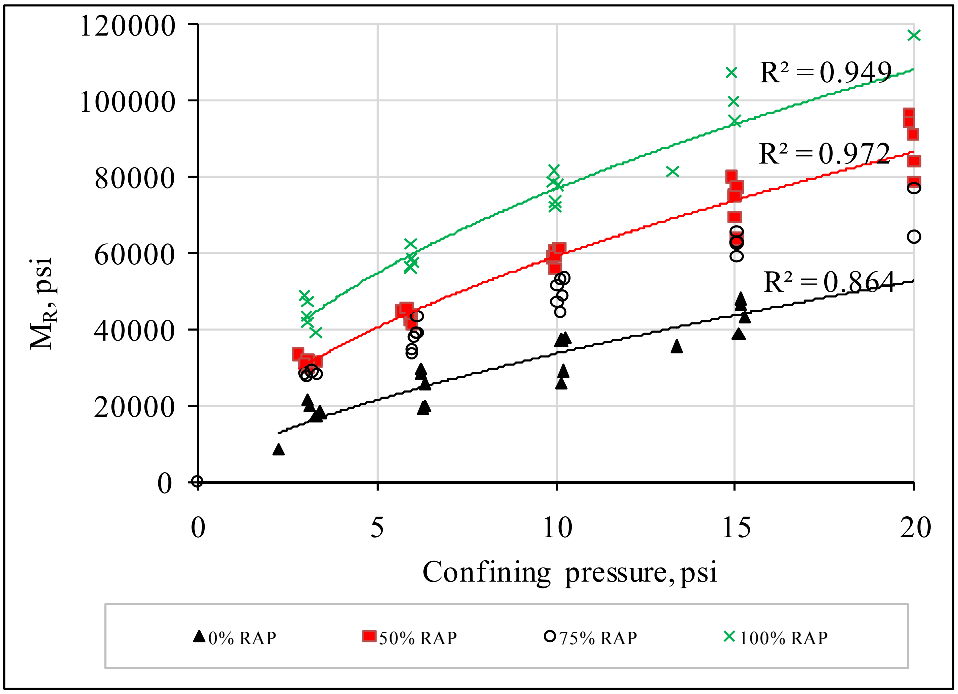


Figure 5.23 Effect of RAP content on M_R of base layer (average of tested samples)

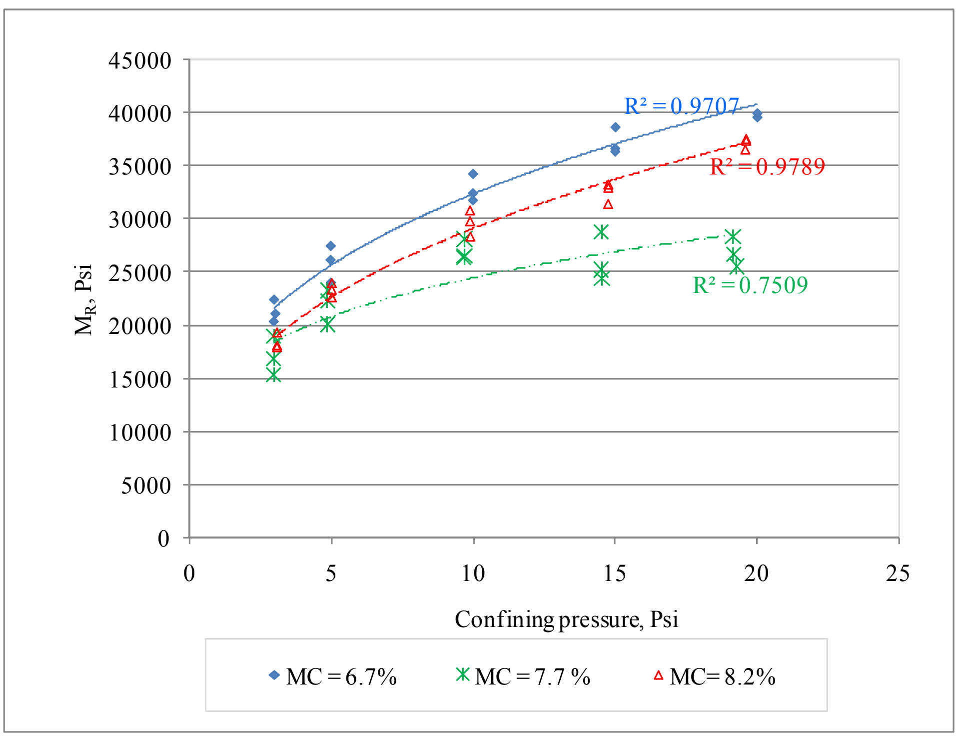


Figure 5.24 Effect of moisture content on 50% RAP + 50% Taconite, Mn/DOT data (MC =6.7 % is based on average of 2 samples)

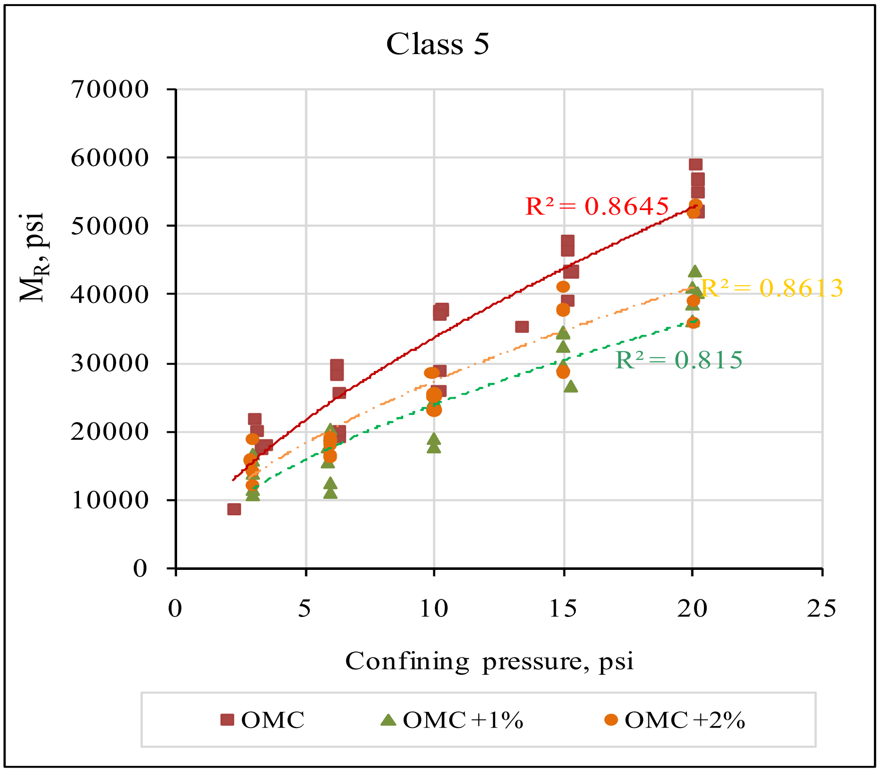


Figure 5.25 Effect of moisture content on Class 5 (OMC results are based on average of tested samples)

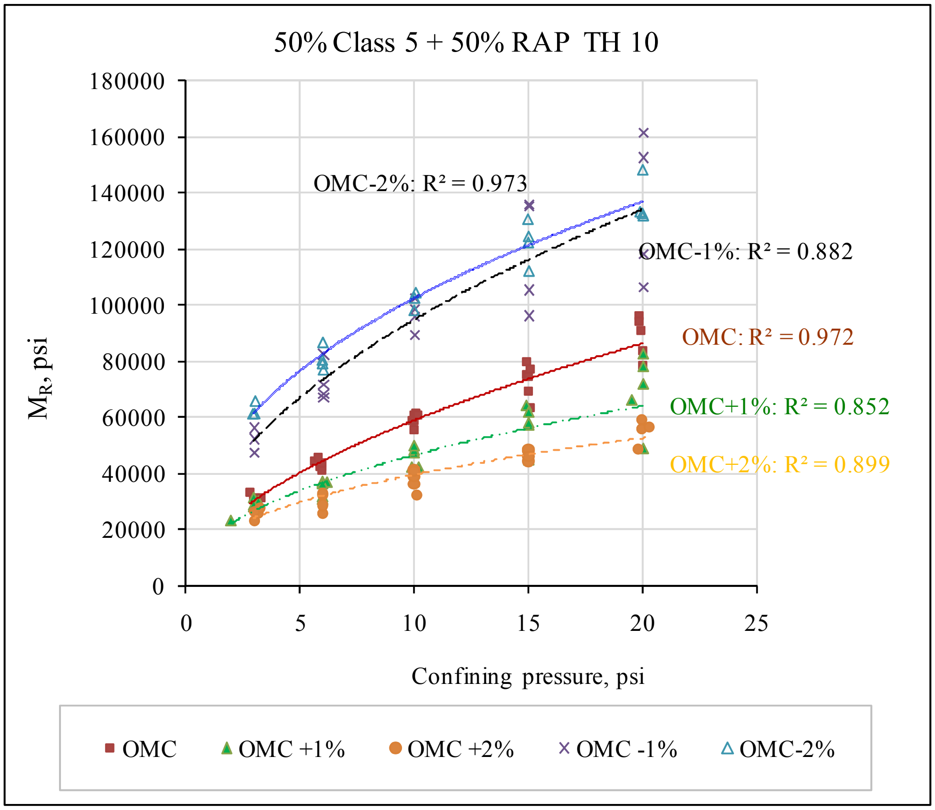


Figure 5.26 Effect of moisture content on 50% RAP TH 10 + 50% Class 5

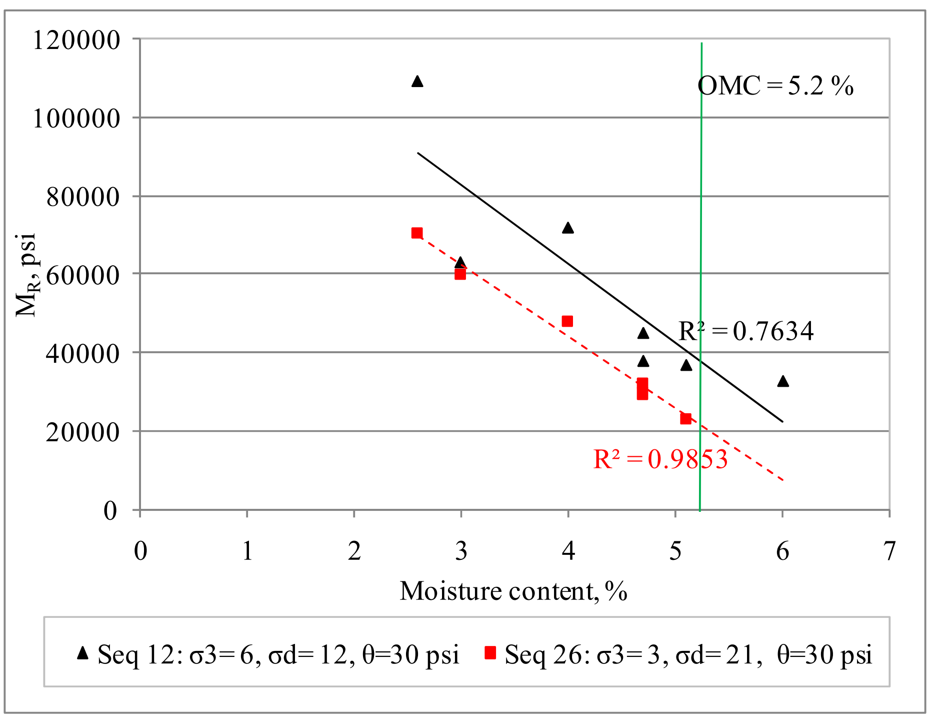


Figure 5.27 Effect of moisture content on M_R of 50% RAP + 50% Class 5 at bulk stress = 30 psi

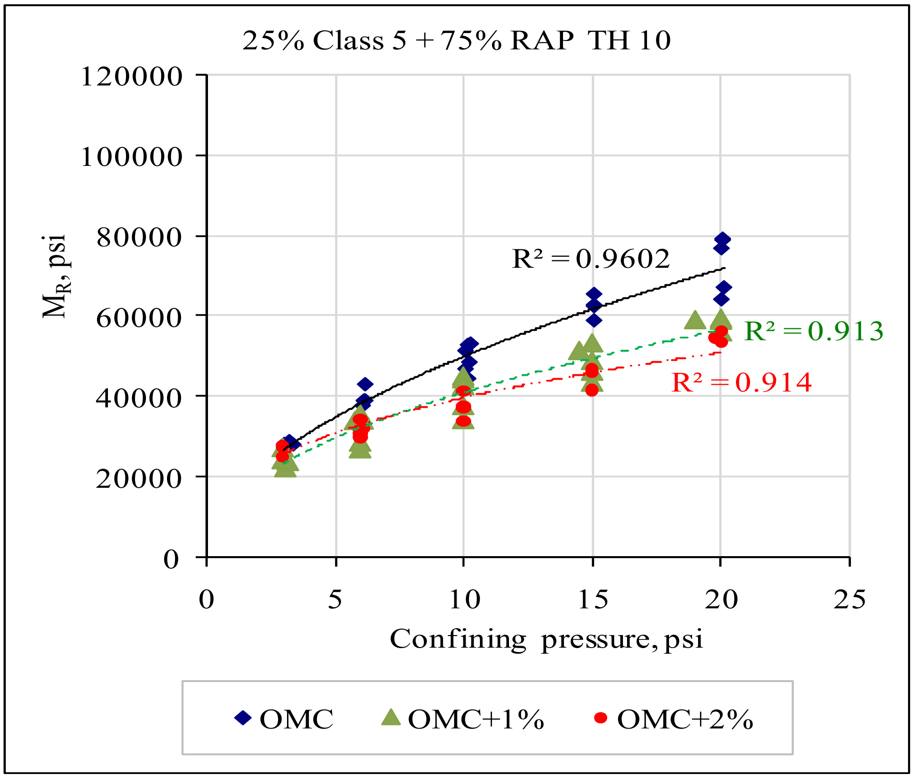


Figure 5.28 Effect of moisture content on 75% RAP TH10 + 25% Class 5 (OMC results are based on average of tested samples)

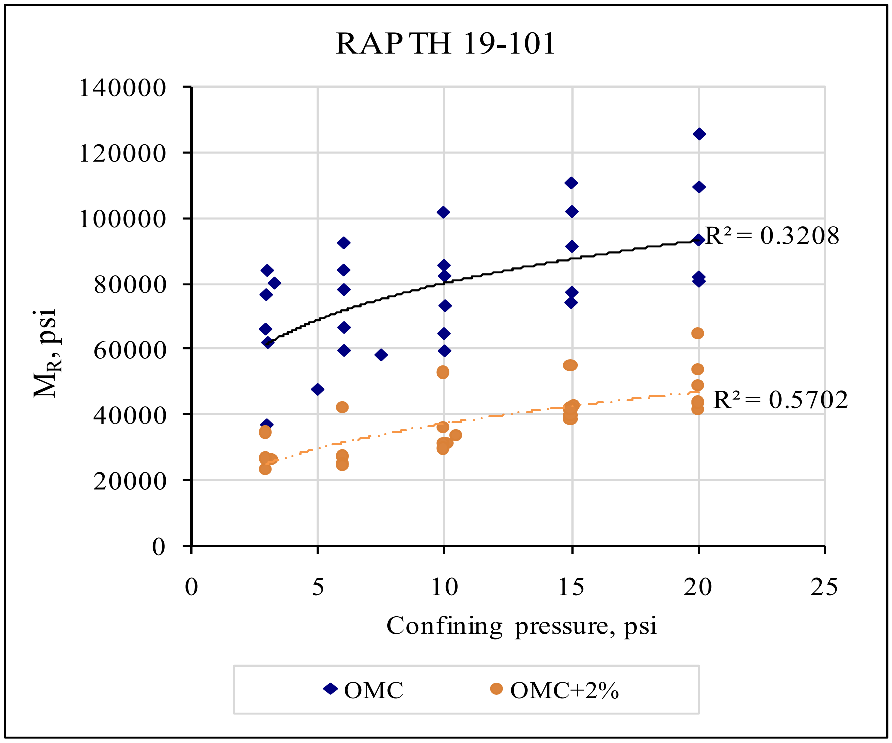


Figure 5.29 Effect of moisture content on RAP TH 19-101 (OMC results are based on average of tested samples)

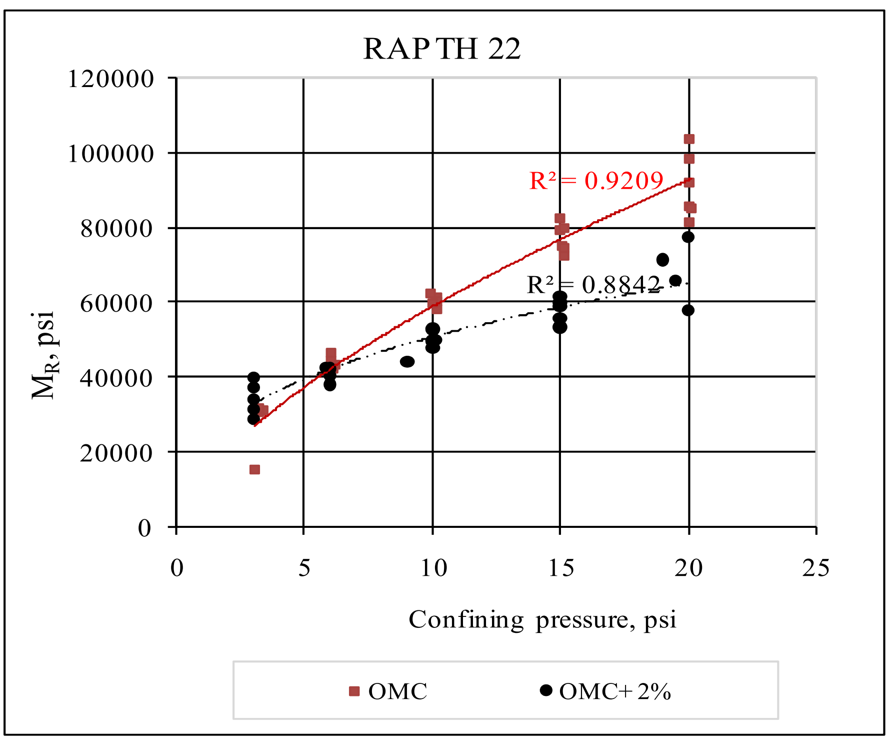


Figure 5.30 Effect of moisture content on RAP TH 22 (OMC results are based on average of tested samples)

5.4.5. Effect of Dry Density on Resilient Modulus

The effect of dry density was investigated based on limited testing at NDSU and data collected from Mn/DOT. Figure 5.31 presents the effect of dry density on samples composed of 50% RAP + 50% Class 6 at two different dry densities (125 and 130 lb/ft^3) at moisture content (MC) = 6.6%. The results did not show the effect of dry density at this moisture content. Figure 5.32 presents the effect of dry density on samples composed of 50% RAP + 50% Taconite at two different dry densities (125 and 135 lb/ft^3) at MC = 6.6%. Results showed that the sample compacted at a higher dry density had higher M_R at high confining pressure, while the difference did not look significant at low confining pressure.

Limited testing was conducted at NDSU. For RAP field sample TH 19-101, the reduction in dry density had decreased the resilient modulus, as presented in Figure 5.33. The results obtained based on this data are explained by Figure 5.34 which describes the relation between dry density and resilient modulus for granular materials. It is clear that the effect of dry density is greatly dependent on the moisture content within the sample. The results also showed that the effect of dry density on M_R is dependent on the state of stress.

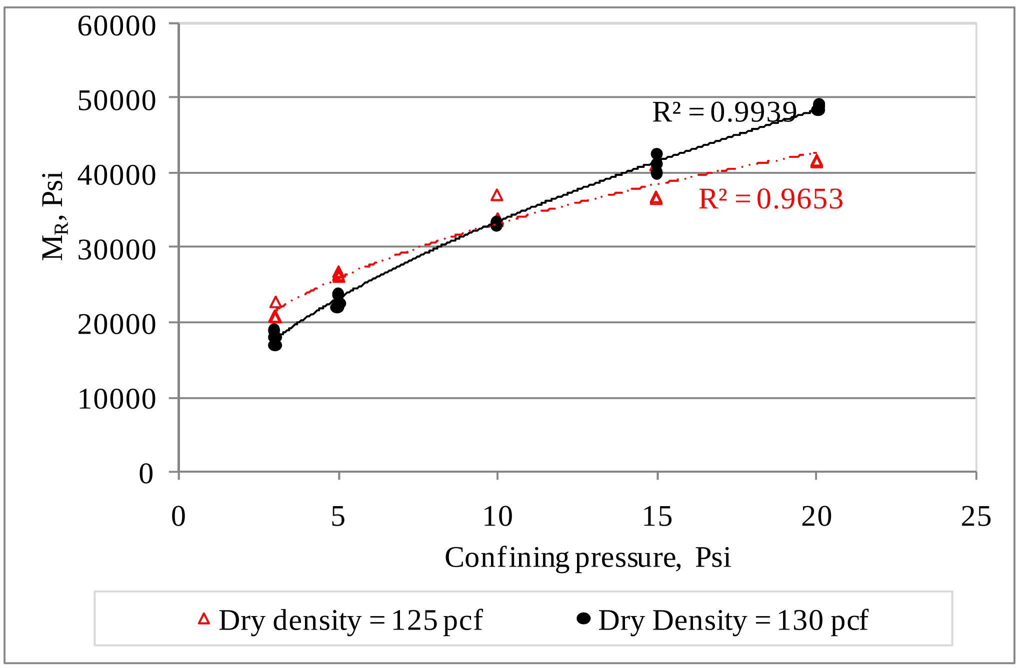


Figure 5.31 Effect of dry density on M_R of 50% RAP + 50% Class 6 (MC = 6.6%), (Mn/DOT data)

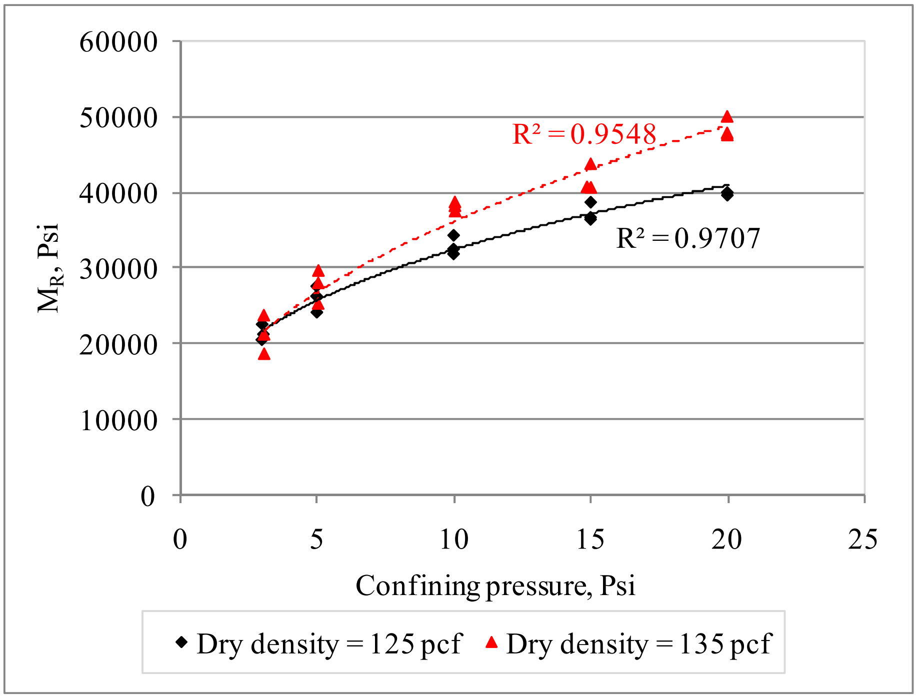


Figure 5.32 Effect of dry density on M_R of 50% RAP + 50% Taconite (MC = 6.5%), (Mn/DOT data), (data for dry density = 125 pcf is based on average of 2 samples)

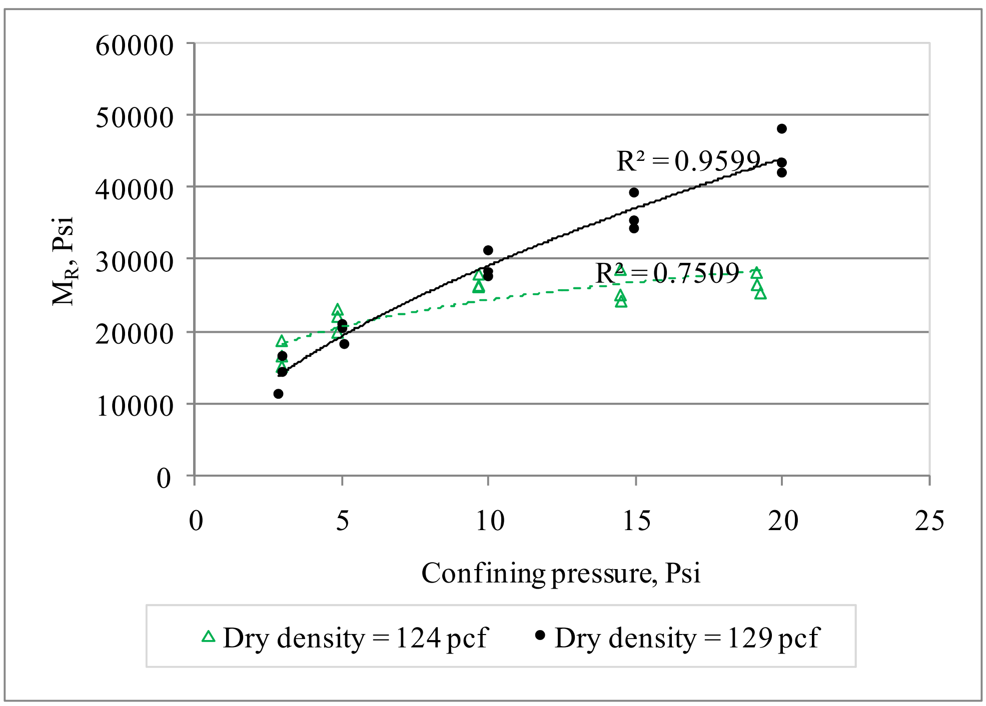


Figure 5.33 Effect of dry density on M_R of 50% RAP + 50% Taconite (MC =7.7 %), (Mn/DOT data)

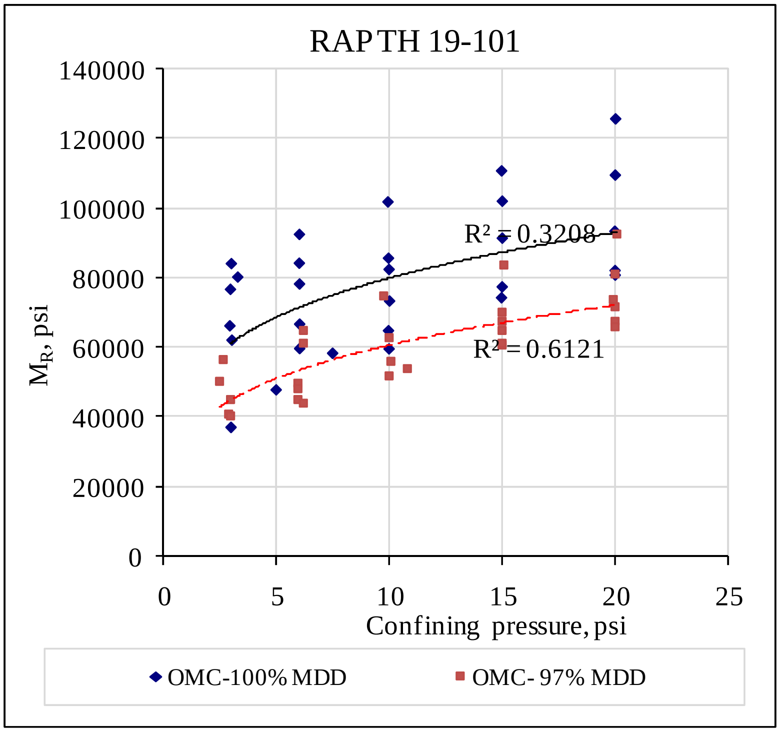


Figure 5.34 Effect of dry density on M_R of RAP TH19-101 (100% MDD is based on average of 2 samples)

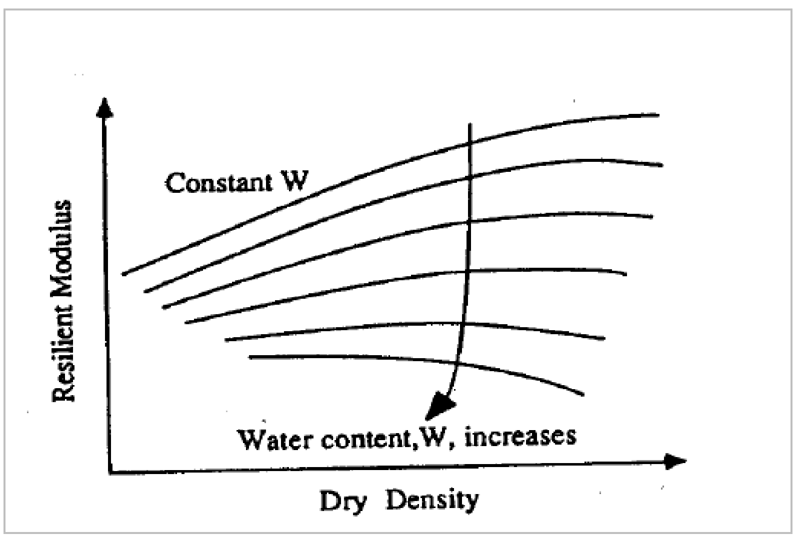


Figure 5.35 Effect of dry density on resilient modulus of granular material (34)

5.4.6. Effect of State of Stress on Resilient Modulus

The resilient modulus of granular material is known to be nonlinear and varies with the state of stress. Several models have been developed to describe the resilient behavior of granular material. The following sections investigate the effect of confining pressure, bulk stress, and the combined effect of deviator stress and confining pressure on resilient modulus of tested samples.

5.4.6.1. Effect of Confining Pressure on Resilient Modulus

Increasing the confining pressure had increased the M_R for tested samples. Figures 5.36 to 5.38 present the effect of the confining pressure on the resilient modulus of some of the tested RAP materials. It is clear that M_R was closely correlated to confining pressure. The M_R of field sample RAP TH 22 was also well related to confining pressure but M_R for RAP TH 19-101 was poorly related to confining pressure, as presented in Figure 5.38. The relation between confining pressure and resilient modulus for all tested samples is presented in Appendix D. The resilient modulus was modeled using Equation 5.2 and the regression coefficients are summarized in Table 5.6.

$$M_R = K_1 * (\sigma_3)^{K_2} \quad (5.2)$$

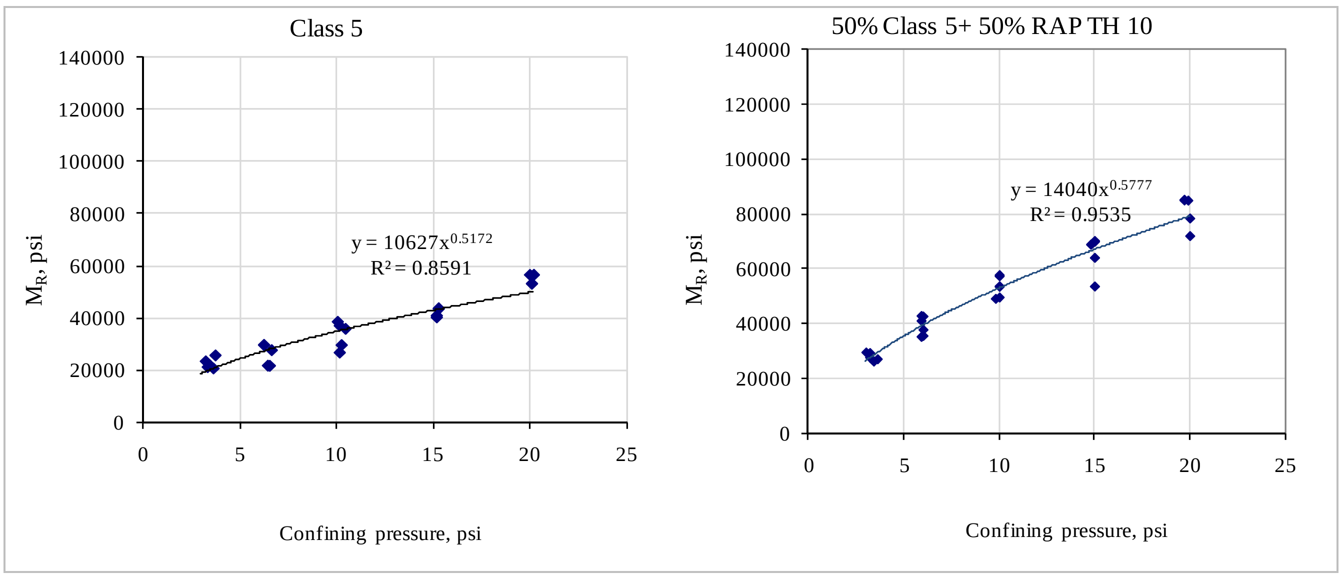


Figure 5.36 M_R vs. confining pressure for Class 5 and 50% Class 5 + 50 % RAP TH10 (OMC, 100 % MDD)

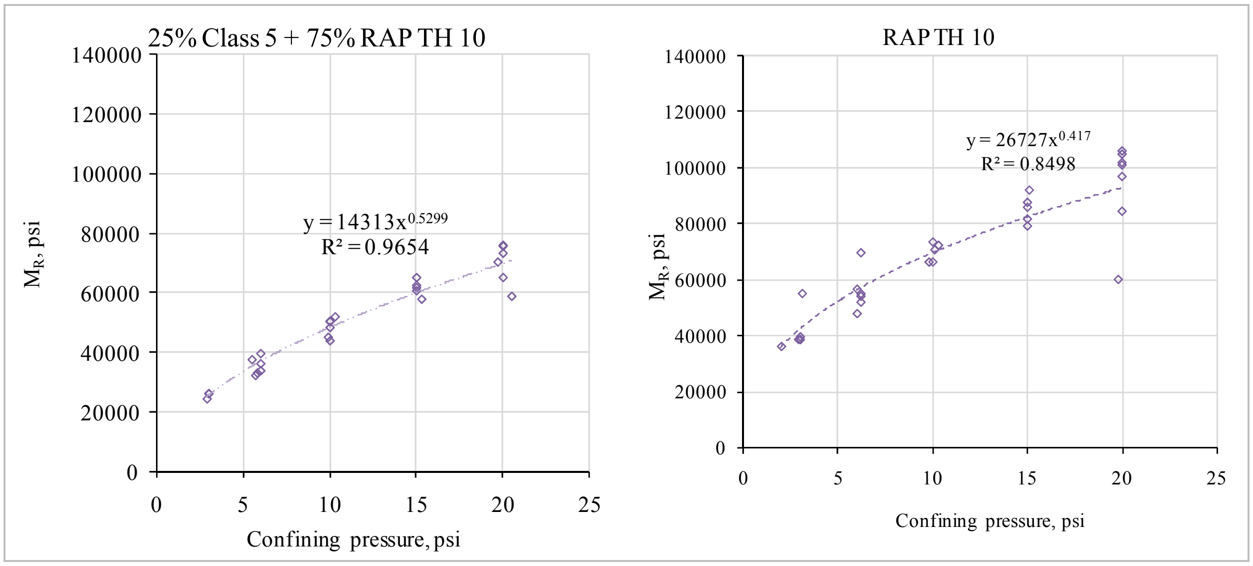


Figure 5.37 M_R vs. confining pressure for 50% Class 5 + 50% RAP TH 10 and 25% Class 5 + 75% RAP TH 10 (OMC, 100% MDD, 2 F-T)

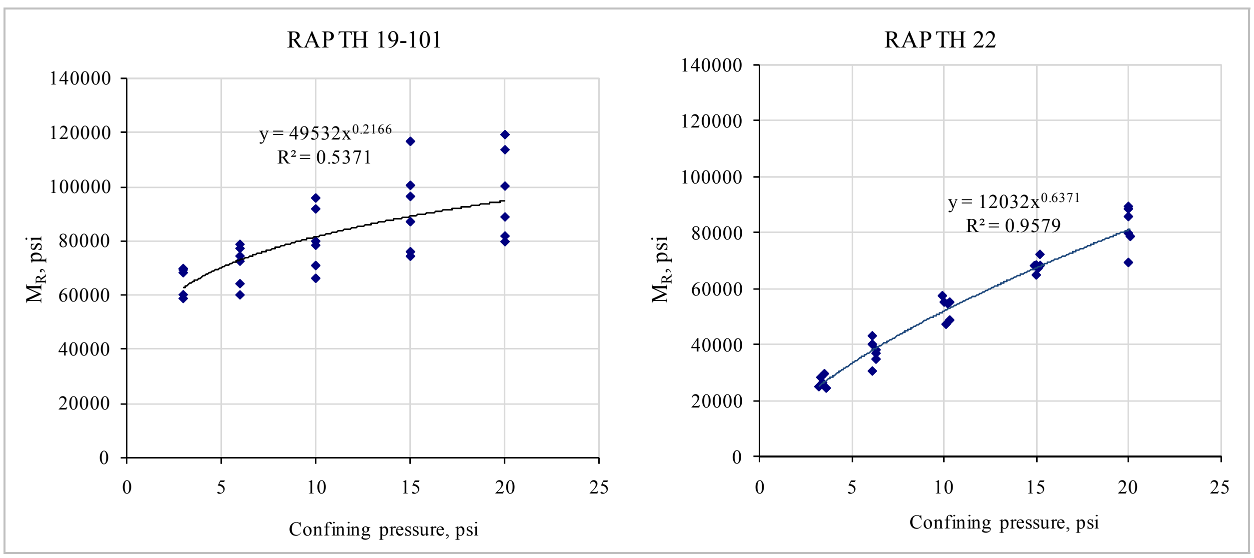


Figure 5.38 M_R vs. confining pressure for field samples, RAP TH 19-101 and RAP TH 22 (OMC, 100% MDD)

5.4.6.2. Effect of Bulk Stress on Resilient Modulus

Increasing bulk stress had increased the M_R for tested samples. Figures 5.39 to 5.41 present the effect of bulk stress on resilient modulus of some of the tested RAP materials. The relation between M_R and the bulk stress was material dependent. M_R of Class 5 had a strong correlation with bulk stress. The M_R of field sample RAP TH 22 was also strongly correlated to bulk stress but M_R for field sample RAP TH-19-101 was poorly related to bulk stress. The relation between bulk stress and resilient modulus for all tested samples is presented in Appendix E. The relation between confining pressure and resilient modulus was found to be better than the relation between resilient modulus and bulk stress for RAP/aggregate blends as it had higher R^2 value.

Table 5.6 Summary of Equation 5.2 Regression Coefficients for all Samples

Sample ID	K_1	K_2	R^2		Sample ID	K_1	K_2	R^2
C-N-1	10627	0.52	0.86		R-F-1	26737	0.42	0.85
C-N-2	7065	0.66	0.86		R-F-2	30650	0.4	0.80
CNOMC-3	9775	0.56	0.88		R-N-3	13326	0.53	0.96
C-F-1	8464	0.678	0.943		R-N-4	25591	.31	0.74
C-F-2	9316	0.644	.885		R-F-3	16555	0.52	0.92
C-N-3	6110	0.59	0.815		R-F-4	28524	0.39	0.75
C-N-4	6899	0.595	0.86		U-N-1	49532	0.22	0.54
C-F-4	9828	0.525	0.89		U-N-2	34302	0.25	0.61
T-N-1	14040	0.578	0.95		U-F-1	30044	0.24	0.59
T-N-2	20167	0.50	0.93		U-F-2	26207	0.32	0.6
T-F-1	17096	0.56	0.97		U-N-4	17509	0.33	0.57
T-F-2	19125	0.53	0.97		V-N-1	21825	0.41	0.55
T-N-3	17265	0.43	0.83		V-N-2	14831	0.46	0.87
T-N-4	15238	0.41	0.91		V-F-1	19194	0.45	0.85
T-F-3	16045	0.53	0.91		V-F-2	16307	0.51	0.89
T-F-4	23523	0.47	0.80		V-N-4	13207	0.39	0.76
S-N-1	12984	0.55	0.95		V-F-4	12851	0.35	0.75
S-N-2	18057	0.47	0.94		W-N-1	18579	0.56	0.97
S-F-1	14289	0.53	0.97		W-N-2	12032	0.64	0.96
S-F-2	19132	0.44	0.97		W-F-1	17414	0.59	0.96
S-N-3	14145	0.46	0.92		W-F-2	17993	0.54	0.97
S-N-4	17226	036	0.91		W-N-4	22410	0.36	0.88
S-F-4	17049	0.45	0.95		W-F-4	19168	0.4	0.84
R-N-1	18602	0.59	0.93					
R-N-2	27509	0.49	0.94					
R-N-OMC-3	2731	0.44	0.82					

Note: Tables 5.3 and 5.4 contain detailed samples description

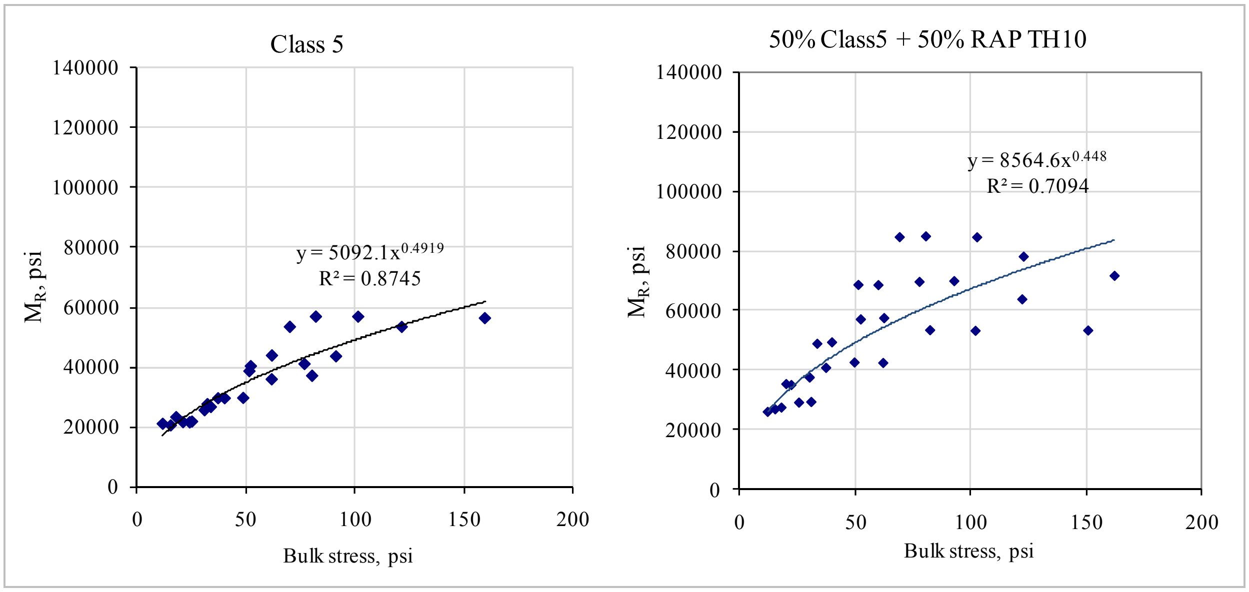


Figure 5.39 M_R vs. bulk stress for Class 5 and 50% Class 5 + 50% RAP TH10 (OMC, 100 % MDD)

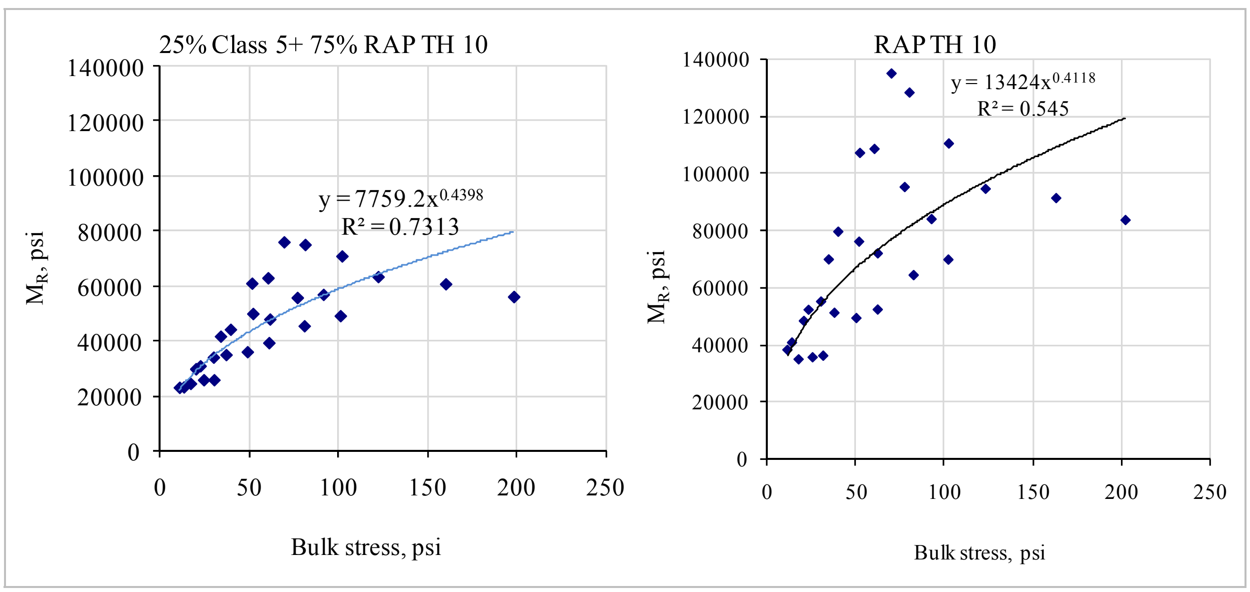


Figure 5.40 M_R vs. bulk stress for 25% Class 5 + 75% RAP TH 10 and 100% RAP TH 10 (OMC, 100% MDD)

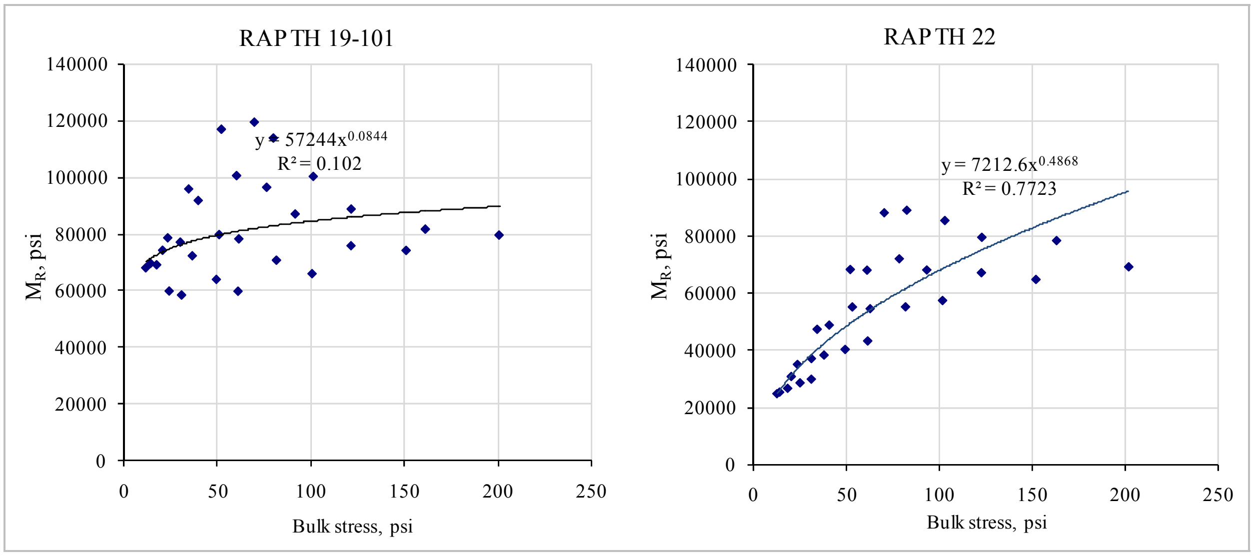


Figure 5.41 M_R vs. bulk stress for field blends, RAP TH 19-101 and RAP TH 22 (samples at OMC and 100% MDD)

5.4.6.3. Effect of Confining Pressure and Deviator Stress on Resilient Modulus

The effects of both confining pressure and deviator stress were investigated. Results showed that increasing the confining pressure had in all cases increased the resilient modulus. However, the deviator stress effect was dependent on the sample and the confining pressure.

Figure 5.42 shows that for Class 5 at low confining pressure, increasing deviator stress had increased the M_R slightly. While at high confining pressures, increasing deviator stress did not affect the M_R. The trend was different for RAP TH 10 and RAP TH 19-101 as presented in Figures 5.43 and 5.44. For those materials, increasing deviator stress has decreased resilient modulus at all confining pressures, which is expected for granular material. The effect of both confining pressure and deviator stress on all tested samples is presented in Appendix F.

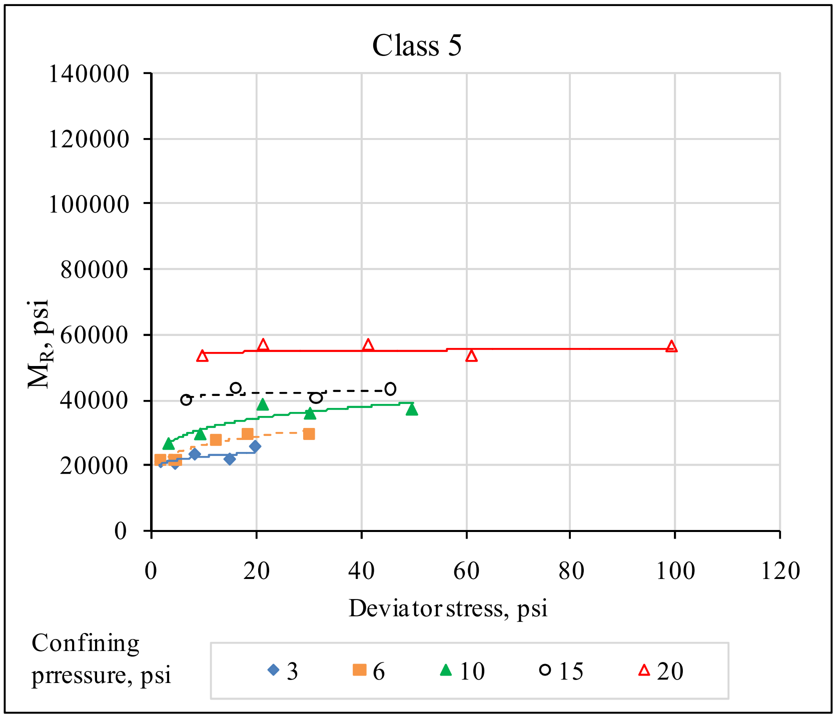


Figure 5.42 M_R vs. deviator stress at different confining pressure for Class 5 (OMC, 100 % MDD)

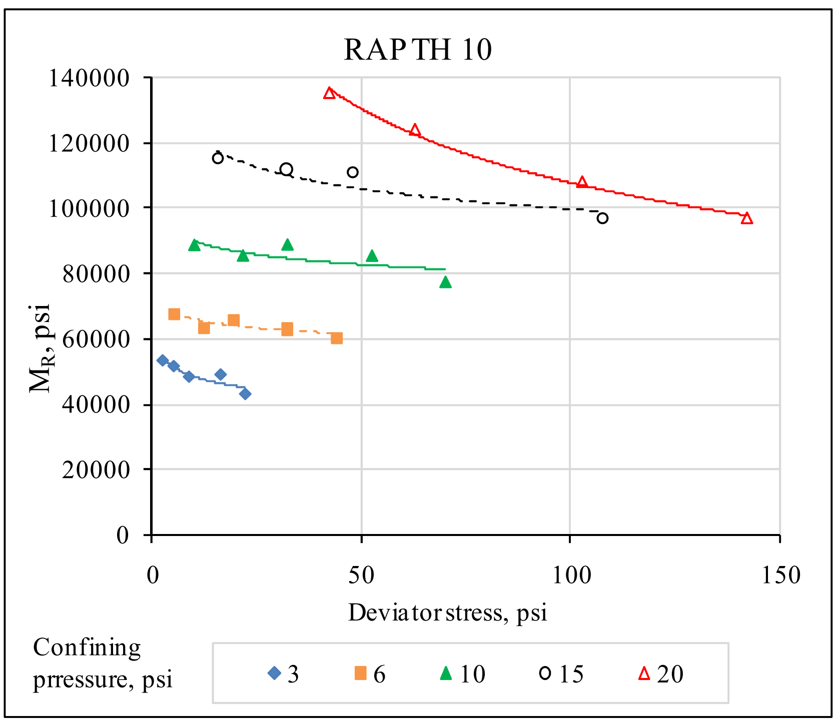


Figure 5.43 M_R vs. deviator stress at different confining pressure for 100% RAP TH 10 (OMC, 100% MDD, replicate)

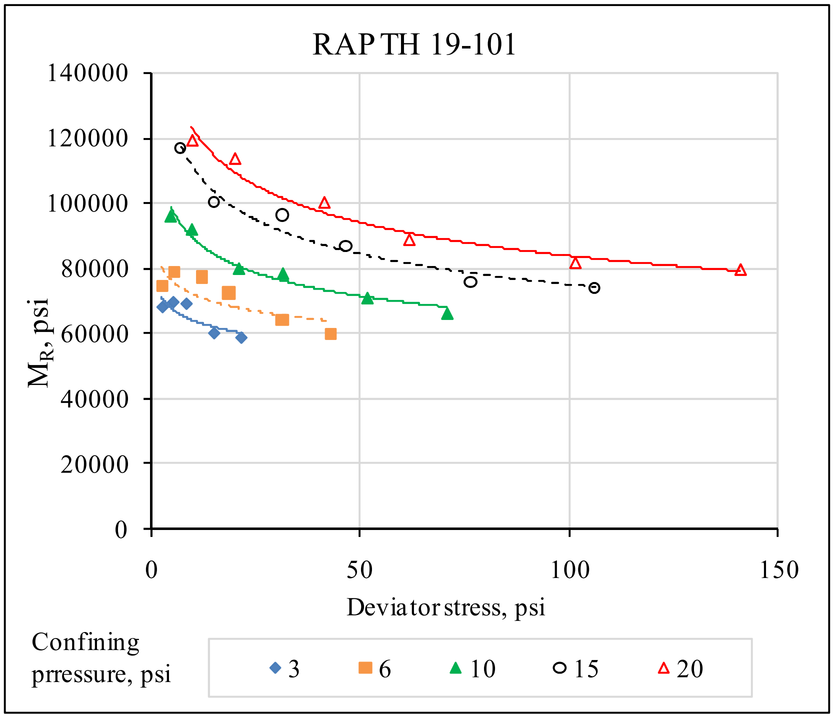


Figure 5.44 M_R vs. deviator stress at different confining pressure for RAP TH 19-101 (OMC, 100% MDD)

Chapter 6

Summary and Conclusion

The use of RAP as a base material can reduce the amount of virgin aggregate needed, reduce construction cost, reduce lane closure time and eliminate disposal issues. Currently Mn/DOT allows the use of RAP as Class 7, which is an aggregate base course containing salvage/recycled aggregate material. This research investigated the effect of RAP on the structural capacity of the base layer, defined by resilient modulus (M_R) and shear strength. The effect of freeze-thaw (F-T) and severe moisture conditions on the structural capacity of RAP material as a base layer was investigated.

Data from testing on RAP material from Mn/ROAD cell 26 was collected. RAP samples were collected from different highways in Minnesota. The investigated material included one source of 100% RAP from Trunk Highway 10 (RAP TH 10), one source of virgin aggregate (Minnesota Class 5), and three Class 7 samples where RAP was mixed with virgin aggregate and is in use as a base layer. RAP TH 10 was blended with the virgin aggregate at 50% and 75% RAP content to investigate the effect of RAP content on the base layer structural capacity.

The collected samples were evaluated in the laboratory starting with aggregate gradation and asphalt extraction. Moisture density relations for the samples were determined using the standard Proctor test and the Superpave gyratory compactor. Aggregate/RAP resistance to abrasion and degradation was evaluated using the Micro-Deval test. The structural capacity of the RAP, as compared to virgin aggregate, was evaluated using the resilient modulus test following the National Cooperative Highway Research Program (NCHRP) 1-28A test protocol. The triaxial shear test was conducted on the resilient modulus samples, for samples compacted at optimum moisture content and maximum dry density, at two confining pressures to evaluate the shear strength of the tested materials. One set of samples was subjected to two freeze-thaw cycles to evaluate the effect of freeze-thaw on resilient modulus and shear strength of RAP as compared to virgin aggregate.

RAP gradation was coarser than virgin aggregate, and fell within Mn/DOT Class 5 gradation limits. RAP had a higher percentage loss in the Micro-Deval test as compared to virgin aggregate. Optimum moisture content (OMC) for RAP/aggregate blends were lower than OMC for Class 5 based on gyratory compactor at 50 gyrations, however the OMC for RAP/aggregate were higher than Class 5 based on the standard Proctor test. The maximum dry densities (MDD) for RAP aggregate blends and field samples were lower than MDD for Class 5. The resilient modulus for all RAP material was higher than that of Class 5. Resilient modulus of RAP material was found to be dependent on the confining pressure. There was no clear loss of the modulus due to freeze-thaw conditioning for the tested RAP. Decreasing the moisture content increased the resilient modulus for RAP material. The effect of dry density on M_R was dependent on the state of stress, material type and moisture content. There was no clear difference in the friction angle and cohesion between RAP/aggregate blends, field samples and Class 5. There was no change in the internal friction angle for RAP due to freeze-thaw conditioning for the tested samples, except for RAP TH 19-101 material. Maximum deviator stress in the shear test was reduced after F-T conditioning for RAP/aggregate blends at a low confining pressure (4 psi) but the effect of F-T on maximum deviator stress was not clear at a higher confining pressure (8 psi).

Based on the findings from this research, RAP is a viable alternative for virgin aggregate as a base layer. RAP gradations fall within the Mn/DOT gradation band. RAP had a higher resilient modulus and equivalent shear strength as compared to virgin aggregate. The effect of freeze-thaw on RAP material was negligible for the tested material for the testing conditions used.

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Appendix A
Index Properties

A.1. Gradation

Table A.1 Summery of Gradation and Asphalt Content

Sieve Size, mm	**Class 5**	**RAP TH 10**	**RAP TH 19 – MM 101**	**RAP TH 19-MM-104**	**RAP TH 22**	**50% RAP TH 10 + 50% Class 5**	**75% RAP TH 10 + 25% Class 5**
50	100	100	100	100	100	100	100
25	100	100	100	100	100	100	100
19	100	100	100	100	100	100	100
12.5	100	100	100	100	100	100	100
9.5	84	69	91	90	84	76.5	72.75
4.75	68	49	78	76	59	58.5	53.75
2.36	60	35	63	62	45	47	42
2	58	32	62	59	40	44	39
1.18	50	18	44	46	32	34	26
0.85	42	14	40	39	22	28	21
0.6	35	11	24	25	15	23	16
0.425	24	7	20	22	11	15.5	11.25
0.3	13	4	9	12	5	9	6.25
0.25	11	2	8	10	4	6.5	4.25
0.15	4.8	1	2.7	3.7	1.3	3	1.95
0.075	2.9	0.4	1.4	2.1	1.3	1.65	1.025
Other properties							
D_{10}	0.24	0.6	0.32	0.25	0.42	0.32	0.4
D_{30}	0.5	2	0.7	0.7	1.1	0.9	1
D_{60}	2.36	9	2	2	4.75	4.75	7
C_u	9.833333	15	6.25	8	11.30952	14.84375	17.5
C_c	0.441	0.74	0.76	0.98	0.61	0.532	0.36
Asphalt Content, %	N/A	4	1.7	2	2.8	1.8	2.36

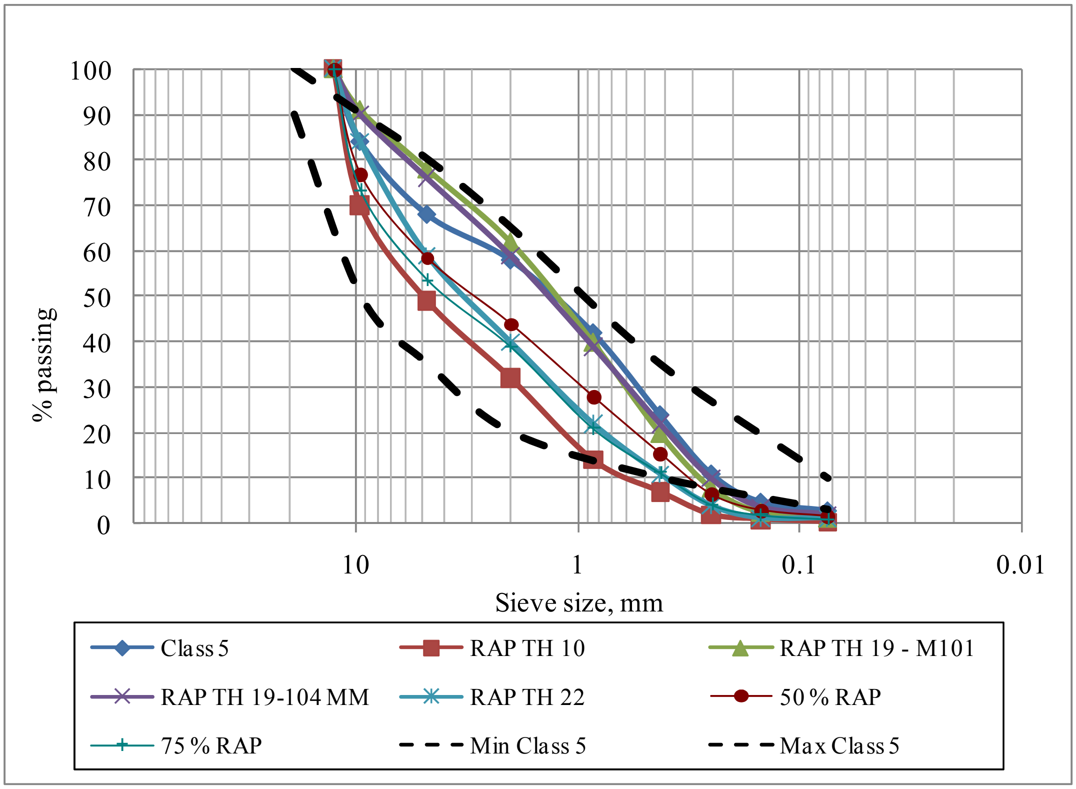

Figure A.1 Aggregate gradation compared to Mn/DOT Class 5 specification

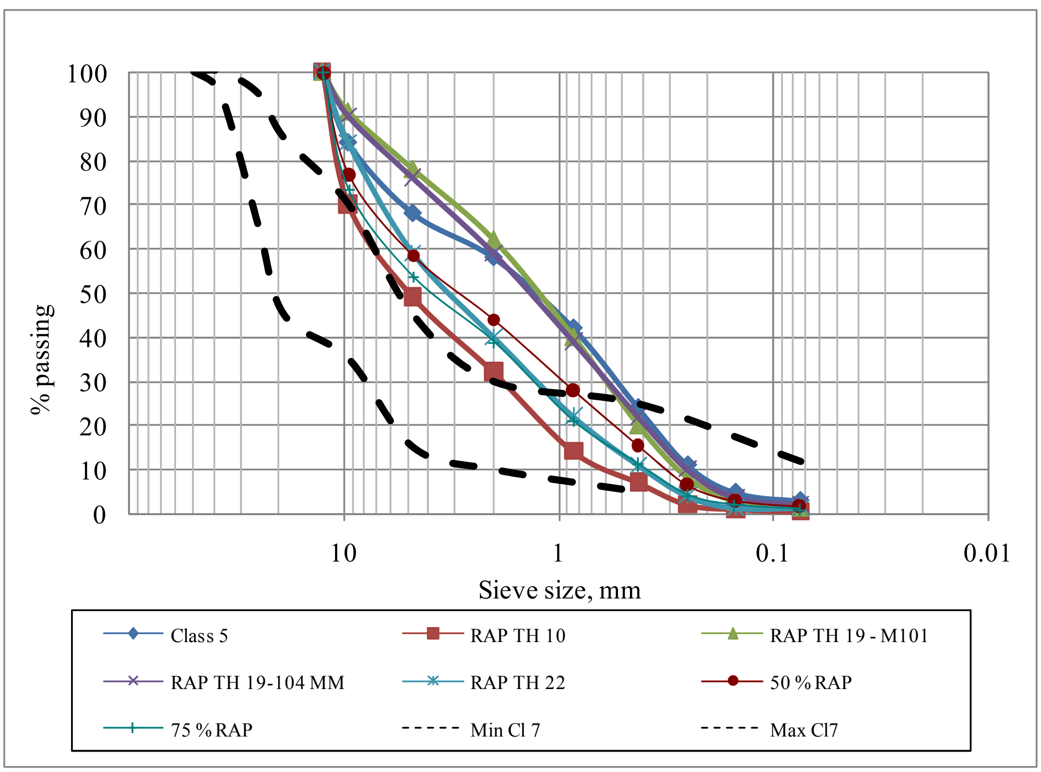

Figure A.2 Aggregate gradation compared to Mn/DOT Class 7 specification

A.2. Moisture Density Relations

Table A.2 Moisture Density Relation for tested material, Part 1

	Gyratory compactor at 50 gyrations		Standard Proctor	
Material	Moisture content	Dry density, pcf	Moisture content	Dry density, pcf
Class 5	1.71	133.03	3.544962948	133.63099
	3.7	134.91	5.126135217	139.90125
	5.67	136.69	6.15261686	142.46967
	6.03	137.354	7.507351669	139.72654
	6.42	138.715		
	6.8	137.86		
	7.53	137.27		
50% RAP TH 10 + 50% Class 5	2.77	129.6	3.375596904	127.16903
	3.6513	134.23	4.613149292	133.97268
	5.19	136.6	5.849722642	136.69238
	6.01	134.36	7.419486343	133.80204
75% RAP TH 10 + 25% Class 5	2.115	127.36	3.123903124	123.38488
	4.062	132	4.532775453	126.95268
	5.24	133.98	5.67710298	132.51671
	5.71	134.83	6.652065081	132.79777
	6.311	133.74		
100% RAP TH 10	3.57	127.04	3.149327672	119.14472
	4.74	129.67	4.366171345	125.93012
	5.45	132.516	5.607850991	130.6108
	6.16	131.218	7.108603667	131.06275
	6.185	128.9		

Table A.3 Moisture Density Relation for tested material, Part 2

	Gyratory compactor at 50 gyrations		Standard Proctor	
Material	Moisture content	Dry density, Lbf	Moisture content	Dry density
RAP TH -19-101	2.27821	115.066	4.709638795	108.6873
	5.0343	116.42	5.954596204	113.51366
	5.9365	124.5431	6.671398155	120.68633
	7.47	123.323	8.563943016	125.96856
	9.11	122.961	13.89769126	112.96501
RAP TH 19-104	3.502129673	124.1667715	5.601948504	117.18483
	5.036968577	126.996817	6.732290385	122.34594
	6.08974359	128.7943797	8.133387556	125.48468
	7.060849598	129.295108	9.702895825	125.11606
	7.735247209	128.3008181		
RAP TH 22	3.9534	126.9	3.4928599	120.89217
	5.1559	132.02	3.780964798	125.80596
	5.2541	133.74	5.81776151	134.80145
	6.4795	132.17	7.571168988	130.8335
	6.7806	131.05		

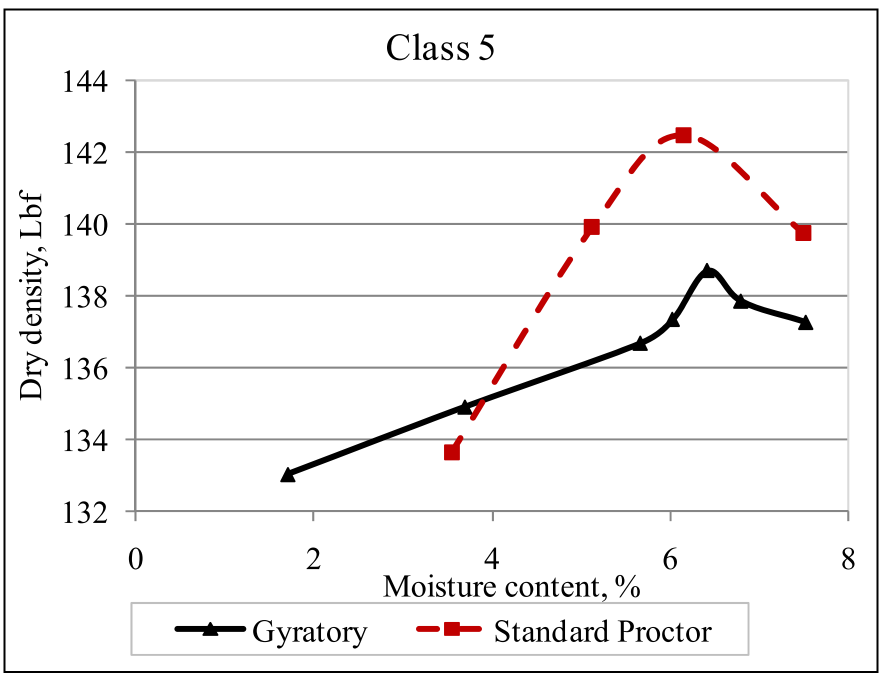

Figure A.3 Moisture density relation for Class 5

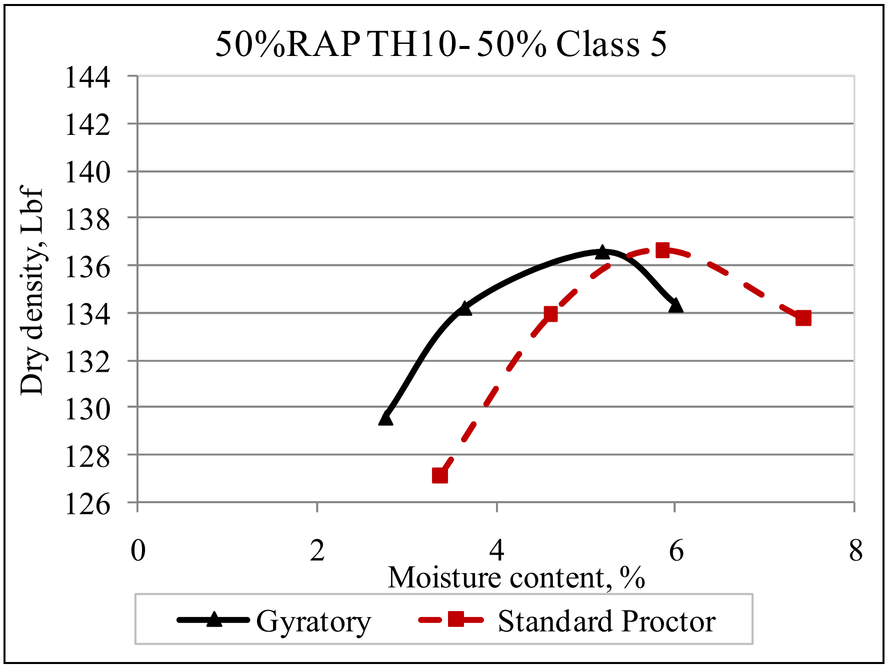

Figure A.4 Moisture density relation for 50% RAP TH-10 + 50% Class 5

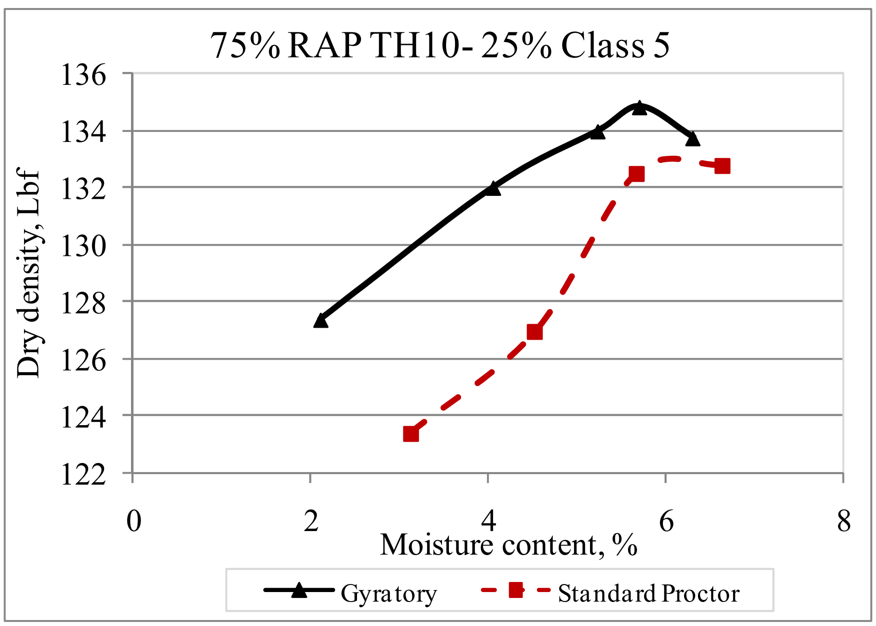

Figure A.5 Moisture density relation for 75% RAP TH-10 + 25% Class 5

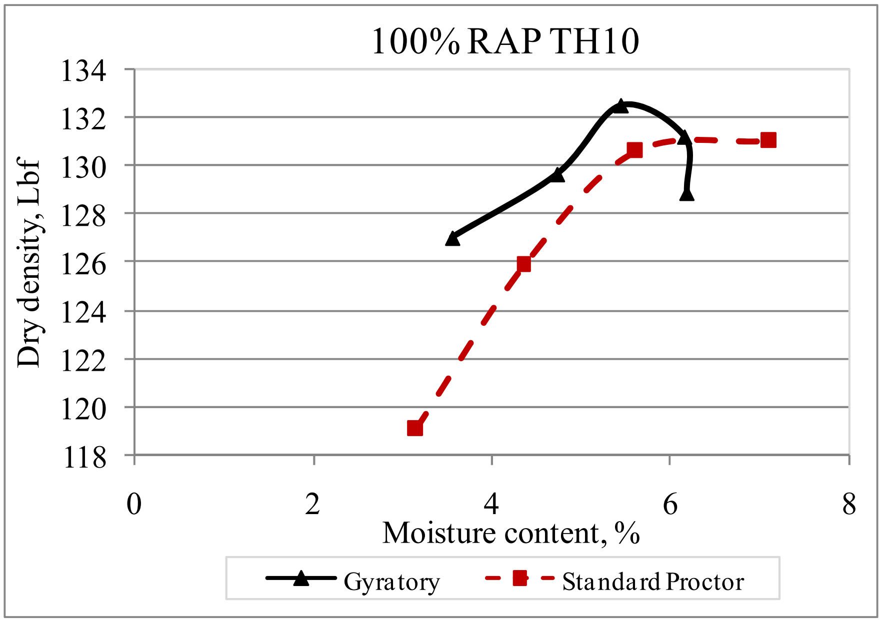

Figure A.6 Moisture density relation for RAP TH-10

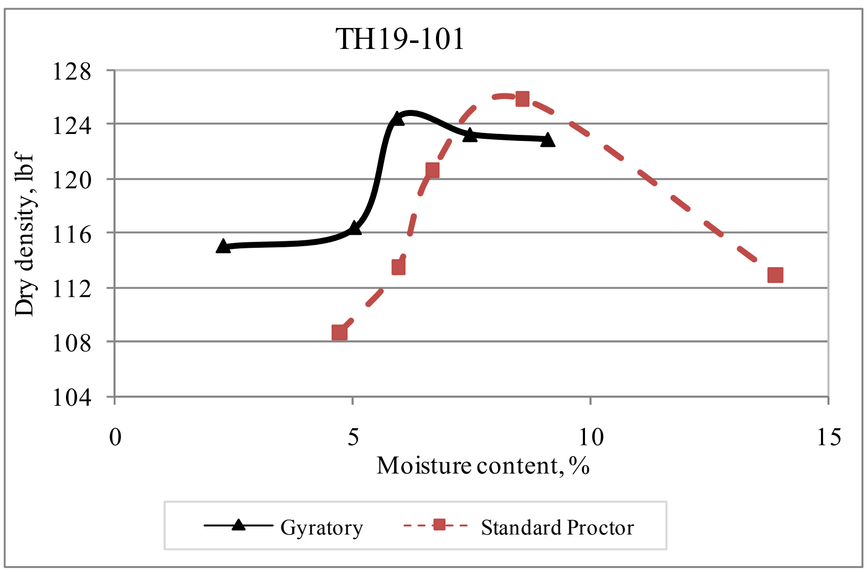

Figure A.7 Moisture density relation for RAP TH 19-MM101

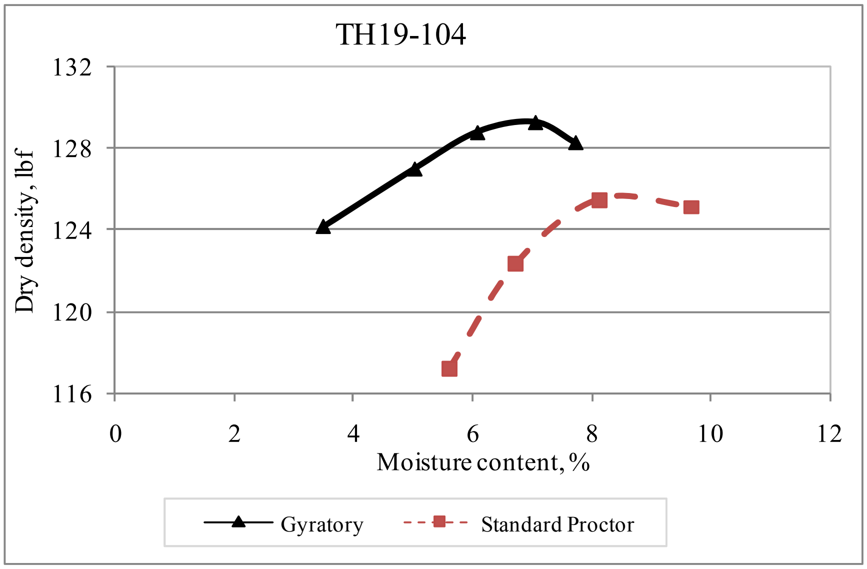

Figure A.8 Moisture density relation for RAP TH 19-MM104

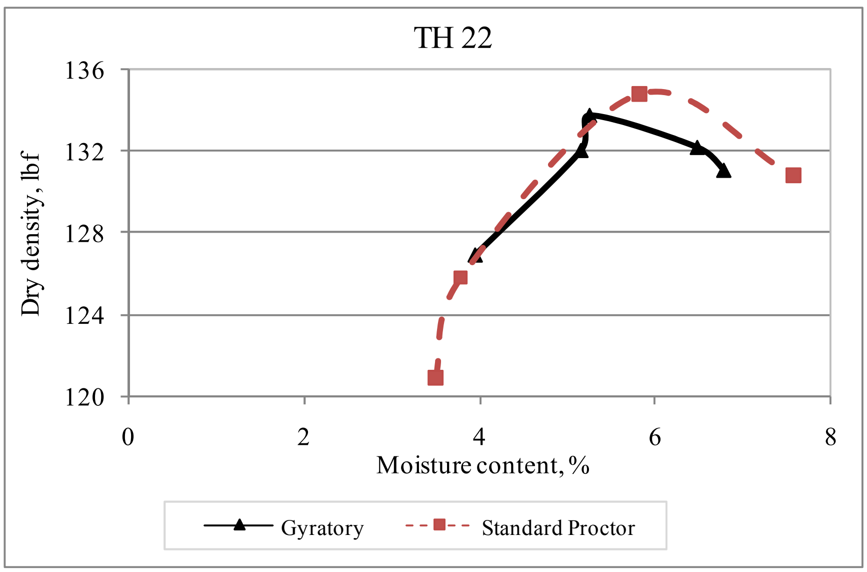

Figure A.9 Moisture density relation for RAP TH 22

Appendix B

Resilient Modulus Equipment Description and Calibration

B.1. Resilient Modulus Testing System Description

- Triaxial pressure chamber: The pressure chamber is used to contain the test specimen and the confining fluid during the test. The triaxial cell used at NDSU is constructed of three-column stainless steel with an external acrylic plastic cell wall, presented in Figure B.1. The cell has 1000 kPa (water) / 250 kPa (air) lateral confining pressure capacity. The cell allows testing a sample of size 6 in diameter *15 in height (The actual sample size used was 6 in diameter * 12 in height).
- Loading device: Electro-Hydraulic testing machine MTS series 312 load frame was used to apply the load, as presented in Figure B.2. It has the capability of applying the required load pulse that is required by the specification.
- Load cell: The load was monitored directly above the sample using electronic load cell located inside the triaxial cell. The load cell capacity is 5000 Lb, with minimum accuracy of ± 2.5 Lbs. The load cell is presented in Figure B.3.
- Axial deformation measuring devices: three on-specimen LVDTs to measure the specimen deformation with range of ± 0.25 in, presented in Figure B.4.
- Data acquisition: A new controller and data acquisition card was purchased from the MTS company. The new system can collect data up to 10,000 points/sec.
- Miscellaneous apparatus:
    - Compaction Split Mold
    - Rubber membranes from 0.25 to 0.79 mm thickness
    - Rubber O-rings
    - Vacuum source
    - 6.4-mm (0.25-in) thick porous stones for (base/subbase)
    - Scales

Figure B.1 Triaxial pressure chamber at NDSU.

Figure B.2 MTS electro-hydraulic loading frame at NDSU.

Figure B.3 5000 Lb electronic load cell at NDSU.

Figure B.4 LVDT (on the right) and LVDT holder (on the left) at NDSU.

B.2. Load Cell Calibration

The load cell was calibrated using proving ring "Humboldt MFG.CO, model H-4454.property of Mn/DOT". Calibration test setup is presented in Figure B.5. Calibration results are presented in Figure B.6. The results showed that the load cell is accurate and its results are equal to the proving ring results and to the MTS external load cell that was calibrated by MTS Inc.

Figure B.5 Load cell calibration setup

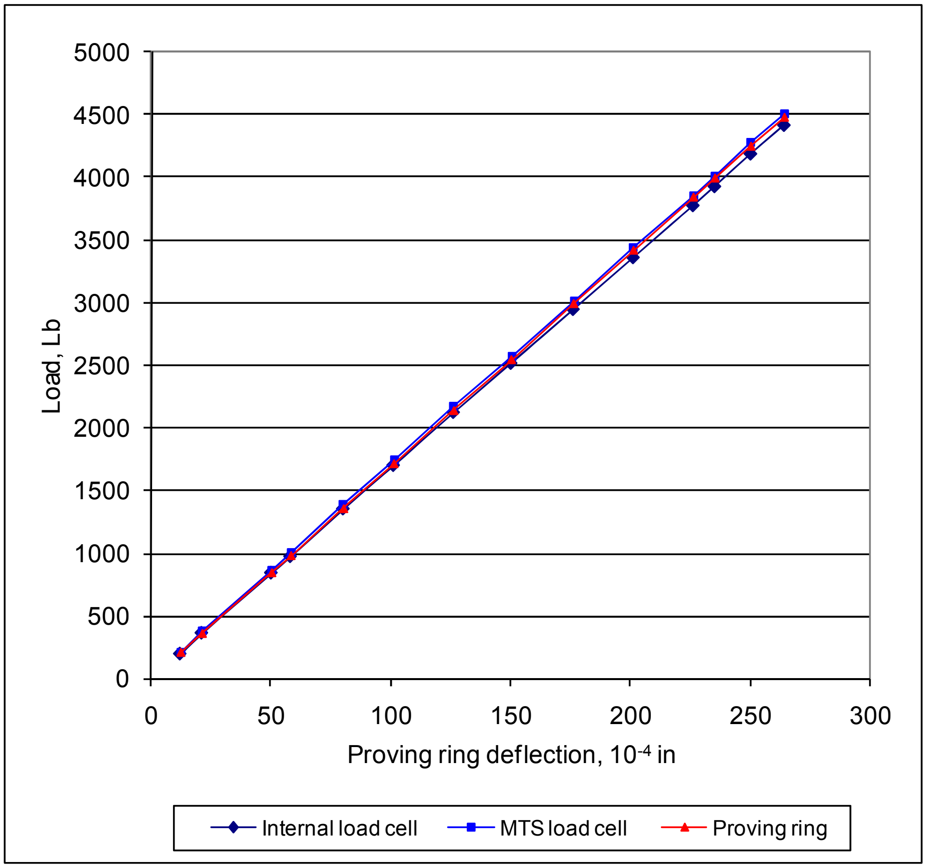

Figure B.6 Load cell calibration results

B.3. System verification with Mn/DOT system

A synthetic rubber specimen (property of the University of Minnesota (U of M)) was used to assure the accuracy of the NDSU resilient modulus testing system compared to the Mn/DOT testing system. Figure B.7 presents the rubber specimen with the LVDTs connected around it. The test was conducted using loads described in NCHRP 1-28A protocol –procedure 1B. Testing results are presented in Table B.1 and Figure B.8. Synthetic rubber sample modulus measured by NDSU was compared to earlier results for the same specimen at Mn/DOT and the U of M. Results are presented in Figure B.9,and they indicate that NDSU resilient modulus testing system produces similar results as those produced by Mn/DOT and the U of M.

Table B.1 Resilient Modulus testing results for Synthetic Rubber Sample

	NDSU Rubber 1			NDSU Rubber 2 (Replicate)	
Confining pressure	Cyclic stress	Resilient modulus		Cyclic stress	Resilient modulus
psi	psi	psi		psi	psi
2	3.151518488	12765.30299		2.976785434	12807.85281
4	2.876490599	13217.22215		2.794926977	13177.93456
6	3.040348605	13039.93688		3.010469975	13228.667
8	2.916998477	12940.81423		2.841306081	13162.03968
12	3.410103186	12581.8229		3.315526882	12662.73192
2	3.104785363	12722.86711		3.006755769	12911.43594
4	3.485804211	12703.73189		3.318118998	12722.18413
6	4.066204845	12334.84461		3.940391349	12383.89679
8	5.186776332	11668.13743		5.210565972	11471.43796
12	8.317891269	9638.367066		8.076549164	9413.340608
2	3.550203683	12569.03213		3.371075998	12550.03944
4	6.123501287	11054.5057		5.946430722	10898.85685
6	9.276327215	9170.16728		9.068168755	9040.503023
8	12.3496585	7833.512518		12.12880629	7683.916802
12	17.98444923	6066.420071		17.5458308	5959.00982
2	4.670229731	11323.71361		4.607523998	11396.72356
4	9.254051021	8789.098547		9.181333611	8767.158413
6	13.75889204	7154.139567		13.53143221	7122.774436
8	18.45316209	6053.299494		18.06222881	5931.55378
12	24.50570548	4997.876935		24.11868383	4955.166403

Figure B.7 Synthetic rubber specimen and LVDTs

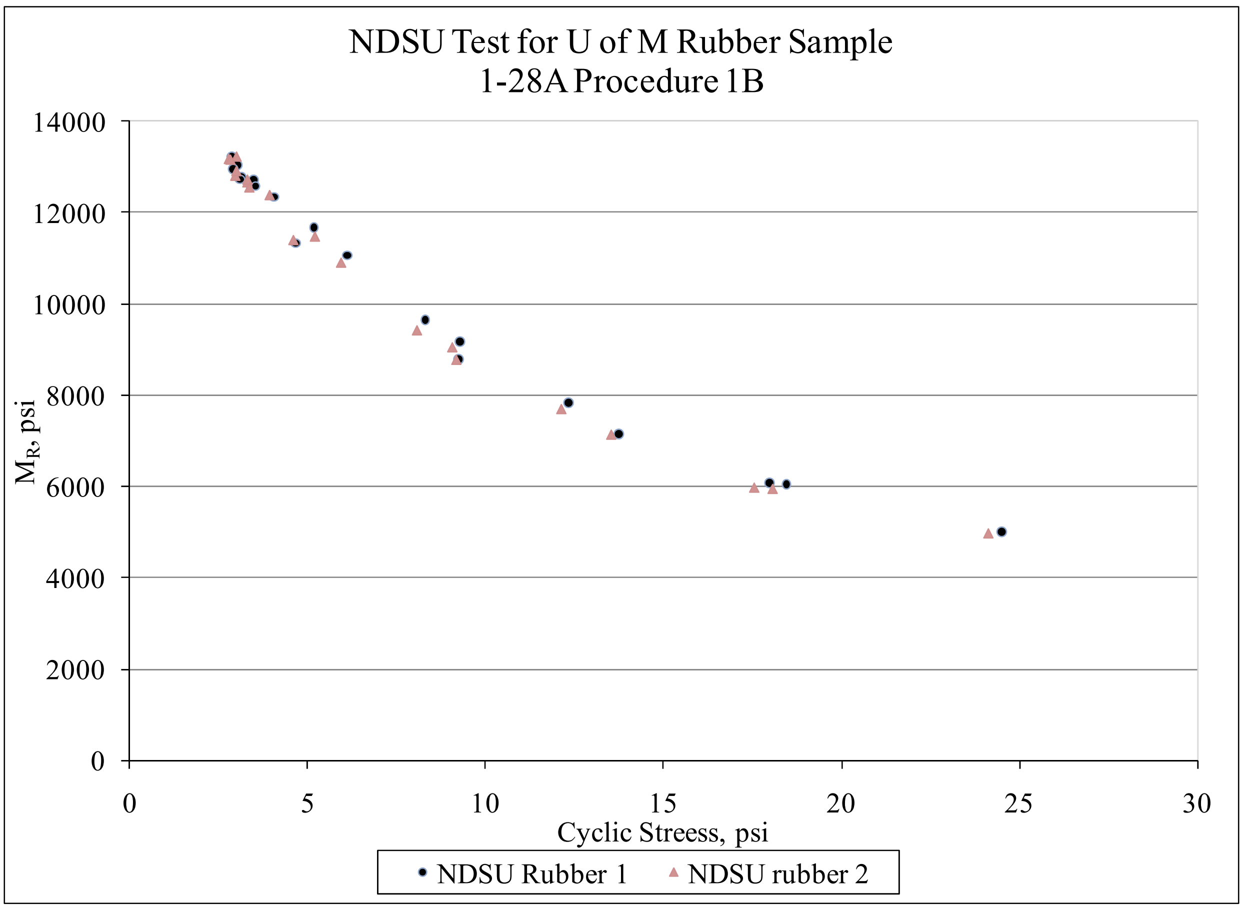

Figure B.8 Resilient modulus testing results for Synthetic Rubber Sample

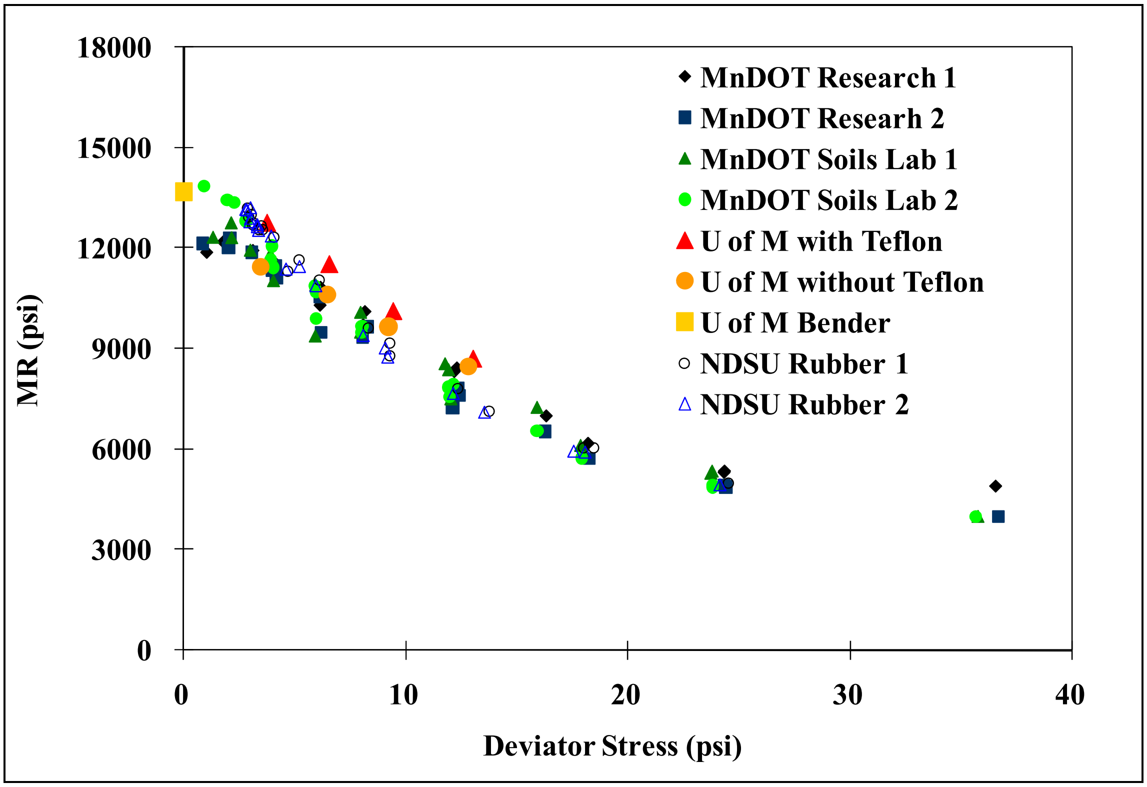

Figure B.9 Comparison between M_R for the Synthetic specimen

Appendix C
Detailed Testing Results

C.1. All Testing Results of Samples Tested at NDSU

Table C.1 List of Tested M_R Samples for Phase 1

Sample ID	Description	Target MC, %	Target Dry Density, Lb/ft^3
C-N-1	100% Class 5, OMC, no freeze	6.4	138.7
C-N- 2	100% Class 5, OMC, No freeze, replicate	6.4	138.7
CNOMC-3	100% Class 5, OMC, No freeze, 2nd replicate	6.4	138.7
C-F-1	100% Class 5, OMC, 2 freeze-thaw cycles	6.4	138.7
C-F-2	100% Class 5, OMC, 2 freeze-thaw cycles, replicate	6.4	138.7
T-N--1	50% Class 5- 50% RAP TH 10, OMC, No freeze	5.2	136.5
T-N-2	50% Class 5- 50% RAP TH 10, OMC, No freeze, replicate	5.2	136.5
T-F-1	50% Class 5- 50% RAP TH 10, OMC, 2 freeze-thaw cycles	5.2	136.5
T-F-2	50% Class 5- 50% RAP TH 10, OMC, 2 freeze-thaw cycles, replicate	5.2	136.5
S-N-1	25% Class 5- 75% RAP TH 10, OMC, No freeze	5.7	134.8
S-N-2	25% Class 5- 75% RAP TH 10, OMC, No freeze, replicate	5.7	134.8
S-F-1	25% Class 5- 75% RAP TH 10, OMC, 2 freeze-thaw cycles	5.7	134.8
S-F-2	25% Class 5- 75% RAP TH 10, OMC, 2 freeze-thaw cycles, replicate	5.7	134.8
R-N-1	100% RAP TH 10, OMC, No freeze	5.5	132.5
R-N-2	100% RAP TH 10, OMC, No freeze, replicate	5.5	132.5
R-F-1	100% RAP TH 10, OMC, 2 freeze-thaw cycles	5.5	132.5
R-F-2	100% RAP TH 10, OMC, 2 freeze-thaw cycles, replicate	5.5	132.5
U-N-1	RAP TH 19-101, OMC, No freeze	5.9	122.5
U-N-2	RAP TH 19-101, OMC, No freeze, replicate	5.9	122.5
U-F-1	RAP TH 19-101, OMC, 2 freeze-thaw cycles	5.9	122.5
U-F-2	RAP TH 19-101, OMC, 2 freeze-thaw cycles, replicate	5.9	122.5
V-N-1	RAP TH 19-104, OMC, No freeze	7	129.3
V-N-2	RAP TH 19-104, OMC, No freeze, replicate	7	129.3
V-F-1	RAP TH 19-104, OMC, 2 freeze-thaw cycles	7	129.3
V-F-2	RAP TH 19-104, OMC, 2 freeze-thaw cycles, replicate	7	129.3
W-N-1	RAP TH 22, OMC, No freeze	5.25	133.74
W-N-2	RAP TH 22, OMC, No freeze, replicate	5.25	133.74
W-F-1	RAP TH 22, OMC, 2 freeze-thaw cycles	5.25	133.74
W-F-2	RAP TH 22, OMC, 2 freeze-thaw cycles, replicate	5.25	133.74

MC= Moisture content

Table C.2 List of Tested Samples for Phase 2

Sample ID	Description	Target MC, %	Target Dry Density, Lb/ft^3
C-N-3	100% Class 5, OMC + 1%, No freeze	7.4	138.7
C-N-4	100% Class 5, OMC + 2%, No freeze	8.4	138.7
C-F- 4	100% Class 5, OMC + 2%, 2 freeze-thaw cycles	8.4	138.7
T-N- 3	50% Class 5- 50% RAP TH 10, OMC + 1%, No freeze	6.2	136.5
T-N- 4	50% Class 5- 50% RAP TH 10, OMC + 2%, No freeze	7.2	136.5
T-F- 3	50% Class 5- 50% RAP TH 10, OMC + 1%, 2 freeze-thaw cycles	6.2	136.5
T-F- 4	50% Class 5- 50% RAP TH 10, OMC + 2%, 2 freeze-thaw cycles, replicate	7.2	136.5
S-N- 3	25% Class 5- 75% RAP TH 10, OMC + 1%, No freeze	6.7	134.8
S-N-4	25% Class 5- 75% RAP TH 10, OMC + 2%, No freeze	7.7	134.8
S-F-4	25% Class 5- 75% RAP TH 10, OMC + 2%, 2 freeze-thaw cycles, replicate	7.7	134.8
R-N- 3	100% RAP TH 10, OMC + 1%, No freeze	6.5	132.5
R-N-4	100% RAP TH 10, OMC + 2%, No freeze, replicate	7.5	132.5
R-F- 3	100% RAP TH 10, OMC + 1%, 2 freeze-thaw cycles	6.5	132.5
R-F- 4	100% RAP TH 10, OMC + 2%, 2 freeze-thaw cycles, replicate	7.5	132.5
U-N- 4	RAP TH 19-101, OMC + 2%, No freeze, replicate	7.9	122.5
V-N- 4	RAP TH 19-104, OMC + 2%, No freeze	9	129.3
V-F- 4	RAP TH 19-104, OMC + 2%, 2 freeze-thaw cycles	9	129.3
W-N- 4	RAP TH 22, OMC + 2%, No freeze	7.25	133.74
W-F-2	RAP TH 22, OMC + 2%, 2 freeze-thaw cycles, replicate	7.25	133.74

MC= Moisture content

Table C.3 Moisture Content Control for Phase 1

Sample ID	Description	Target MC, %	MC of sample before test, %	Δ MC, %
C-N-1	100% Class 5, OMC, no freeze	6.4	6.4	0
C-N-2	100% Class 5, OMC, no freeze, replicate	6.4	6.4	0
CNOMC-3	100% Class 5, OMC, no freeze, 2nd replicate	6.4	6.5	0.1
C-F-1	100% Class 5, OMC, 2 freeze-thaw cycles	6.4	6.4	0
C-F-2	100% Class 5, OMC, 2 freeze-thaw cycles, replicate	6.4	6.57	0.17
T-N-1	50% Class 5- 50% RAP TH 10, OMC, no freeze	5.2	5.15	-0.05
T-N-2	50% Class 5- 50 RAP TH 10, OMC, no freeze, replicate	5.2	4.87	-0.33
T-F-1	50% Class 5- 50% RAP TH 10, OMC, 2 freeze-thaw cycles	5.2	5.25	-0.05
T-F-2	50% Class 5- 50% RAP TH 10, OMC, 2 freeze-thaw cycles, replicate	5.2	5.22	0.02
S-N-1	25% Class 5- 75% RAP TH 10, OMC, no freeze	5.7	5.4	-0.3
S-N-2	25% Class 5- 75% RAP TH 10, OMC, no freeze, replicate	5.7	5.93	0.23
S-F-1	25% Class 5- 75% RAP TH 10, OMC, 2 freeze-thaw cycles	5.7	5.75	0
S-F-2	25% Class 5- 75% RAP TH 10, OMC, 2 freeze-thaw cycles, replicate	5.7	5.75	0
R-N-1	100% RAP TH 10, OMC, No freeze	5.5	5.4	0.1
R-N-2	100% RAP TH 10, OMC, No freeze, replicate	5.5	5.1	-0.4
R-F-1	100% RAP TH 10, OMC, 2 freeze-thaw cycles	5.5	5.42	-.08
R-F-2	100% RAP TH 10, OMC, 2 freeze-thaw cycles, replicate	5.5	5.5	0
U-N-1	RAP TH 19-101, OMC, no freeze	5.9	6.3	0.4
U-N-2	RAP TH 19-101, OMC, no freeze, replicate	5.9	6.08	0.18
U-F-1	RAP TH 19-101, OMC, 2 freeze-thaw cycles	5.9	5.8	-0.1
U-F-2	RAP TH 19-101, OMC, 2 freeze-thaw cycles, replicate	5.9	6.0	0.1
V-N-1	RAP TH 19-104, OMC, no freeze	7	7.1	0.1
V-N-2	RAP TH 19-104, OMC, no freeze, replicate	7	6.7	-0.30
V-F-1	RAP TH 19-104, OMC, 2 freeze-thaw cycles	7	6.6	-0.4
V-F-2	RAP TH 19-104, OMC, 2 freeze-thaw cycles, replicate	7	6.7	-0.30
W-N-1	RAP TH 22, OMC, no freeze	5.25	5.5	0.25
W-N-2	RAP TH 22, OMC, no freeze, replicate	5.25	5.45	0.20
W-F-1	RAP TH 22, OMC, 2 freeze-thaw cycles	5.25	5.5	0.25
W-F-2	RAP TH 22, OMC, 2 freeze-thaw cycles, replicate	5.25	5.45	0.20

MC= Moisture content

Table C.4 Moisture Content Control for Phase 2

Sample ID	Description	Target MC, %	MC of sample before test, %	Δ MC, %
C-N-3	100% Class 5, OMC + 1%, no freeze	7.4	7.4	0
C-N-4	100% Class 5, OMC + 2%, no freeze	8.4	8.65	0.25
C-F- 4	100% Class 5, OMC + 2%, 2 freeze-thaw cycles	8.4	8.3	-0.1
T-N- 3	50% Class 5- 50% RAP TH 10, OMC +1%, no freeze	6.2	5.95	-0.25
T-N- 4	50% Class 5- 50% RAP TH 10, OMC + 2%, no freeze	7.2	7	-0.20
T-F- 3	50% Class 5- 50% RAP TH 10, OMC + 1%, 2 freeze-thaw cycles	6.2	5.95	-0.25
T-F- 4	50% Class 5- 50% RAP TH 10, OMC + 2%, 2 freeze-thaw cycles, replicate	7.2	7.35	0.15
S-N- 3	25% Class 5- 75% RAP TH 10, OMC + 1%, no freeze	6.7	6.5	-0.20
S-N-4	25% Class 5- 75% RAP TH 10, OMC + 2%, no freeze	7.7	7.64	-0.06
S-F-4	25% Class 5- 75% RAP TH 10, OMC + 2%, 2 freeze-thaw cycles, replicate	7.7	7.84	0.14
R-N- 3	100% RAP TH 10, OMC + 1%, No freeze	6.5	6.3	-0.20
R-N-4	100% RAP TH 10, OMC + 2%, No freeze, replicate	7.5	7.5	0
R-F- 3	100% RAP TH 10, OMC + 1%, 2 freeze-thaw cycles	6.5	6.36	-0.14
R-F- 4	100% RAP TH 10, OMC + 2%, 2 freeze-thaw cycles, replicate	7.5	7.4	-0.10
U-N- 4	RAP TH 19-101, OMC+2%, No freeze, replicate	7.9	8.4	0.50
U-N-OMC-97MDD	RAP TH 19-101, OMC, no freeze, replicate	5.9	6	0.1
V-N- 4	RAP TH 19-104, OMC+2%, no freeze	9	9.5	0.50
V-F- 4	RAP TH 19-104, OMC+2%, 2 freeze-thaw cycles	9	9.4	0.40
W-N- 4	RAP TH 22, OMC+2%, no freeze	7.25	7.1	-0.15
W-F-4	RAP TH 22, OMC+2%, 2 freeze-thaw cycles, replicate	7.25	7.50	0.25

MC= Moisture content

Table C.5 Specimen Compaction Control for Phase 1

Sample ID	# of gyrations top	# of gyrations bottom	Total Sample height, mm	ADD, lbf	ADD/MDD, %
C-N-1	57	46	293.14	139.27	100.34
C-N-2	49	47	293.4	139.25	100.33
C-F-1	55	59	293.4	139.6	100.6
C-F-2	69	77	293.05	138.9	100.1
T-N-1	73	66	301.7	136.88	100.27
T-N-2	61	48	303.3	136.2	99.8
T-F-1	45	40	301.4	136.7	100.16
T-F-2	48	50	301.46	136.8	100.2
S-N-1	40	35	305.1	135.1	100.2
S-N-2	51	55	302.7	135.3	100.4
S-F-1	54	57	303.4	135.3	100.3
S-F-2	42	35	303.4	135.2	100.3
R-N-1	140	136	305	132.34	99.88
R-N-2	115	101	304.4	132.5	100
R-F-1	50	45	302.2	132.56	100.05
R-F-2	59	58	305.2	132.55	100
U-N-1	120	97	305.2	123.5	100.8
U-N-2	104	130	293.6	123.09	100.5
U-F-1	150	150	311.4	121.8	99.4
U-F-2	150	150	314.3	121.44	99.4
V-N-1	134	96	305.1	129.9	100.47
V-N-2	83	83	306	129.96	100.5
V-F-1	120	50	307	129.56	100.2
V-F-2	50	50	306.5	129.62	100.25
W-N-1	119	81	306.75	134.16	100.31
W-N-2	102	98	306.96	134.25	100.38
W-F-1	66	66	305.2	133.83	100.06
W-F-2	73	67	305.4	133.93	100.14

ADD = Average dry density
MDD= Maximum dry density

Table C.6 Specimen Compaction Control for Phase 2

Sample ID	# of gyrations top	# of gyrations bottom	Total Sample height, mm	ADD, lbf	ADD/MDD, %
C-N-3	150	150	299.74	137.6	99.11
C-N-4	150	150	301.8	134.8	97.12
C-F- 4	150	150	297	136.7	98.5
T-N- 3	150	50	305	136.9	100.29
T-N- 4	150	150	304.95	134.4	98.46
T-F- 3	57	40	302.2	136.6	100.1
T-F- 4	150	150	312	133.6	97.9
S-N- 3	150	150	306.2	131.6	97.63
S-N-4	150	150	307.7	130.45	96.77
S-F-4	150	150	306.4	130.65	96.92
R-N- 3	64	69	323.4	131.9	99.56
R-N-4	150	150	306.9	129.2	97.5
R-F- 3	82	130	302.2	132.4	99.92
R-F- 4	150	150	308	129.6	97.8
U-N- 4	150	150	307.4	123.8	101
U-N-OMC-97MDD	150	150	319.5	119.46	97.5
V-N- 4	150	150	312.6	124.48	96.27
V-F- 4	150*	150*	307.1	125	96.7
W-N- 4	150	150	306.9	131.2	98.1
W-F-4	150*	150*	303	130.9	97.9

*Gyratory pressure = 700 KPa

Table C.7 M_R Results for Class 5 (OMC, 100% MDD), One Sample and a Replicate

C-N-1					C-N-2			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi		Sequence	Confining Pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1	3				1	3.00	0.86	12795.78
2	6.5	1.79	21478.21		2	6.40	2.16	16543.45
3	10.2	3.45	26540.21		3	10.20	4.08	24725.27
4	15.2	6.77	40193.62		4	15.10	7.03	35272.46
5	20.1	9.99	53293.35		5	20.20	10.51	47584.96
6	3.4	1.78	20917.25		6	3.60	1.95	13330.21
7	6.6	4.54	21415.60		7	6.40	4.83	18304.00
8	10.3	9.49	29453.41		8	10.30	10.12	26970.35
9	15.3	16.17	43740.17		9	15.50	16.24	40631.08
10	20.2	21.59	56721.10		10	20.20	22.11	53457.96
11	3.7	4.54	20384.56		11	3.60	4.69	14577.18
12	6.7	12.38	27482.79		12	6.30	12.85	22616.01
13	10.1	21.41	38508.64		13	10.60	22.52	35086.19
14	15.2	31.39	40892.25		14	15.20	32.91	48101.76
15	20	41.61	56708.29		15	20.10	43.47	59437.09
16	3.3	8.26	23153.69		16	3.60	8.69	16752.59
17	6.3	18.46	29446.66		17	6.40	19.74	26707.03
18	10.5	30.46	35776.83		18	10.30	32.65	39511.40
19	15.3	45.55	43456.50		19	15.10	48.44	49733.62
20	20.1	61.30	53283.92		20	20.30	63.53	55450.46
21	3.5	14.91	21668.44		21	2.70	15.90	19749.64
22	6.3	30.00	29551.32		22	6.40	31.85	30271.05
23	10.2	49.89	36962.79		23	10.30	52.05	37345.69
24	15.2				24	15.2		
25	20.1	99.44	56211.38		25	20.4	102.4817	50449.77
26	3.8	19.76	25466.50		26	3.7	20.94403	19946.56
27	6.3				27	6.8	43.05084	30342.93
28	10.4				28	10.2	71.1862	38558.7
29	15.3				29	15.3		
30					30	20.2	140.7208	49341.07

Table C.8 M_R Results for Class 5 (OMC, 100% MDD, 2nd replicate)

C-N-OMC-3			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1	3	0.72	17371.41
2	6	1.71	19097.48
3	10	3.59	26425.84
4	15	7.13	41548.48
5	20	10.50	55568.96
6	3	1.58	17494.52
7	6	4.55	20093.78
8	10	9.88	30025.83
9	15	16.16	45653.85
10	20	21.78	60255.97
11	3	4.55	18816.47
12	6	11.76	26471.01
13	10	21.40	39375.87
14	15	31.86	50079.05
15	20	42.53	60902.76
16	2.5	8.13	19891.56
17	6	18.12	28541.63
18	10	31.04	37865.59
19	15	46.56	50315.96
20	20	62.00	56100.64
21	3	14.14	23657.20
22	6	29.68	29103.08
23	10	49.86	36389.96
24	15	75.09	45046.13
25	20	100.68	49694.03

Note: Table C.1 contains detailed sample description

Table C.9 M_R Results for Class 5 (OMC, 100% MDD, Freeze-Thaw Conditioned), One Sample and a Replicate

C-F-1				C-F-2			
Sequence	Confining Pressure, psi	Cyclic stress, psi	Resilient modulus, psi	Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1	3.2	0.92	18888.52	1	3.30	0.86	19130.78
2	6	2.25	23443.39	2	6.10	2.13	21329.83
3	10.5	4.11	33046.29	3	10.10	4.19	32473.30
4	15.1	6.80	46985.02	4	14.90	7.15	44662.86
5	20.1	10.02	62543.91	5	20.10	10.72	61291.10
6	3.2	1.86	16631.78	6	3.00	1.82	16672.73
7	6.1	4.72	24634.13	7	6.70	4.93	23800.38
8	10.2	10.07	36453.70	8	10.10	10.30	34338.74
9	15.4	16.08	50600.25	9	15.10	17.12	52025.09
10	20.2	22.17	66432.33	10	20.20	23.01	67398.84
11	3.2	4.43	17033.53	11	3.20	4.62	17122.76
12	6	12.87	26186.03	12	6.00	13.25	27607.77
13	10	22.40	40372.19	13	9.80	23.04	41711.35
14	15.2	32.49	53544.10	14	15.20	33.50	54862.44
15	20.1	42.25	71361.36	15	20.00	43.62	70381.19
16	3.2	8.35	19653.31	16	3.00	8.66	19384.40
17	6	19.34	30430.71	17	6.00	20.03	31618.62
18	10.2	32.11	46549.80	18	9.50	32.87	45077.36
19	15	46.95	60000.22	19	15.30	48.30	59834.08
20	20	62.06	68801.00	20	20.00	63.61	71330.97
21	3.1	15.49	21627.60	21	3.00	15.92	24961.33
22	6.1	31.32	33769.80	22	6.00	31.97	38527.37
23	10.1	51.30	43997.75	23	10.00	52.14	46064.37
24	15.1	76.69	55172.23	24	15.00	77.35	55828.40
25	20.2	101.70	68454.03	25	20	103.24	69556.63
26	3.4	20.72	22863.37	26	3	20.98	24605.09
27	6			27	5	43.21	
28	10.2			28	10	70.80	
29	15.2			29	15	106.11	
30	20.1			30	20.1	141.51	

Table C.10 M_R Results for Class 5 (OMC + 1%, OMC + 2%)

C-N-3			
OMC +1%, 99% MDD			
Sequence	Confining Pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1	3		
2	6	1.49	10847.82
3	10	3.46	17506.31
4	15.3	6.83	26396.89
5	20	10.28	35911.66
6	3	1.37	10509.54
7	6	4.17	12265.20
8	10	9.23	18727.58
9	15	15.65	29432.31
10	20.2	21.67	40046.03
11	3	4.03	11282.69
12	5.9	10.67	15295.73
13	10	20.44	24265.32
14	15	30.98	34320.05
15	20.1	41.73	43210.69
16	3	7.35	13639.28
17	5.9	16.50	17493.30
18	10	29.48	25368.52
19	15	45.07	32176.87
20	20	61.06	40811.03
21	3	12.78	15562.33
22	6	27.71	20108.16
23	10	47.62	25258.63
24	15	72.85	34128.56
25	20	98.71	38351.77
26	3	18.18	16462.56
27	6	39.169686	19219.17

C-N-4			
OMC +2%, 97% MDD			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1			
2	0.7	1.26	18381.49
3	10	3.00	25377.06
4	15	6.39	37510.94
5	20.1	9.59	52901.02
6	3	1.14	18725.71
7	6	3.71	16104.31
8	10	8.76	24869.88
9	15	14.50	41065.99
10	20	20.01	51724.00
11	2.9	3.60	15678.78
12	6	9.93	18928.04
13	9.9	18.80	28421.29
14	15	29.13	37798.41
15	20	40.14	38932.24
16	3	6.78	12097.78
17	6	15.16	16516.66
18	10	27.55	23030.48
19	15	43.31	28567.45
20	20	59.53	35808.33
21	3	11.76	14022.66
22	6	25.45	18059.18
23	10		
24	15		

Table C.11 M_R Results for Class 5 (OMC + 2%, Freeze-Thaw Conditioned)

C-F-4				
MDD, OMC+2%				
Sequence	Confining Pressure, psi	Cyclic stress, psi	Bulk stress, Psi	Resilient modulus, psi
1.00				
2.00				
3.00	10.00	3.58	33.58	26384.55
4.00	15.00	6.98	51.98	37148.48
5.00	20.00	10.35	70.35	48929.27
6.00				
7.00	5.90	4.43	22.13	18666.63
8.00	10.20	9.63	40.23	29344.84
9.00	15.00	15.81	60.81	41143.29
10.00	20.00	21.52	81.52	50358.13
11.00	3.00	4.34	13.34	15953.97
12.00	6.00	11.53	29.53	24465.43
13.00	10.00	21.15	51.15	33893.53
14.00	15.00	31.67	76.67	43465.22
15.00	20.00	42.05	102.05	51066.44
16.00	3.00	7.71	16.71	18365.39
17.00	6.00	17.85	35.85	25850.98
18.00	10.00	30.68	60.68	34742.26
19.00	15.00	45.64	90.64	43629.17
20.00	20.00	61.28	121.28	50128.83
21.00	3.00	13.72	22.72	21649.44
22.00	6.00	29.32	47.32	30110.21
23.00	10.00	48.06	78.06	33839.13
24.00	15.00	72.28	117.28	37677.94

Table C.12 M_R Results for 50% Class 5 + 50% RAP TH 10 (OMC, 100% MDD), One Sample and a Replicate

T-N-1				T-N-2			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi	Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1				1			
2	6	2.36	35579.50	2	6.00	2.59	52141.50
3	9.8	4.34	49048.06	3	10.00	4.59	68042.80
4	14.8	7.08	68787.95	4	15.00	7.22	90818.95
5	19.7	10.22	84772.14	5	20.00	10.00	107198.27
6	3.4	2.13	26266.05	6	2.30	2.29	39958.36
7	5.9	4.88	35238.38	7	6.00	5.16	49076.84
8	10	10.09	49533.48	8	10.00	10.09	61454.79
9	14.8	15.71	68691.95	9	15.10	16.01	81234.79
10	19.7	21.51	85018.18	10	20.00	21.70	102899.06
11	3.6	4.79	27112.71	11	3.10	4.87	35374.48
12	6	12.45	37786.95	12	6.00	12.49	44905.66
13	10	22.53	57231.08	13	10.00	22.84	63854.27
14	15	32.86	69768.91	14	15.10	33.23	84250.31
15	19.9	43.02	84725.94	15	20.00	43.29	96720.74
16	3.2	8.64	27698.35	16	3.00	8.69	32298.97
17	5.9	19.83	41012.31	17	6.00	20.30	46678.18
18	10	32.59	57658.95	18	10.20	32.95	64765.63
19	15	47.88	70051.89	19	15.00	48.20	79386.21
20	20	62.87	78222.17	20	20.00	63.39	89222.86
21	3.2	16.23	29367.95	21	3.00	16.60	33776.32
22	5.9	32.11	42826.49	22	5.50	32.40	46345.83
23	10	52.45	53602.21	23	10.00	52.87	64376.18
24	15	77.21	63929.44	24	15.00	77.71	74585.94
25	20	102.09	71831.56	25	20.00	102.84	85183.46
26	3	22.15	29568.29	26	3.00	22.23	32067.20
27	6	44.20	42636.56	27	5.70	44.41	48240.72
28	10	72.02	53398.23	28	10.30	72.63	68468.99
29	15	105.66147	53524.36	29	15.10	107.13	73549.99
30				30	20.00	141.45	71099.69

Table C.13 M_R Results for 50% Class 5 + 50% RAP TH 10 (OMC + 1% and OMC + 2%)

T-N- 3				T-N-4			
OMC +1%, 100% MDD				OMC +2%, 98.5% MDD			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi	Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1	3	0.98	35775.87	1	3.2	0.87	24643.27
2	6	2.19	37153.94	2	6	1.92	25877.70
3	10	4.22	47393.71	3	10.1	3.66	32553.76
4	14.9	7.23	64333.79	4	15	6.77	44620.84
5	20	10.43	82843.84	5	20	10.14	56240.07
6	3	2.05	31343.13	6	3	1.86	23187.57
7	6	4.85	31684.22	7	6	4.53	28642.51
8	9.9	10.14	42262.90	8	10	9.68	36288.44
9	15	15.78	61952.13	9	15	16.25	48165.84
10	20	21.76	78287.76	10	20	21.48	59462.47
11	3.2	5.00	30053.75	11	3.1	4.61	25555.43
12	6	12.67	36759.24	12	6	12.31	32677.57
13	10	22.01	48350.90	13	10	21.43	41459.82
14	15	32.23	57306.93	14	15	31.43	49186.69
15	20	42.49	72027.93	15	20.3	41.54	57089.75
16	3	8.73	28120.64	16	3.21	8.22	27831.62
17	6.2	19.40	36874.84	17	6	18.28	32514.81
18	10	32.09	49928.93	18	10	30.59	39114.68
19	15	47.18	58111.45	19	15	45.58	46122.16
20	19.5	62.16	66290.28	20	19.8	60.68	48963.91
21	3	15.75	28778.33	21	3	14.90	26495.37
22	6	31.43	36368.18	22	6	29.94	33237.53
23	10.2	51.30	42234.38	23	10	49.03	41198.42
24	15	75.86	44849.96	24	15		
25	20	100.72	48912.33	25			
26	2	21.40	23137.49	26			
27	6	43.37	30793.40	27			
28	10	70.96	37188.68	28			

Table C.14 M_R Results for 50% Class 5 + 50% RAP TH 10 (OMC, 100% MDD, Freeze-Thaw Conditioned), One Sample and a Replicate

T-F-1				T-F-2			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi	Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1	3	1.16	33328.52	1	3.00	1.01	38705.65
2	6.5	2.64	45713.90	2	6.00	2.33	49464.89
3	10	4.62	58301.57	3	10.00	4.13	61944.06
4	15.1	7.22	77971.29	4	15.10	6.70	77588.46
5	20	10.32	97154.43	5	21.00	9.45	94642.94
6	3.3	2.41	35216.76	6	3.00	2.09	37172.24
7	6	5.26	44293.64	7	5.80	4.62	44531.66
8	9.9	10.08	56458.73	8	10.00	9.34	57795.63
9	15.2	15.77	79591.44	9	15.00	14.90	76604.11
10	20.1	20.81	98694.32	10	20.10	20.32	98193.82
11	3.6	4.96	35556.39	11	3.00	4.31	33999.53
12	6.4	12.26	44523.17	12	6.00	11.28	43588.67
13	10.2	22.19	63113.76	13	10.00	21.65	63287.18
14	15	32.77	79104.50	14	14.80	32.05	78514.20
15	20	42.90	99170.57	15	19.60	42.01	102784.34
16	3.4	8.53	33232.18	16	3.20	8.16	33950.73
17	6	19.79	46975.80	17	5.90	19.38	48338.79
18	10	32.61	65166.51	18	9.70	31.76	69010.69
19	15.1	47.96	79901.58	19	15.20	46.93	88089.47
20	20.1	63.17	88593.06	20	19.80	61.76	95754.82
21	3.4	16.07	33318.08	21	3.30	15.56	38151.44
22	6.1	32.27	48299.07	22	6.00	31.02	52620.60
23	10.3	52.58	63377.12	23	10.20	51.17	67633.73
24	15.1	77.77	81278.71	24	15.00	76.77	83115.27
25	20	103.18	93438.39	25	20.00	102.19	89690.04
26	3.4	22.00	33497.21	26	3.00	21.53	35761.03
27	6	44.07	51501.98	27	6.20	43.51	51476.71
28	10.1	72.87	73622.17	28			
29	15	107.80	80863.54	29			
30	20.5	142.42	79660.11	30			

Table C.15 M_R Results for 50% Class 5 + 50% RAP TH 10 (OMC +1% and OMC + 2%, Freeze-Thaw Conditioned)

T-F-3					T-F-4			
OMC +1%, 100% MDD					MC = OMC +2%, 98% MDD			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi		Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1	3	0.8719561	35676.229		1			
2	5.8	2.067	38718.357		2	6	2.3258854	49043.09
3	10.2	3.8567	52507.423		3	10	4.216162	70378.979
4	15	7.059	73641.255		4	15	7.2373405	95321.234
5	19.9	10.394	93413.641		5	20	10.477824	110984.21
6	3	1.854	32052.74		6	2.5	2.0461918	38979.879
7	6	4.5597819	38069.64		7	5.8	4.9433756	51546.118
8	10	10.011963	51968.166		8	10	10.155306	71176.826
9	15	16.078301	74276.825		9	15	16.029196	96034.85
10	20	21.37389	95545.981		10	20	21.392725	114943.73
11	3	4.5837578	29182.203		11	3	4.8307308	43002.05
12	6.2	12.101732	39837.232		12	6	12.37761	57016.944
13	10.1	21.573665	54654.357		13	10	21.66488	77194.216
14	15	31.773871	62113.784		14	15.2	32.0596	102102.65
15	20	41.986362	85198.009		15	20.5	42.455291	117642.67
16	3.2	8.0245063	28922.587		16	3	8.3851208	41299.561
17	5.9	18.663708	38436.128		17	6	18.913975	59240.158
18	10.1	31.32971	55427.563		18	10	31.836703	81779.432
19	15	46.360283	64235.622		19	15	47.189868	87889.61
20	20	62.084556	72881.123		20	20	62.005671	101776.54
21	3	14.547449	28663.486		21	3	15.109388	41863.483
22	6	30.626909	41134.339		22	6	31.047716	61970.873
23	10	50.69734	51648.712		23	10	51.075822	69399.958
24	15	75.823397	58499.425		24	15	75.169838	71749.062
25	20	101.06105	69081.949		25	20	99.725468	74637.922
26	3	20.150524	27154.435		26	3.4	20.620543	34136.18
27	6	42.607175	44500.085		27	5.9	42.941252	50571.306
28	10	71.045199	55466.014		28	10	69.84855	57099.112
29	15	103.572	51955.45		29	15	100.22448	51234.423
30	20	136.04219	102696.61		30			

Table C.16 M_R Results for 25% Class 5 + 75% RAP TH 10 (OMC, 100% MDD), One Sample and a Replicate

S-N-1				S-N-2			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi	Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1	3	0.98	22391.44	1	3	1.10	31540.60
2	6	2.31	29724.71	2	6	2.44	36835.48
3	10	4.15	41677.86	3	10.3	4.21	47213.45
4	15	6.72	61084.70	4	15.1	6.83	64337.89
5	20	9.71	76239.26	5	20.1	9.95	82035.29
6	3	2.11	22910.80	6	3.1	2.26	31711.36
7	6	4.75	30819.23	7	6	4.93	38072.08
8	10	9.74	44172.38	8	10.1	9.83	49559.57
9	15.1	15.43	63067.40	9	15	15.72	67779.51
10	20	21.53	75271.32	10	20.1	21.89	82417.65
11	3	4.56	23065.34	11	3.1	4.73	31933.90
12	6	12.17	33955.55	12	6.1	12.43	41602.15
13	10.1	21.97	49966.36	13	10.4	22.34	56267.05
14	15	32.15	55851.15	14	15.1	32.56	61913.39
15	20	42.17	71096.59	15	20	42.86	82445.02
16	3	8.34	24358.18	16	3.7	8.65	31882.91
17	6	19.24	34920.55	17	6.2	19.90	43080.36
18	10	31.77	47934.73	18	10.3	32.33	57719.67
19	15	46.75	56990.63	19	15.1	47.35	67885.63
20	20.2	61.83	63493.94	20	20	62.41	70666.64
21	3	15.71	25683.20	21	3	16.55	30787.53
22	6	31.17	35959.54	22	6.3	31.76	42089.23
23	10	51.09	45499.66	23	10.4	51.68	51559.24
24				24			
25	20	100.28	60882.40	25	20	100.82	67329.15
26	3	21.51	25692.69	26	3.4	22.22	32136.01
27	6	43.24	39281.68	27	6.3	43.72	46830.78
28	10	71.27	49168.72	28	10.1	70.34	53592.09
29	15			29			
30	20.2	137.82	56194.39	30	20.2	138.69	60981.90

Table C.17 M_R Results for 25% Class 5 + 75% RAP TH 10 (OMC + 1% and OMC + 2%)

S-N-3			
OMC +1%, 97.6% MDD			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1			
2	6	2.02	27010.65
3	10	3.77	34309.91
4	15	7.03	46365.72
5	20	10.38	56210.04
6	3.1	1.87	22278.20
7	6	4.82	28670.63
8	10	10.01	37793.33
9	15	16.02	49046.65
10	20	21.38	59616.27
11	3.2	4.72	23858.42
12	5.8	12.39	34050.49
13	10	21.47	45151.22
14	15	31.59	53432.52
15	19	41.63	59243.10
16	3	8.13	24291.42
17	6.1	18.56	34160.21
18	10	31.12	44476.88
19	14.5	45.87	51552.66
20	20	61.02	59054.85
21	3	14.75	27314.97
22	6	30.30	35755.32
23	10	49.57	42790.95
24	15	73.47	43614.46

S-N-4			
OMC+2%, 97% MDD			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1			
2	6.1	2.11	32092.66
3	10	3.72	37804.64
4	15	6.89	45991.40
5	19.8	10.20	54698.05
6	3	1.95	27864.85
7	6	4.74	31094.71
8	10	9.71	37162.52
9	15	15.60	46756.96
10	20	20.80	56236.87
11	3	4.68	28124.61
12	6	11.99	34413.42
13	10	20.94	41474.51
14	15	30.73	46240.45
15	20	40.61	53559.97
16	3	8.22	25329.66
17	6	18.14	30141.37
18	10	30.07	34166.11
19	15	44.42	41632.94

Table C.18 M_R Results for 25% Class 5 + 75% RAP TH 10 (OMC, 100% MDD, Freeze-Thaw Conditioned), One Sample and a Replicate

S-F-1				S-F-2			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi	Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1				1			
2	5.8	2.59	33255.23	2	6	2.47	40978.17
3	9.9	4.62	45239.80	3	10.1	4.30	53043.03
4	15	7.34	60828.26	4	15	6.76	65257.69
5	20	10.41	73399.66	5	20	9.86	77179.89
6	3	2.32	26297.86	6	3	2.29	33120.87
7	5.7	5.25	32408.45	7	6	5.03	40840.19
8	10	10.21	44053.63	8	10	9.86	51597.85
9	15	15.49	61839.94	9	14.7	15.26	63810.73
10	20	20.55	76108.50	10	20	20.69	76222.12
11	2.9	5.11	24577.19	11	2.9	4.86	31810.01
12	6	12.31	34003.04	12	6.1	12.06	41989.10
13	10	21.66	50659.96	13	10	21.28	53726.84
14	15	32.37	65240.27	14	15	31.20	64580.20
15	20	42.52	75745.40	15	20	41.52	73879.75
16	3	8.74	26327.70	16	3	8.39	30795.46
17	6	19.33	36397.06	17	6	18.97	38707.48
18	10.3	32.23	52116.17	18	10	30.79	53137.67
19	15	47.40	62638.74	19	15	45.94	62268.44
20	19.7	62.74	70461.29	20	20.1	60.99	74167.97
21	3	15.52	26397.94	21	3	15.23	33707.42
22	6	31.64	39775.15	22	6	30.14	43418.90
23	10	52.30	50466.47	23	9.5	50.31	52929.20
24	15.3	77.07	57983.75	24	15	75.29	58220.42
25	20	102.06	65268.39	25	20	100.45	65330.35
26	3	21.30	26334.26	26	3	20.62	28833.86
27	5.5	43.58	37735.98	27	6.2	41.86	40136.68
28	10	71.72	48500.37	28	10.2	69.70	51727.46
29	15.1			29	15	104.51	55447.56
30	20.5	140.02	58958.60	30			

Table C.19 M_R Results for 25% Class 5+ 75% RAP TH 10 (OMC +2%, 96% MDD, Freeze-Thaw Conditioned)

S-F-4				
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi	Notes
1				
2	6	2.26	41076.76	Due to high SNR for LVDT 1, the deformation was calculated based on only 2 lvdts
3	10	4.06	47641.79	
4	15	7.02	60873.67	
5	20	10.31	71830.46	
6	3	1.99	30869.99	
7	6	4.70	35793.74	
8	10	9.97	46471.56	
9	15	16.12	58576.86	
10	20	21.52	69596.94	
11	3	4.65	28276.36	
12	6	12.36	36801.99	
13	10	21.41	50436.99	
14	15	31.44	63114.41	
15	20	41.63	68701.26	
16	3	8.19	28911.45	
17	6	18.38	37300.37	
18	10	30.79	48348.76	
19	15	45.32	54433.02	
20	20	59.98	60526.34	
21	3	14.55	27294.14	
22	6	29.63	37812.39	
23	10	47.11	39811.47	

Table C.20 M_R Results for 100% RAP TH 10 (OMC, 100% MDD)

R-N-1				R-N-2			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi	Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1	3	1.06	35764.77	1			
2	6	2.63	48278.38	2			
3	10	4.66	69854.24	3			
4	15	7.28	107233.62	4			
5	20	10.05	135115.35	5			
6	3	2.33	38108.31	6	3	2.48	53357.36
7	6	5.28	52177.06	7	5.9	5.42	67636.23
8	10	10.03	79591.36	8	9.9	10.16	88630.72
9	14.9	15.46	108629.87	9	14.8	15.66	114938.88
10	20	20.21	128398.12	10	20.2	20.38	151009.19
11	3	4.93	40663.62	11	3.3	5.11	51557.44
12	6	12.33	55075.83	12	6	12.41	63557.08
13	10	21.80	76113.58	13	9.8	21.75	85364.58
14	15	32.49	95250.86	14	14.8	31.95	111595.34
15	20	42.39	110525.08	15	20	42.50	135068.56
16	3	8.65	34805.48	16	3.3	8.77	48221.42
17	6	19.86	51114.37	17	6.2	19.61	65984.57
18	10	32.32	71966.47	18	10	32.37	88768.24
19	15	47.64	83999.87	19	15	47.71	110640.27
20	20	63.14	94609.69	20	20.1	62.90	123927.06
21	3.2	16.54	35487.68	21	3.2	16.30	48932.91
22	6	32.24	49263.29	22	5.8	32.13	63192.18
23	10	52.53	64347.69	23	10	52.54	85312.80
24				24	14.9	0.09	8676.39
25	20.1	102.92	91376.90	25	20	102.74	107979.41
26	3.4	22.52	36067.06	26	3.1	22.19	42823.10
27	6	44.27	52257.23	27	6	43.98	60439.58
28	10.1	72.12	69779.28	28	9.9	70.09	77195.42
29	15			29	15	107.34	96696.76
30	20	142.03	83657.53	30	20	141.94	96987.34

Table C.21 M_R Results for 100% RAP TH 10 (OMC, 100% MDD, 2nd replicate)

R-N-OMC_3			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1	3	1.05	58300.93
2	6	2.40	73929.53
3	10	4.31	95689.02
4	15	7.19	113903.41
5	20	10.43	130895.05
6	3	2.21	54742.50
7	6	5.06	66124.46
8	10	10.05	75999.99
9	15	15.72	97431.99
10	19.8	21.13	114631.80
11	3	4.87	48591.21
12	6	12.05	56106.70
13	10	21.50	73697.65
14	15.1	31.52	91325.00
15	20	41.75	105245.69
16	3	8.45	41985.35
17	6	18.99	54935.50
18	10.2	31.39	71703.17
19	15	46.69	88208.93
20	20	61.94	100413.36
21	2.8	15.40	44667.23
22	6	31.09	56311.49
23	10	51.29	70137.26
24	15.1	76.34	74207.60
25	20	101.29	90872.23
26	3.5	21.38	37870.52
27	5.9	43.33	54793.27
28	10	71.44	68255.87
29	15	105.21	70127.91

Table C.22 M_R Results for 100% RAP TH 10 (OMC + 1%, 100% MDD)

R-N-3			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1			
2	6	2.15	30131.25
3	10.2	4.01	40316.11
4	15	7.14	57527.26
5	19.5	10.25	69288.81
6	2.5	1.96	23212.63
7	5.5	4.83	28206.09
8	10	9.91	40911.50
9	15	15.80	58272.77
10	20	20.96	70470.09
11	3	4.77	22857.33
12	6	12.27	32719.71
13	10	21.29	46461.61
14	15	31.57	59598.22
15	20.1	41.74	68250.17
16	3	8.40	24903.66
17	6	18.65	33165.53
18	10	31.21	46149.00
19	15	46.62	56507.75
20	20	61.36	65473.18
21	3.2	14.90	25940.45
22	6	30.58	36197.59
23	10	50.72	44233.99
24	15	75.32	52556.51
25	20	100.40	65197.31
26	3	20.54	26300.45
27	6	42.60	39337.48

Table C.23 M_R Results for 100% RAP TH 10 (OMC + 2%, 97.5% MDD)

R-N-4			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1			
2	6	2.25	45186.46
3	10	3.85	51198.75
4	15	6.90	59161.60
5	20	10.11	70707.94
6	3.1	2.09	44101.48
7	6	4.86	47282.97
8	9.6	9.90	55025.87
9	15	15.77	67053.11
10	20	21.01	74242.13
11	3	4.77	39974.89
12	6	12.43	45927.55
13	10	21.20	54138.68
14	15	31.09	64732.86
15	20.2	41.23	66261.86
16	2.9	8.40	34882.48
17	6.5	18.42	44037.55
18	10	30.46	47731.08
19	15	45.12	52918.43
20	20	59.58	49954.88
21	3	14.89	29747.14
22	6	30.38	36611.69
23	10	50.07	44434.34

Table C.24 M_R Results for 100% RAP TH 10 (OMC, 100% MDD, Freeze-Thaw Conditioned), One Sample and a Replicate

R-F-1					R-F-2			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi		Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1					1			
2	6	2.71	48137.66		2	6.5	2.80	72287.55
3	10	4.77	66476.26		3	10	4.78	90645.36
4	15	7.33	85922.95		4	16	7.48	143446.29
5	20	10.24	105935.67		5	20	10.31	69420.29
6	3	2.53	39874.61		6	3	2.73	67828.28
7	6.2	5.45	52195.41		7	6	5.44	71629.41
8	9.8	10.19	66446.07		8	9.9	10.34	85948.57
9	15.1	15.75	92019.38		9	15	16.02	105228.73
10					10	20	21.49	123736.38
11	3.1	5.34	55260.32		11	3.5	4.94	51110.95
12	6.2	12.42	69779.16		12	5.6	12.60	61971.92
13					13	10	22.60	83981.09
14	20	32.68	104798.08		14	14.5	32.83	100093.08
15	20	42.83	100950.99		15	20	43.14	119421.22
16	3	8.56	38920.45		16	2.9	8.91	45897.96
17	6.2	19.87	55172.05		17	6	20.20	63626.95
18	10.1	32.48	70800.18		18	10	32.74	85079.95
19	15	47.77	87673.99		19	15	47.92	96073.83
20	20	62.97	101804.12		20	20	63.04	106855.40
21	2	16.30	36454.64		21	3	16.46	46586.29
22	6.2	32.05	54327.83		22	5.9	32.12	62445.39
23	10.3	52.27	72424.62		23	10	52.33	78744.91
24	15	77.06	79257.48		24	15	77.00	83666.44
25	20	101.93	96852.18		25	20	102.42	94891.59
26	2.9	21.90	38941.75		26	3	21.93	40934.27
27	6	43.46	56814.20		27	6	43.53	58935.99
28	10	71.86	73585.51		28	10	71.59	71649.24
29	15	106.19	81740.40		29	15	106.86	80753.15
30	20	140.01	84502.35		30	20	141.25	79920.91

Table C.25 M_R Results for 100% RAP TH 10 (OMC + 1%, 100% MDD, Freeze-Thaw Conditioned)

R-F-3			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1			
2	6	2.31	37244.49
3	10	4.11	52636.60
4	15.2	6.78	73732.05
5	20	9.91	91473.40
6	3	2.05	29255.95
7	6	4.90	39627.13
8	10	9.55	55736.79
9	15	15.38	74932.20
10	20	21.23	90945.49
11	2.9	4.62	29662.40
12	6	11.22	40909.01
13	10	21.30	63185.60
14	15	31.57	74527.61
15	20	41.60	84286.08
16	3	7.92	28337.47
17	6	17.92	41364.47
18	10	31.07	59873.71
19	15	45.93	68168.48
20	20	60.69	76894.81
21	3	14.20	29990.51
22	6	30.09	43038.39
23	10	50.31	54377.60
24	15	74.75	61531.69
25	20	99.40	66594.02
26	3	19.71	29071.36
27	6	41.74	42299.22
28	10	69.40	53036.62
29	15	103.20	55716.50
30	20	136.04	56496.18

Table C.26 M_R Results for 100% RAP TH 10 (OMC + 2%, 98% MDD, Freeze-Thaw Conditioned)

R-F-4			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1			
2	6	2.38	59966.35
3	10	4.20	87037.92
4	15	7.24	121138.70
5	20	10.18	126666.17
6	2	2.09	44833.07
7	5.9	4.93	61146.21
8	10	10.03	78417.14
9	15	15.71	94213.15
10	20	21.08	106750.60
11	3	4.75	48834.97
12	6	12.13	58286.60
13	10	21.42	75230.19
14	15	31.24	89669.66
15	20	41.00	94250.43
16	3	8.06	42272.21
17	6	18.47	54239.01
18	10	30.71	70634.60
19	15	45.41	80106.27
20	20	59.70	78643.26
21	3	14.67	38057.21
22	6	30.03	50841.38
23	10	49.63	65391.78
24	15	72.63	70376.77
25	20	97.29	78790.80
26	3	19.59	38365.08
27	6	41.15	55446.50
28	10	68.64	62054.58
29	15	99.66	65471.09
30	20	132.23	71097.23

Table C.27 M_R Results for RAP TH 19-101 (OMC, 100% MDD), One Sample and a Replicate

U-N-1				U-N-2			
OMC, 100% MDD				OMC, 100% MDD			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi	Confining pressure, psi	Cyclic stress, psi	Bulk stress, Psi	Resilient modulus, psi
1							
2	6	2.770823	74248.61				
3	10	4.751283	95734.81				
4	15	7.237704	116700.9				
5	20	9.878699	119187.2				
6	3	2.751838	68090.95	3.03	2.42941	11.51941036	99929.3933
7	6	5.520318	78597.94	6.06	5.439018	23.61901831	106153.804
8	10	9.853983	91704.17	9.9	10.2607	39.96069918	111639.498
9	15	15.36486	100418.2	14.97	15.95759	60.86758776	120733.731
10	20	20.10226	113603.3	20.07	21.54951	81.7595071	137311.164
11	3	5.37252	69635.92	3.6	5.357216	16.15721559	90690.2564
12	6	12.24791	77080.36	6.05	12.61471	30.76470526	91182.5332
13	10	21.0729	79740.55	9.95	21.90898	51.75898104	91390.6338
14	15	31.50415	96319.45	15.03	31.9429	77.0328963	107469.517
15	20	41.44235	100154.8	20.04	42.09753	102.217526	118558.702
16	3	8.576723	69135.53	2.95	9.027474	17.87747447	84171.4759
17	6	18.69148	72312.53	6.07	19.42822	37.63821951	84062.5108
18	10	31.57801	78238.64	10	31.80977	61.80976936	86439.4208
19	15	46.76428	86981.36	15.03	47.12226	92.2122606	95614.8862
20	20	61.74129	88718.78	20	62.14471	122.1447066	97835.1263
21	3	15.30061	59952.1	2.9	16.1859	24.88590376	72444.4888
22	6	31.56566	64017.13	6.08	31.70551	49.94550603	69343.1874
23	10	51.72821	70749.32	10.04	51.84518	81.96518195	75839.2679
24	15	76.63503	75843.84	15.02	76.58211	121.6421129	78875.8575
25	20	101.4264	81657.67	20.02	101.6736	161.733564	82380.1412
26	3	21.91072	58551.27	3.08	22.10793	31.34793409	65660.3109
27	6	43.1364	59868.75	6.08	43.06423	61.30423404	59528.118
28	10	70.80337	66017.41	9.95	70.82121	100.6712073	63602.6531
29	15	106.1458	74193.64	14.96	106.194	151.0740236	74299.0728
30	20	140.9049	79561.56	20.03	140.6683	200.758286	81897.5592

Note: Table 3 contains detailed samples description

Table C.28 M_R Results for RAP TH 19-101 (OMC, 97.5% MDD)

U-N-OMC-97MDD			
OMC, 97.5 % MDD			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1	3.2	1.31	55078.67
2	6.2	2.63	64677.93
3	9.8	4.53	74976.75
4	15.1	7.14	83681.03
5	20.1	10.12	92500.08
6	2.7	2.56	56496.21
7	6.2	5.18	61340.36
8	10	9.99	62743.56
9	15	15.15	70174.82
10	20	20.75	81154.15
11	2.5	5.03	50260.03
12	6	11.86	49671.15
13			
14	15	30.87	67426.75
15	19.9	40.89	73720.06
16	3	8.54	44826.02
17	6	18.24	48113.84
18	10.1	30.33	55643.50
19	15	45.16	64742.56
20	20	59.68	71403.53
21	2.9	15.00	40491.88
22	6	29.72	44814.85
23	10.8	49.12	53792.13
24	15	74.05	60355.82
25	20	99.36	67231.13
26	3	21.14	40214.79
27	6.2	40.98	43699.34
28	10	68.48	51461.09
29	15	103.96	60872.91
30	20	138.84	66061.63

Table C.29 M_R Results for RAP TH 19-101 (OMC + 2%, 100% MDD)

U-N-4			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1			
2			
3	10	3.76	52841.88
4	15	6.68	55058.21
5	20	9.71	64671.07
6			
7	6	4.61	42183.83
8	10	9.02	36181.89
9	15.1	14.70	42839.08
10	20	20.11	53638.92
11	3	4.42	34546.08
12	6	10.85	27170.87
13	10.1	19.28	30999.18
14	15	28.70	41842.88
15	20	38.44	48771.47
16	3.2	7.52	26520.09
17	6	15.96	25163.81
18	10	27.02	31051.98
19	15	41.33	38597.50
20	20	55.93	41692.46
21	3	12.86	23369.02
22	6	25.15	24464.54
23	10	44.10	29766.56
24	15	68.02	39667.98
25	20	92.80	43745.72
26	3	18.17	26670.00
27			
28	10.5	63.31	33564.52
29	15	96.09	41571.40
30			

Table C.30 M_R Results for RAP TH 19-101 (OMC, 100% MDD, Freeze-Thaw Conditioned), One Sample and a Replicate

U-F-1				U-F-2			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi	Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1				1			
2	6	2.46	56784.69	2	6	2.72	59697.20
3	10	4.08	60680.26	3	10	4.53	71137.11
4	15	6.42	66582.50	4	15	7.11	84240.78
5	20	9.60	76441.78	5	20.1	10.22	92216.15
6	3	2.37	50741.58	6	3.2	2.55	49961.94
7	6	5.10	49724.70	7	6	5.31	55597.20
8	10	9.58	53395.52	8	10	9.94	57518.88
9	15	15.13	59866.97	9	15	15.25	67320.43
10	20	20.71	70962.31	10	19.9	21.28	84525.43
11	3	4.87	44229.41	11	3	5.00	46527.97
12	6	11.87	43647.43	12	6	12.02	42646.67
13	10	20.97	45969.87	13	10	21.24	47225.89
14	15	30.77	57183.33	14	15.1	31.56	64282.06
15	20	40.65	65283.53	15	20	41.69	72630.92
16	3	8.54	40630.89	16	2.5	8.43	36606.98
17	6	18.38	40322.74	17	6	18.61	39195.83
18	10	30.24	46760.75	18	10	30.87	48111.93
19	15	45.28	54554.02	19	15	46.07	59142.33
20	20	60.43	62390.68	20	20	61.13	64752.32
21	3	15.35	35439.42	21	3	15.34	32473.04
22	6	29.69	38357.56	22	6	30.01	37451.87
23	10	49.11	45215.36	23	10	49.82	46859.89
24	15	73.93	52443.35	24	15	74.69	53690.50
25	20	98.68	57407.13	25	19.8	99.81	59006.82
26	3	21.17	38285.84	26	3	20.95	34398.29
27	6	40.44	38349.01	27	5.8	40.92	36423.61
28	10	67.47	43162.19	28	10	68.86	43115.77
29	15	102.20	51089.92	29	15.8	103.89	54785.30
30	20			30	20	138.41	63743.32

Table C.31M$_R$ Results for RAP TH 19-104 (OMC, 100% MDD), One Sample and a Replicate

V-N-1				V-N-2			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi	Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1	3.2			1			
2	6	2.36	59794.83	2	6.20	2.57	38531.60
3	10	4.14	71374.59	3	9.90	4.38	48770.13
4	15.2	6.87	96373.95	4	15.50	6.89	62607.61
5	20	9.86	118561.15	5	20.80	10.02	73766.25
6	3.1	2.25	53113.19	6	3.90	2.39	36857.43
7	5.9	4.91	52091.11	7	6.10	5.03	34314.51
8	10.3	9.46	61857.09	8	10.70	9.77	42465.01
9	15	14.92	77766.86	9	15.30	15.13	52468.87
10	20.1	20.45	98448.40	10	20.00	20.72	64061.60
11	3.4	4.75	44568.33	11	3.50	4.79	29426.81
12	6.1	11.52	43584.92	12	6.00	11.66	30726.31
13	10.1	20.73	49017.90	13	10.50	21.51	40046.93
14	15	30.98	62069.62	14	15.10	31.82	52285.06
15	20	41.19	67268.82	15	20.50	42.08	60958.82
16	3.1	8.03	35741.80	16	3.70	8.18	26329.84
17	6.2	17.98	37085.82	17	6.30	18.57	30792.15
18	10.3	30.40	46097.33	18	10.00	31.18	39493.46
19	15	45.44	53150.68	19	15.50	46.29	48965.57
20	20	60.50	59310.08	20	20.30	61.60	57754.18
21	3.1	14.38	29540.29	21	3.10	15.13	22929.98
22	6.3	29.22	34385.07	22	6.90	30.04	30610.47
23	10	49.54	43875.23	23	10.30	50.57	40851.72
24	15	74.75	49719.89	24	15.30	75.58	49972.36
25	20			25	20.10	100.20	52648.44
26	3.5	20.43	30143.93	26	3.00	20.67	25726.50
27	6.2	40.95	36918.63	27	6.30	41.13	31123.96
28				28	10.30	70.35	40703.95
29	15.8	104.78	59439.52	29			
30				30			

Table C.32 M_R Results for RAP TH 19-104 (OMC + 2%, 97% MDD)

V-N-4			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1			
2			
3	10.00	3.32	36594.92
4	15.00	6.19	41426.24
5	20.00	9.41	50276.51
6	3.00	1.63	32494.19
7	6.00	4.10	25072.32
8	10.00	8.72	29406.91
9	15.00	14.38	37942.92
10	20.00	19.76	48145.41
11	3.50	4.06	23021.69
12	6.00	10.68	24912.27
13	10.00	19.31	35032.73
14	15.00	28.84	38336.11
15	20.00	38.35	43521.65
16	3.00	6.97	18413.99
17	6.50	15.92	24538.49
18	10.20	27.43	29576.59
19	15.00	41.41	36196.92
20	20.00	55.12	37910.09
21	3.10	12.30	17000.46
22	6.00	26.46	24520.02
23	10.00	44.50	29217.86

Table C.33 M_R Results for RAP TH 19-104 (OMC, 100% MDD, Freeze-Thaw Conditioned), One Sample and a Replicate

V-F-1					V-F-2			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi		Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1					1			
2	6.1	2.48	51585.78		2	5.8	2.427721	45151.472
3	10	4.24	62208.07		3	9.9	4.310312	58654.227
4	15	6.88	78783.05		4	15	7.041652	74094.809
5	20	10.30	90686.31		5	20	10.17916	92342.911
6	2.8	2.30	39870.88		6	3	2.252522	36984.536
7	6.7	4.96	49889.66		7	6.3	5.020164	44774.39
8	10	9.90	57310.37		8	11	9.809618	54763.006
9	15.2	15.58	70036.27		9	15	15.31885	66810.164
10	20	21.68	87547.21		10	20.2	20.83779	81481.509
11	4	4.82	41278.66		11	3	4.762295	33455.742
12	6	11.84	42291.44		12	5.8	11.66493	37464.222
13	10	21.68	50230.92		13	10	20.96863	48307.026
14	15.2	31.89	69355.83		14	14.5	31.23334	61454.305
15	20	42.06	80010.72		15	20	41.46713	72999.82
16	3	8.19	34202.73		16	3	8.06027	30388.224
17	6	18.71	39403.17		17	6.2	18.06502	37165.521
18	10	31.25	50451.15		18	10	30.63283	48466.979
19	15	46.73	64596.70		19	15	45.86502	58385.306
20	19.7	62.00	75777.11		20	20	61.07805	66790.633
21	3.1	15.07	30660.73		21	3.2	14.10705	26159.854
22	6	30.06	36520.70		22	6	29.22028	34276.67
23	10	50.79	51561.00		23	10	49.62086	46218.701
24	15.2	76.18	61965.83		24	15.1	74.73282	62981.205
25	20.2	101.65	69720.06		25	20.1	100.1434	72489.504
26	3.3	20.21	28180.54		26	3.1	19.5638	24640.742
27	6	41.02	34437.04		27	6.2	40.43508	34044.528
28	10	70.54	48558.66		28			
29	14.9	105.76	59549.87		29			
30	20.2	140.58	65834.90		30			

Table C.34 M_R Results for RAP TH 19-104 (OMC + 2%, 97% MDD, Freeze-Thaw Conditioned)

V-F-4			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1			
2	6	1.91	27671.28
3	10	3.51	31912.55
4	15	6.38	35975.55
5	20	9.25	39547.25
6	3	1.76	23378.88
7	6	4.34	24294.87
8	10	8.75	27267.71
9	15	14.20	33978.16
10	20	19.44	40992.93
11	3.2	4.21	21484.56
12	6	10.61	23997.52
13	10	18.98	30334.17
14	15	28.11	36245.56
15	20	36.85	33556.97
16	3.5	7.08	15562.31
17	6.1	15.48	19371.45
18	10	26.79	25647.84
19	14.5	38.69	28481.08
20			

Table C.35 M_R Results for RAP TH 22 (OMC, 100% MDD), One Sample and a Replicate

W-N-1			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1			
2	6.10	2.27	30669.87
3	10.10	4.16	47310.45
4	15.00	7.23	68371.39
5	20.00	10.43	88357.66
6	3.60	2.08	24611.66
7	6.30	5.00	34917.63
8	10.30	10.03	48793.71
9	14.90	16.50	68139.96
10	20.00	22.54	89237.55
11	3.20	4.71	25143.69
12	6.30	12.45	36991.16
13	10.30	22.45	55168.99
14	15.20	32.90	72152.11
15	20.00	42.97	85619.40
16	3.40	8.42	26492.62
17	6.30	19.23	38216.73
18	10.20	32.29	54568.26
19	15.21	47.64	68209.33
20	20.00	62.80	79707.55
21	3.30	15.40	28424.89
22	6.10	31.19	40215.99
23	10.00	51.85	55210.05
24	15.10	77.25	67239.44
25	20.10	102.60	78562.14
26	3.50	20.83	29745.79
27	6.10	43.26	43198.31
28	9.90	72.01	57449.96
29	15.00	106.83	64857.82
30	20.00	141.62	69300.50

W-N-2			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1			
2			
3	10.1	4.705573	72675.4746
4	15	7.373165	96523.2782
5	20	10.38807	119304.769
6	3	2.367251	38159.7324
7	6	5.248743	49364.5295
8	10	10.191	67994.1816
9	15	15.65363	90415.5213
10	20	20.70552	108136.8
11	3.5	4.987702	37811.0154
12	6.1	12.39938	49439.3592
13	10	22.0573	67681.2348
14	15.1	32.60163	87551.3154
15	20	42.81086	98276.493
16	3	8.721829	35177.3637
17	6	19.7855	48086.15
18	10.2	32.52658	65989.0714
19	14.9	47.87853	82029.5467
20	20	62.96704	91622.3816
21	3	16.04054	34445.5589
22	6	32.00035	48473.5088
23	10	52.44942	64089.238
24	15.2	77.33261	78133.4703
25	20.1	102.756	91823.1826
26	3	21.69188	33537.765
27	6	43.84229	49932.7865
28	9.9	71.89867	67399.3108
29	15.2	107.594	84832.3154
30	20.1	142.6369	93459.3209

Table C.36 M_R Results for RAP TH 19-104 (OMC + 2%, 98% MDD)

W-N-4			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1	3	1.032317	40211.4
2	5.8	2.230576	42885.51
3	10.1	3.908962	50334.59
4	15	7.034996	62065.43
5	20	10.37593	77740.03
6	3	2.106322	37592.03
7	6	4.909398	40500.87
8	10	9.95788	47931.03
9	15	15.92622	59132.67
10	19	21.22118	71677.66
11	3	4.763688	34140.52
12	6	12.2808	42493.71
13	10	21.43723	53129.88
14	15	31.31423	60148.11
15	19.5	41.1564	66151.79
16	3	8.285667	31619.2
17	6	18.38725	40769.56
18	10	30.65965	49939.5
19	15	45.43908	53686.18
20	20	60.09581	58196.47
21	3	14.46199	29022.19
22	6	29.92784	38290.94
23	9	49.06351	44464.46
24	15	72.7422	56002.73

Table C.37 M_R Results for RAP TH 22 (OMC, 100% MDD, Freeze-Thaw Conditioned), One Sample and a Replicate

W-F-1				W-F-2			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi	Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1				1			
2				2	6.1	2.67	47385.61
3				3	10	4.61	62384.88
4	15.2	7.353905	93255.01	4	15	7.12	79649.08
5	20	10.17811	118872.3	5	20.2	10.00596	99715.04
6				6	3.4	2.424327	37348.7
7	6	5.270214	48648.42	7	6.1	5.242971	47049.67
8	10	10.18468	66614.54	8	10.1	9.930718	60994.06
9	15	16.01496	91195.11	9	15.1	15.41614	80833.5
10	20.2	21.6298	118353.9	10	20	20.12987	99451.13
11	3	4.993537	36678.42	11	3.3	4.99015	37432.82
12	6.4	12.54777	50040.69	12	6.2	12.15996	47566.74
13	10	22.62743	68109.17	13	10.1	21.29075	65291.52
14	14.9	32.91193	91271.21	14	15	31.59003	82163.82
15	20	43.06892	102856.4	15	20	41.97878	94142.16
16	3	8.761432	34883.39	16	3.4	8.610078	35399.81
17	6.1	20.15368	50117.65	17	6.2	19.04574	48334.28
18	10.2	32.92072	68270.47	18	10	31.7412	64709.97
19	15.1	48.07816	84758.74	19	15.2	47.16881	78679.36
20	20	63.17165	92080.48	20	20.1	62.33828	86811.55
21	3	16.26826	33696.57	21	3.3	15.51923	34195.38
22	6.1	32.17065	48188.79	22	6	31.37901	46763.41
23	10	52.61908	61542.49	23	10.1	52.16599	62188.69
24	15	77.65546	78542	24	15.2	77.28051	70351.94
25	20.1	102.8068	88195.7	25	20.1	102.6082	81439.18
26	3.4	21.8872	34438.93	26	3.5	21.4517	31509.84
27	6	43.93008	48941.78	27	6.4	43.5258	46000.52
28	10.2	72.56	71658.58	28	10	72.06996	61151.36
29				29	15.2	107.0951	71130.09

Table C.38 M_R Results for RAP TH 19-104 (OMC + 2%, 98% MDD, Freeze-Thaw Conditioned)

W-F-4			
Sequence	Confining pressure, psi	Cyclic stress, psi	Resilient modulus, psi
1	3	0.943986	44270.96
2	6	2.154839	46396.11
3	10.1	3.849648	52196.98
4	15	6.603847	57821.39
5	19.5	9.706825	74618.37
6	3	1.960968	36171.36
7	5.8	4.739419	36077.83
8	10	9.485286	41875.51
9	15	15.10549	56189.45
10	20	20.39342	72878.27
11	3	4.524745	31307.94
12	6	11.75062	37101.48
13	10	20.47944	49056.68
14	15	30.51338	58923.85
15	20	40.64164	69613
16	3.2	7.917966	29809.29
17	6	17.81591	38306.09
18	10	29.62592	48087.98
19	15	44.42776	53278.89
20	20	59.44431	61486.34
21	3	13.78801	28605.09
22	6	28.71819	39373.58
23	10.2	43.51569	34663.32
24			

C.2. Resilient Modulus Testing Conducted by Mn/DOT

Table C.39 100% RAP, Sample 1

MC= 6.83%					
Dry density = 124.68 pcf					
Sequence	Confining pressure	Devi. stress	Bulk stress	Resilient strain	M_R
	psi	psi	psi		psi
1	3.0885	2.619527186	11.88502719	0.000161854	16186.46339
2	3.09337996	5.328127147	14.60826703	0.000288425	18476.29228
3	3.08362	7.983443879	17.23430388	0.000387265	20615.41448
4	5.03925992	4.440164708	19.55794447	0.000185309	23963.47625
5	5.0416999	8.871572053	23.99667175	0.000343859	25800.21635
6	5.03925992	13.36278434	28.4805641	0.000511145	26143.15532
7	9.94656032	8.780819241	38.6205002	0.000245814	35722.41423
8	9.95144028	17.80447782	47.65879866	0.000499547	35642.85375
9	9.94412024	26.84717487	56.67953559	0.000803553	33411.16832
10	14.88811984	8.88309865	53.54745817	0.000215002	41320.28365
11	14.893	13.23012346	57.90912346	0.000308515	42884.53421
12	14.88567996	27.00718721	71.66422709	0.000623835	43292.60468
13	19.82723962	13.25119601	72.73291487	0.000256739	51613.84405
14	19.83456002	17.78883364	77.2925137	0.000334256	53224.73704
15	19.83456002	35.9820046	95.48568466	0.000707613	50850.84721

Table C.40 100% RAP, Sample 2

MC= 6.86%					
Dry density = 124.56 pcf					
Sequence	Confining pressure	Deviator stress	Bulk stress	Resilient strain	M_R
	psi	psi	psi		psi
1	2.942	2.684966497	11.51097	0.000102966	26085.36
2	2.94932	5.437508273	14.28547	0.000192974	28179.15
3	2.95664	7.895117383	16.76504	0.000269088	29341.77
4	4.91228	4.586775531	19.32362	0.000132176	34702.74
5	4.92692	8.82766888	23.60843	0.000250836	35194.4
6	4.93912	13.29550309	28.11286	0.000380123	34978.2
7	9.87824	8.828832225	38.46355	0.000179328	49238.7
8	9.8758	17.81502391	47.44242	0.000393966	45222.53
9	9.87824	26.80749764	56.44222	0.000706141	37964.04
10	14.81248	8.840090381	53.27753	0.000164611	53705.43
11	14.81004	13.32297695	57.7531	0.000249435	53413.16
12	14.81004	26.79162874	71.22175	0.000549498	48756.64
13	19.72964	13.3212832	72.5102	0.000203225	65554.96
14	19.7272	17.8382334	77.01983	0.000273027	65337.71

Table C.41 100% RAP, Sample 3

MC= 7.28%					
Dry density = 124.14 pcf					
Sequence	Confining pressure	Devi. stress	Bulk stress	Resilient Strain	M_R
	Conf psi	psi	psi		psi
1	2.89074	2.625766	11.29799	0.000165951	15824.7671
2	2.89316	5.35551	14.03499	0.000296046	18091.11456
3	2.92004	7.879796	16.63992	0.000394691	19964.76645
4	4.89276	4.496592	19.17487	0.000184858	24326.0154
5	4.90008	9.00608	23.70632	0.000351566	25618.13786
6	4.89032	13.28549	27.95645	0.000517734	25661.44954
7	9.8392	9.014052	38.53165	0.000249544	36123.0756
8	9.83188	17.91247	47.40811	0.000524561	34148.24857
9	9.81968	26.57564	56.03468	0.000841684	31574.66558
10	14.76856	8.829518	53.1352	0.000221931	39787.78016
11	14.771	13.2896	57.6026	0.000323558	41075.99811
12	14.77096	26.76875	71.08163	0.000649747	41200.77078
13	19.71496	13.2979	72.44278	0.00026918	49405.28388
14	19.71006	17.82125	76.95142	0.000352686	50532.90396
15	19.70518	35.66926	94.7848	0.000755092	47239.51205

Table C.42 70%RAP + 30% CL6

MC= 7.6.76%					
Dry density = 125.26 pcf					
Sequence	Confining pressure	Devi. stress	Bulk stress	Resilient strain	M_R
	psi	psi	psi		psi
1	3.00055998	2.62299326	11.6246732	0.00011294	23236.6568
2	2.9907999	5.32591649	14.2983162	0.00024817	21461.7176
3	2.98835996	7.96262952	16.9277094	0.00034375	23164.682
4	4.8829999	4.46784084	19.1168405	0.00016854	26509.4339
5	4.99036014	8.85634948	23.8274299	0.00031747	27897.6822
6	4.99280012	13.4373887	28.4157891	0.00047544	28263.414
7	10.0345001	8.84439793	38.9478982	0.00022523	39274.2892
8	10.0345001	17.913877	48.0173773	0.0004797	37344.6829
9	10.0222998	26.8479602	56.9148596	0.00074254	36157.7901
10	14.9052	8.9328097	53.6484097	0.00020201	44227.0223
11	15.0199797	13.3409867	58.4009257	0.00030923	43142.5844
12	15.0126596	26.8787102	71.916689	0.00059446	45215.5868
13	20.093399	13.3364455	73.6166425	0.00025467	52371.6232
14	20.0811996	17.892121	78.1357198	0.00034035	52570.8274
15	20.0836395	35.5103789	95.7612973	0.00066417	53466.0577

Table C.43 50% RAP + 50% Class 6, Samp1e 1

MC =6.6%					
Dry Density = 130 pcf					
Sequence	Confining pressure	Deviator stress	Bulk stress	Resilient strain	M_R
	psi	psi	psi		psi
1	3.02984	2.652933	11.74245	0.00015554	17061.7596
2	3.03228	5.329171	14.42601	0.00029519	18054.9362
3	3.003	7.940864	16.94986	0.00041831	18984.0085
4	4.97816	4.416248	19.35073	0.00019951	22136.3275
5	5.02458	8.862313	23.93605	0.00037196	23827.8457
6	5.0295	13.36043	28.44893	0.00058862	22698.0592
7	9.99058	8.889971	38.86171	0.0002655	33485.7183
8	9.9857	17.97272	47.92982	0.0005434	33074.6724
9					
10	14.99802	8.886851	53.88091	0.0002213	40160.7359
11	15.00534	13.4709	58.48692	0.0003252	41424.1296
12	14.99558	26.88015	71.86689	0.00063028	42648.8755
13	20.1056	13.46295	73.77975	0.00027359	49213.1533
14	20.1056	17.9107	78.2275	0.00036293	49352.6802
15	20.0934	35.92432	96.20452	0.00073809	48672.782

Table C.44 50% RAP + 50% Class 6, Samp1e 2

MC= 6.7%					
Dry density = 125 pcf					
Sequence	Confining pressure	Deviator stress	Bulk stress	Resilient strain	M_R
	psi	psi	psi		psi
1	3.0469799	2.681553421	11.82249312	0.000129219	20763.80747
2	3.09093998	5.37408868	14.64690862	0.000259841	20683.37263
3	3.0885	8.010709854	17.27620985	0.000352613	22718.29852
4	5.0661001	4.447514412	19.64581471	0.000170266	26124.21883
5	5.0538998	9.014681562	24.17638096	0.000342117	26350.27235
6	5.0538998	13.61805889	28.77975829	0.000508727	26769.562
7	10.0345001	8.996098366	39.09959867	0.000265387	33900.56338
8	10.0222998	17.82995743	47.89685683	0.000530325	33621.11565
9	10.0101004	26.73333367	56.76363487	0.000720628	37097.62703
10	14.99801998	8.846368215	53.84042816	0.000241969	36564.16626
11	14.9906998	13.31055188	58.28265128	0.00036148	36823.37742
12	14.9785004	26.82445024	71.75995144	0.000652902	41085.14901
13	20.0200996	13.34964171	73.40994051	0.000321632	41506.53312
14	20.0200996	17.83441005	77.89470885	0.000427245	41743.27836

Table C.45 30% RAP + 70% Class 6

MC= 6.6%					
Dry density = 130.35 pcf					
Sequence	Confining pressure	Deviator stress	Bulk stress	Resilient strain	M_R
	psi	psi	psi		psi
1	3.02007994	2.658001398	11.71824122	0.00023678	11226.55373
2	2.9542	5.341082612	14.20368261	0.00038104	14017.43784
3	2.95175998	7.978502736	16.83378268	0.00049705	16052.55966
4	5.09538002	4.44987003	19.73601009	0.00025208	17653.01417
5	4.93911992	8.935487186	23.75284695	0.00046059	19400.08926
6	4.9317999	13.28376018	28.07915988	0.00065835	20177.71107
7	10.07841984	8.860855308	39.09611483	0.0003229	27443.45536
8	10.06377984	17.9169046	48.10824412	0.00061614	29079.5867
9	10.05645982	26.80025896	56.96963842	0.00087367	30675.565
10	14.98825992	8.848171951	53.81295171	0.00026876	32925.58941
11	14.9785004	13.42355181	58.35905301	0.00038921	34488.98012
12	14.98582004	26.8968993	71.85435942	0.0006995	38451.60716
13	20.0200996	13.40082049	73.46111929	0.00031075	43123.92693
14	20.0200996	17.92702759	77.98732639	0.00040255	44534.05383
15	20.0200996	35.7156242	95.775923	0.00076118	46921.83504

Table C.46 50% RAP + 50%Taconite, Samp1e 1

MC = 6.7%					
Dry density = 125.2 pcf					
Sequence	Confining pressure	Deviator stress	Bulk stress	Resilient strain	M_R
	psi	psi	psi		psi
1	3.00787996	2.713583413	11.73722329	0.000118269	22949.26136
2	2.98347996	5.332162588	14.28260247	0.000232078	22976.37836
3	3.01763992	7.970601423	17.02352118	0.000309492	25754.24316
4	4.97083998	4.462348037	19.37486798	0.000165715	26934.36002
5	4.9562001	8.845957946	23.71455825	0.000295123	29976.41758
6	4.9562001	13.43081986	28.29942016	0.000435755	30822.48836
7	9.9979	8.847754774	38.84145477	0.000240431	36802.09442
8	10.00034008	17.84966199	47.85068223	0.000445697	40049.40303
9	9.99545994	26.84544485	56.83182467	0.000737336	36409.58755
10	15.01753958	8.858846277	53.91146502	0.000190112	46609.39743
11	15.01753958	13.32334113	58.37595987	0.000292826	45501.00358
12	15.01997964	26.84835958	71.9082985	0.000572569	46891.83402
13	20.0200996	13.40707393	73.46737273	0.00026212	51150.85444
14	20.02253986	17.84315382	77.9107734	0.0003498	51011.82173
15	20.02987972	35.93437242	96.02401158	0.000665729	53978.26358

Table C.47 50% RAP + 50% Taconite, Sample 2

MC = 6.7%					
Dry density = 124.5 pcf					
Sequence	Confining pressure	Deviator stress	Bulk stress	Resilient strain	M_R
	psi	psi	psi		psi
1	3.10313992	2.6284967	11.93791646	0.000136136	19313.24846
2	3.01275992	5.370244177	14.40852394	0.000301386	17819.75753
3	3.00299996	7.926811583	16.93581146	0.000413982	19148.67498
4	5.05145982	4.522170952	19.67655041	0.000213766	21157.25947
5	5.0416999	8.826087602	23.9511873	0.000394371	22383.49487
6	5.05145982	13.29755777	28.45193723	0.000550083	24173.9827
7	10.0222998	8.962130256	39.02902966	0.00031933	28069.54448
8	10.02961998	18.00649731	48.09535725	0.000632622	28463.44307
9	10.02717992	26.78989311	56.87143287	0.000986492	27156.74821
10	15.0272999	8.999076564	54.08097626	0.000337425	26671.59475
11	15.0272999	13.38080184	58.46270154	0.000491473	27227.35554
12	15.0395002	26.85385531	71.97235591	0.000883258	30403.30405
13	20.0323009	13.37836505	73.47526775	0.000477893	27995.2489
14	20.02500034	17.98453622	78.05953724	0.000622448	28893.92506

Table C.48 50% RAP + 50% Taconite, Sample 3

MC= 6.5%					
Dry density = 135 pcf					
Sequence	Confining pressure	Deviator stress	Bulk stress	Resilient strain	M_R
	psi	psi	psi		psi
1	3.06654	2.77071459	11.9703344	0.0001499	18482.73
2	3.06166	5.32344419	14.508424	0.000253	21045.09
3	3.05432	7.95598729	17.1189471	0.0003374	23586.82
4	5.0417	4.39407203	19.5191717	0.0001749	25131.4
5	5.04658	8.87610627	24.0158459	0.0003186	27859.41
6	5.05146	13.4778502	28.6322296	0.0004569	29501.6
7	10.05402	8.81325249	38.9753117	0.0002358	37378.53
8	10.0467	17.9256192	48.0657183	0.0004646	38585.02
9	10.0467	26.9066857	57.0467842	0.0007068	38068.92
10	14.8808	8.8446137	53.4870138	0.000218	40586.71
11	15.01998	13.2993264	58.3592654	0.0003283	40516.63
12	15.0151	26.9350775	71.980376	0.0006172	43639.38
13	20.01522	13.3894033	73.4350629	0.0002822	47453.15
14	20.0079	17.843086	77.8667866	0.0003738	47743.4
15	20.0079	35.8358712	95.8595718	0.0007178	49924.02

Table C.49 50% RAP + 50% Taconite, Sample 4

MC= 8.2%					
Dry density = 123.8 pcf					
Sequence	Confining pressure	Deviator stress	Bulk stress	Resilient strain	M_R
	psi	psi	psi		psi
1	3.1129	2.727664	12.06636	0.00015062	18115.76
2	3.10802	5.369696	14.69376	0.00029936	17939.07
3	3.1129	7.903086	17.24179	0.00040895	19327.07
4	5.0417	4.441693	19.56679	0.00019619	22648.02
5	5.0417	8.814759	23.93986	0.00037744	23355.32
6	5.0417	13.2999	28.425	0.00055448	23986.7
7	9.9124	8.820867	38.55807	0.00028607	30834.91
8	9.9124	17.83511	47.57231	0.00059831	29810.45
9	9.9246	26.78677	56.56057	0.00094458	28358.64
10	14.7832	8.806805	53.15641	0.00026714	32969.96
11	14.77588	13.3133	57.64094	0.00042341	31443.99
12	14.7832	26.77882	71.12843	0.00080476	33276
13	19.63926	13.30888	72.22666	0.00035423	37573.96
14	19.60754	17.82236	76.64498	0.00048739	36567.26
15	19.6417	35.79437	94.71947	0.00095718	37395.99

Table C.50 50% RAP + 50% Taconite, Sample 5

MC = 7.7 %					
Dry density = 124.1 pcf					
Sequence	Confining pressure	Deviator stress	Bulk stress	Resilient strain	M_R
	psi	psi	psi		psi
1	2.98104	2.74009593	11.68322	0.0001781	15382.73
2	2.98104	5.34451328	14.28763	0.0003178	16816.53
3	2.97616	7.99028773	16.91877	0.0004219	18941.49
4	4.88056	4.51409634	19.15578	0.0002247	20087.71
5	4.88056	8.88934853	23.53103	0.0003993	22262.37
6	4.87812	13.3603547	27.99471	0.0005739	23280.18
7	9.69026	8.87811531	37.9489	0.0003345	26541.11
8	9.69026	17.8317151	46.9025	0.0006344	28109.67
9	9.6805	26.8300953	55.8716	0.0010182	26350.8
10	14.539	8.86425079	52.48125	0.0003635	24385.12
11	14.5146	13.3360917	56.87989	0.0005284	25239.34
12	14.5146	26.7952321	70.33903	0.0009323	28741.12
13	19.28526	13.3372026	71.19298	0.000523	25502.36
14	19.16804	17.8289422	75.33306	0.0006693	26636.92
15	19.1534	35.8534986	93.3137	0.0012651	28339.8

Table C.51 50% RAP + 50% Taconite, Sample 6

MC = 7.7 %					
Dry density = 129.5 pcf					
Sequence	Confining pressure	Deviator stress	Bulk stress	Resilient strain	M_R
	psi	psi	psi		psi
1	2.86384	2.59728	11.1888	0.000228099	11388.84617
2	3.003	5.34863	14.35763	0.000371931	14381.45757
3	3.00056	7.969558	16.97124	0.000477575	16687.81442
4	5.07586	4.443068	19.67065	0.000243807	18225.97589
5	5.0539	8.815311	23.97701	0.000426634	20662.8268
6	5.0417	13.42939	28.55449	0.000637879	21053.25247
7	10.00522	8.81263	38.82829	0.000309804	28447.44593
8	9.9979	17.85968	47.85338	0.000567949	31446.0616
9	9.9857	26.88083	56.83793	0.000972382	27644.43041
10	14.9907	8.846128	53.81823	0.000257382	34373.22114
11	14.9907	13.35307	58.32517	0.000375746	35538.33145
12	14.9785	26.92567	71.86117	0.000684715	39324.45353
13	20.0079	13.42392	73.44762	0.000318379	42167.3277
14	20.00058	17.84516	77.8469	0.000410131	43512.66609
15	19.98594	33.81473	93.77255	0.000697751	48279.66747

Appendix D

Relation between Confining Pressure and Resilient Modulus

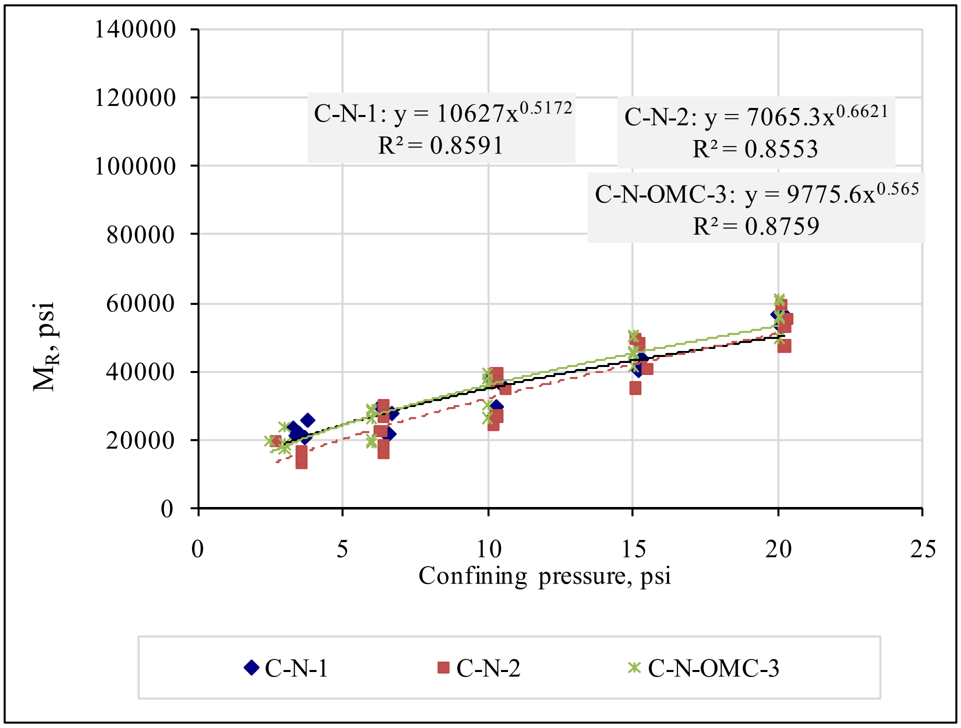

Figure D.1 M_R vs. confining pressure for Class 5 (OMC, 100% MDD, one sample and 2 replicates)

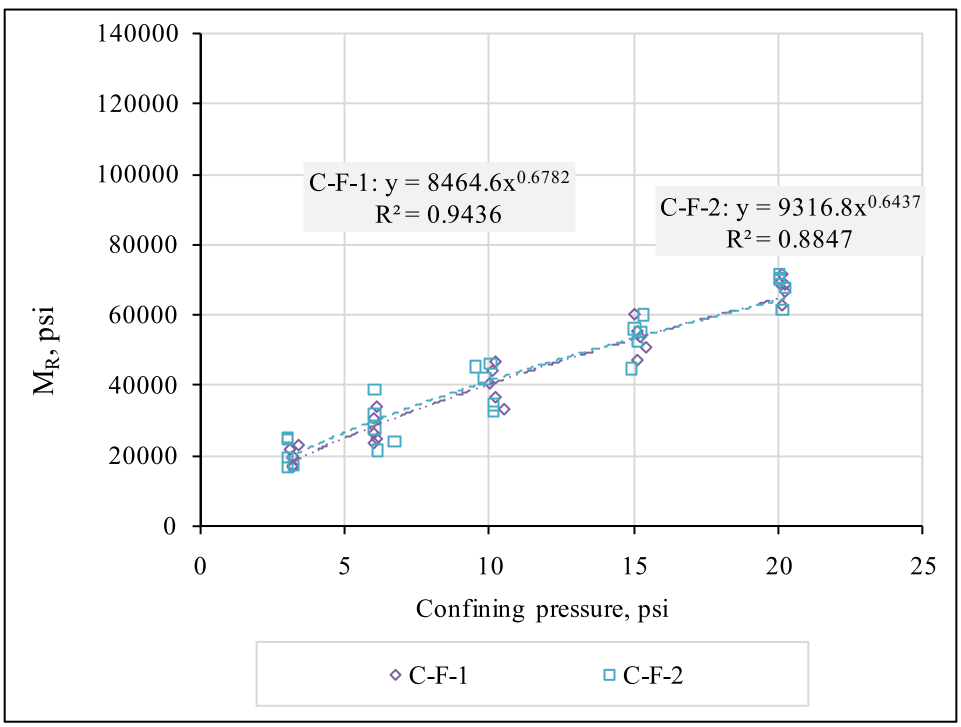

Figure D.2 M_R vs. confining pressure for Class 5 (OMC, 100% MDD, freeze-thaw conditioned), (one sample and a replicate)

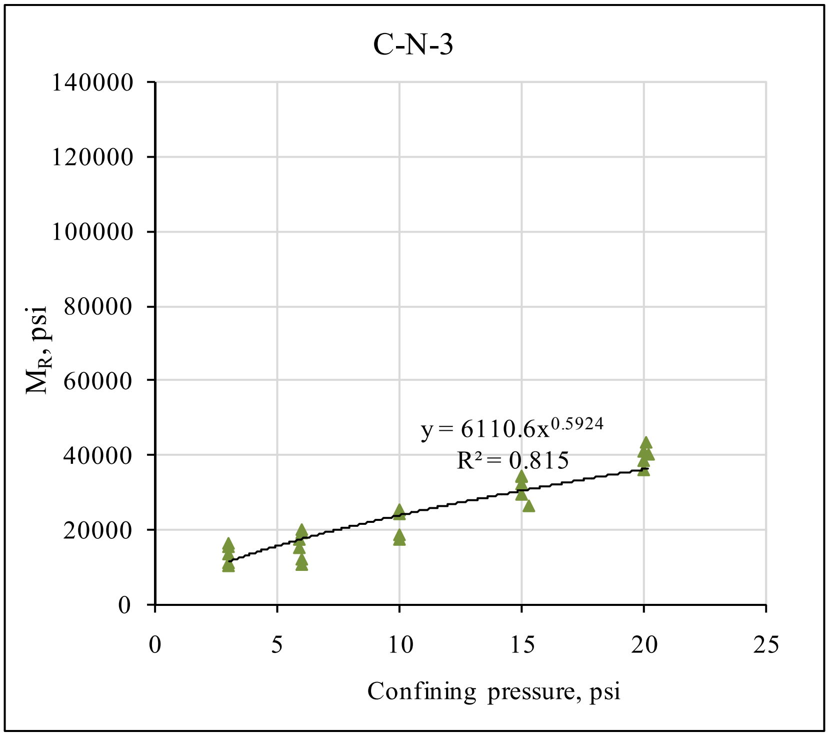

Figure D.3 M_R vs. confining pressure for Class 5 (OMC + 1%, 99% MDD)

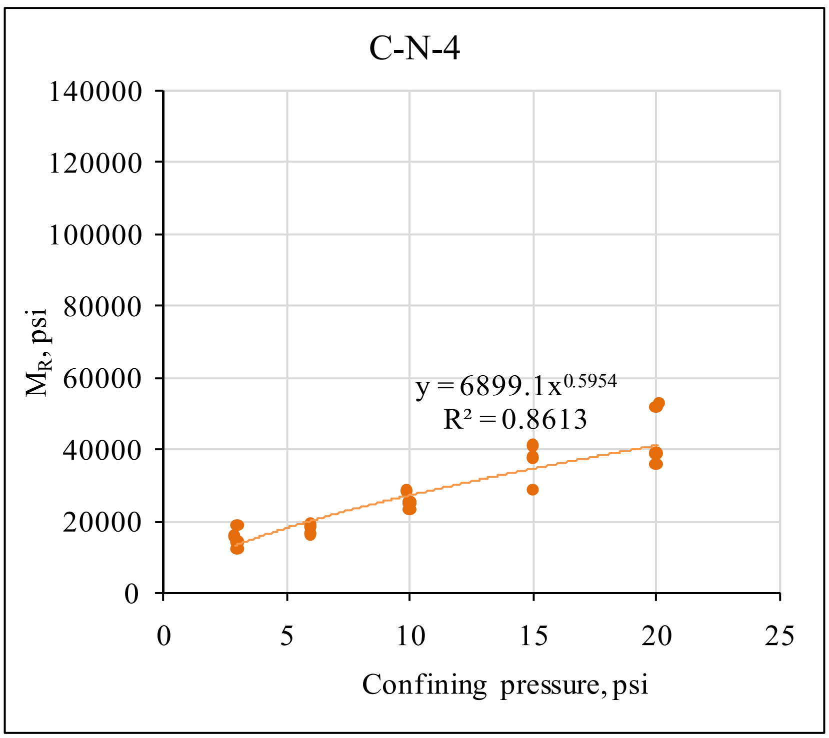

Figure D.4 M_R vs. confining pressure for Class 5 (OMC + 2%, 97% MDD)

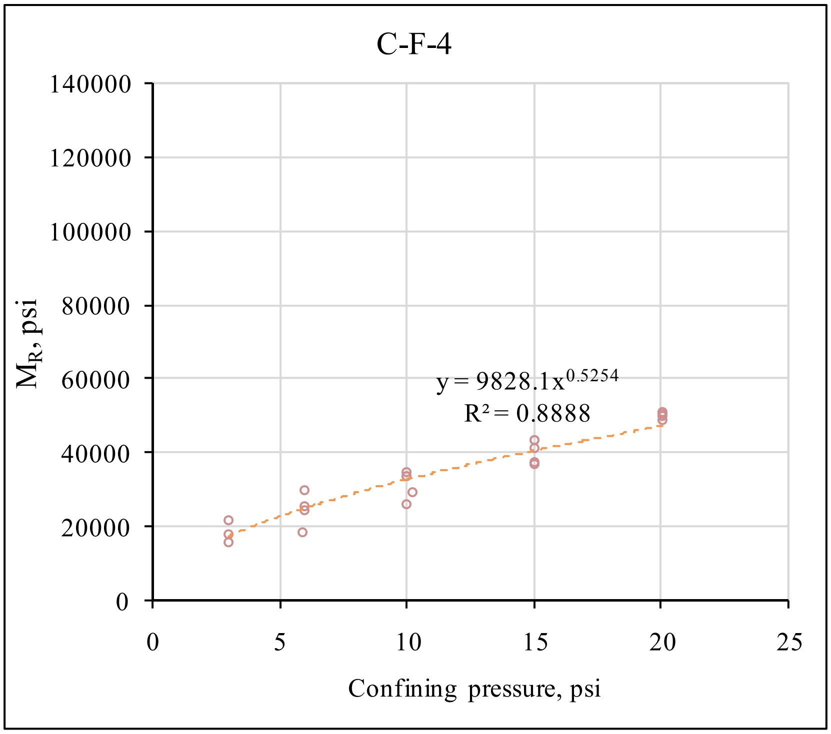

Figure D.5 M_R vs. confining pressure for Class 5 (OMC + 2%, 100% MDD, 2 F-T)

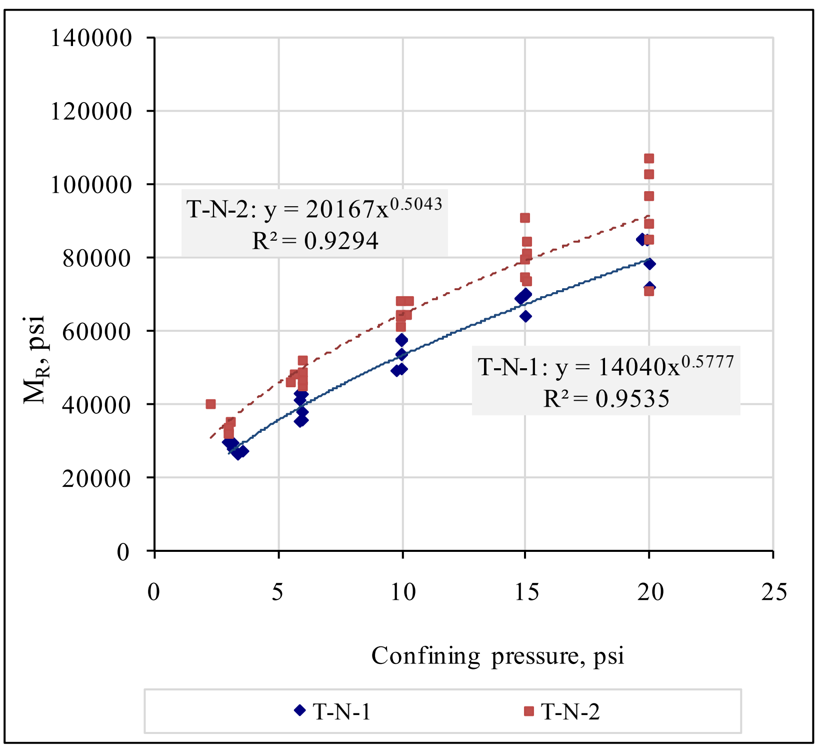

Figure D.6 M_R vs. confining pressure for 50% Class 5 + 50% RAP TH 10 (OMC, 100% MDD), (one sample and a replicate)

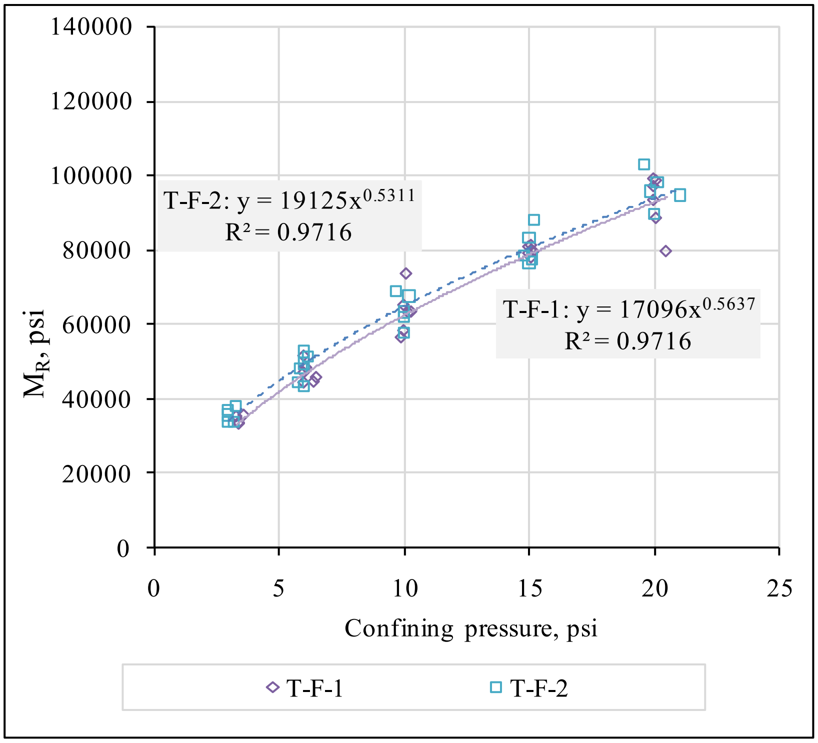

Figure D.7 M_R vs. confining pressure for 50% Class 5 + 50% RAP TH 10 (OMC, 100% MDD, 2 F-T), (one sample and a replicate)

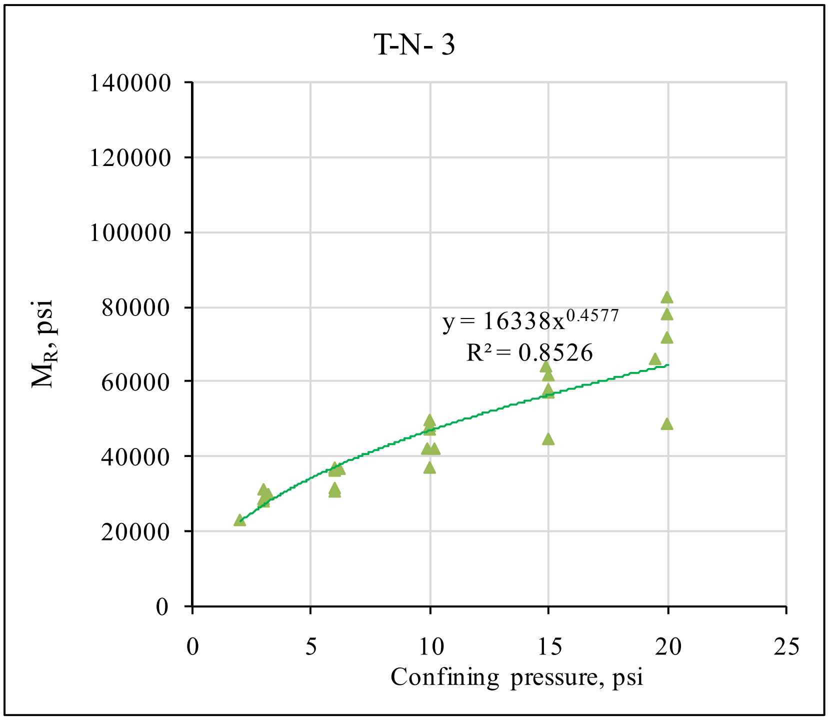

Figure D.8 M_R vs. confining pressure for 50% Class 5 + 50% RAP TH 10 (OMC + 1%, 100% MDD)

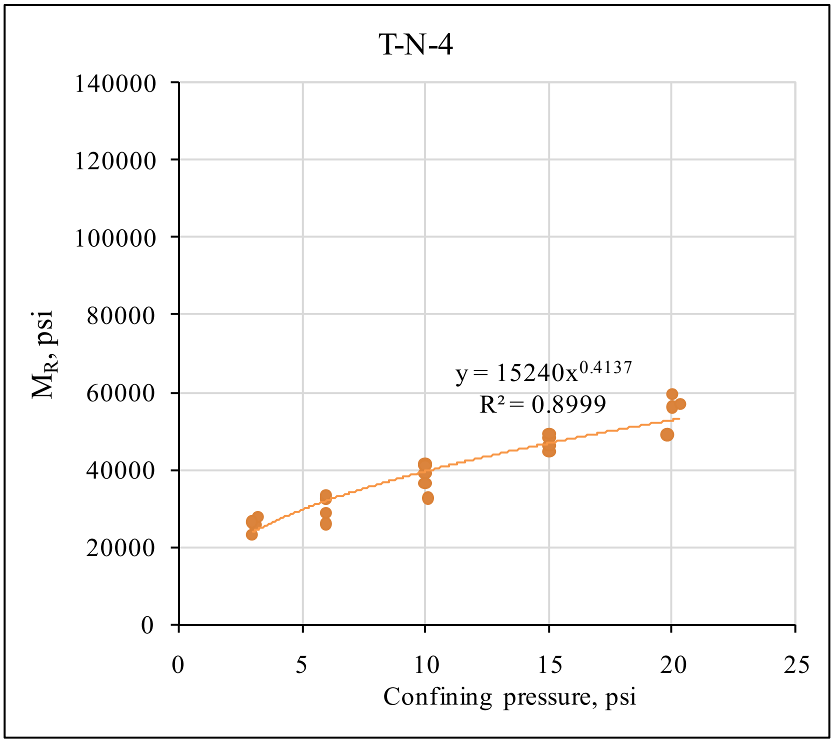

Figure D.9 M_R vs. confining pressure for 50% Class 5 + 50% RAP TH 10 (OMC + 2%, 98.5% MDD)

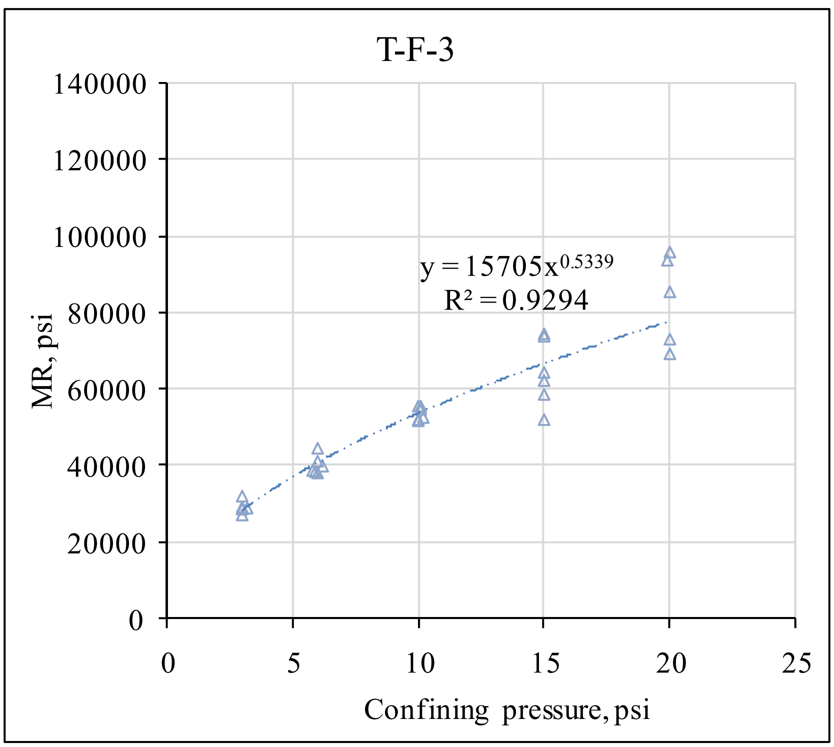

Figure D.10 M_R vs. confining pressure for 50% Class 5 + 50% RAP TH 10 (OMC + 1%, 100% MDD, 2 F-T)

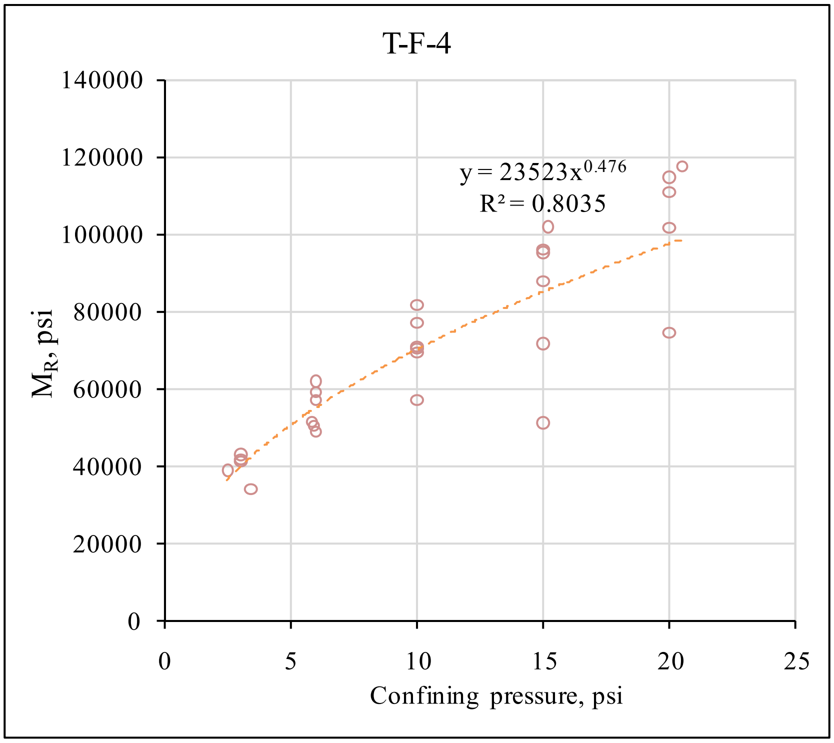

Figure D.11 M_R vs. confining pressure for 50% Class 5 + 50% RAP TH 10 (OMC + 2%, 98% MDD, 2 F-T)

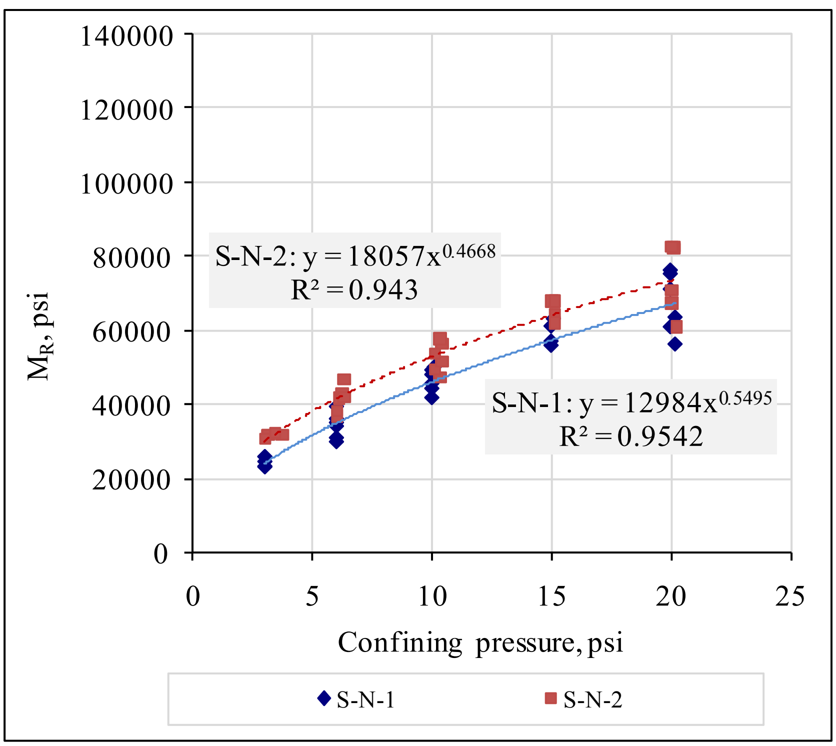

Figure D.12 M_R vs. confining pressure for 25% Class 5 + 75% RAP TH 10 (OMC, 100% MDD), (one sample and a replicate)

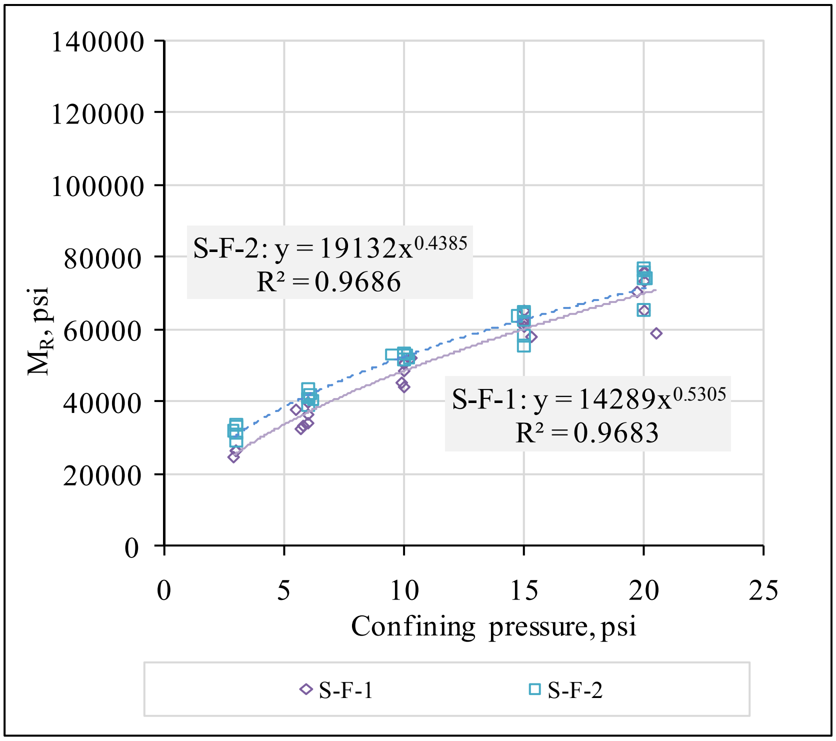

Figure D.13 M_R vs. confining pressure for 25% Class 5 + 75% RAP TH 10 (OMC, 100% MDD, freeze-thaw conditioned), (one sample and a replicate)

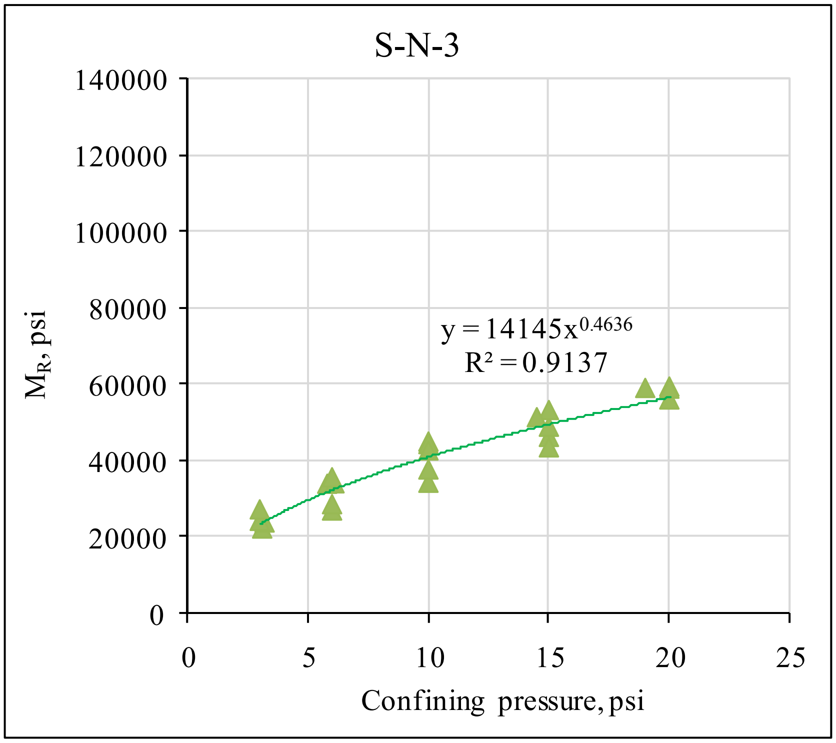

Figure D.14 M_R vs. confining pressure for 25% Class 5 + 75% RAP TH 10 (OMC + 1%, 97.6% MDD)

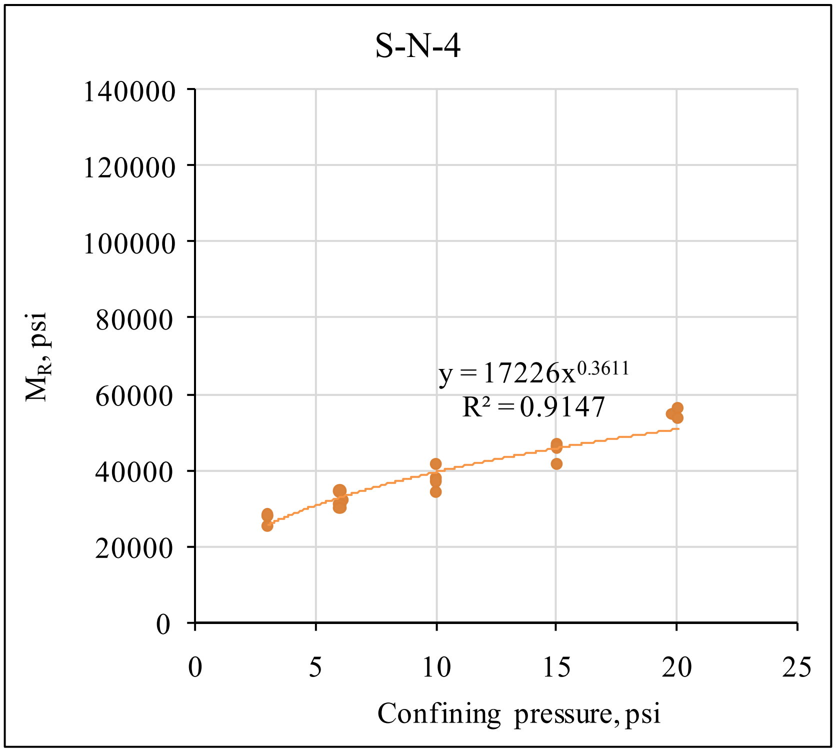

Figure D.15 M_R vs. confining pressure for 25% Class 5 + 75% RAP TH 10 (OMC + 2%, 97% MDD)

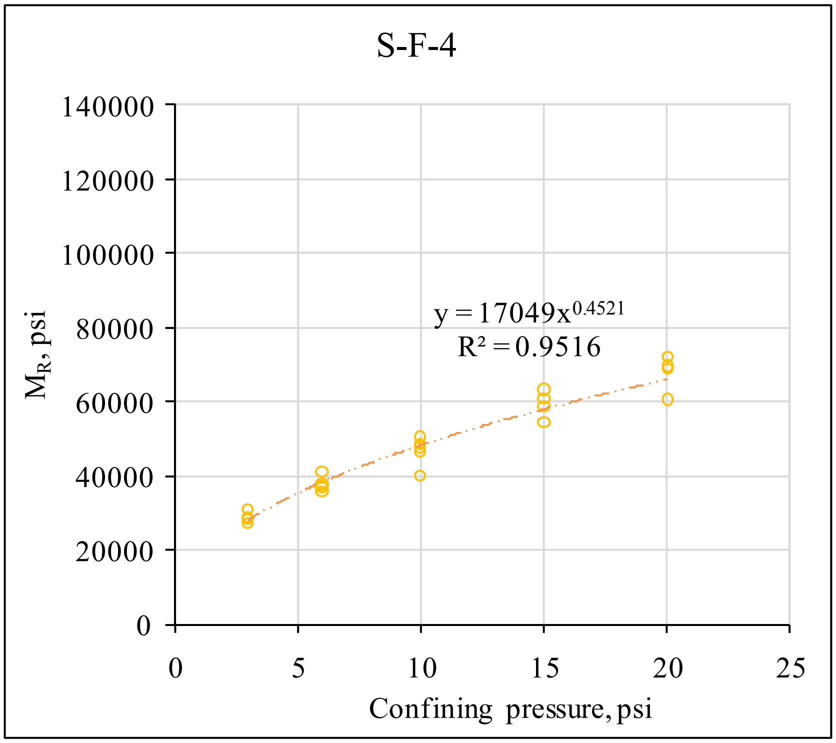

Figure D.16 M_R vs. confining pressure for 25% Class 5 + 75% RAP TH 10 (OMC + 2%, 96% MDD, freeze-thaw conditioned)

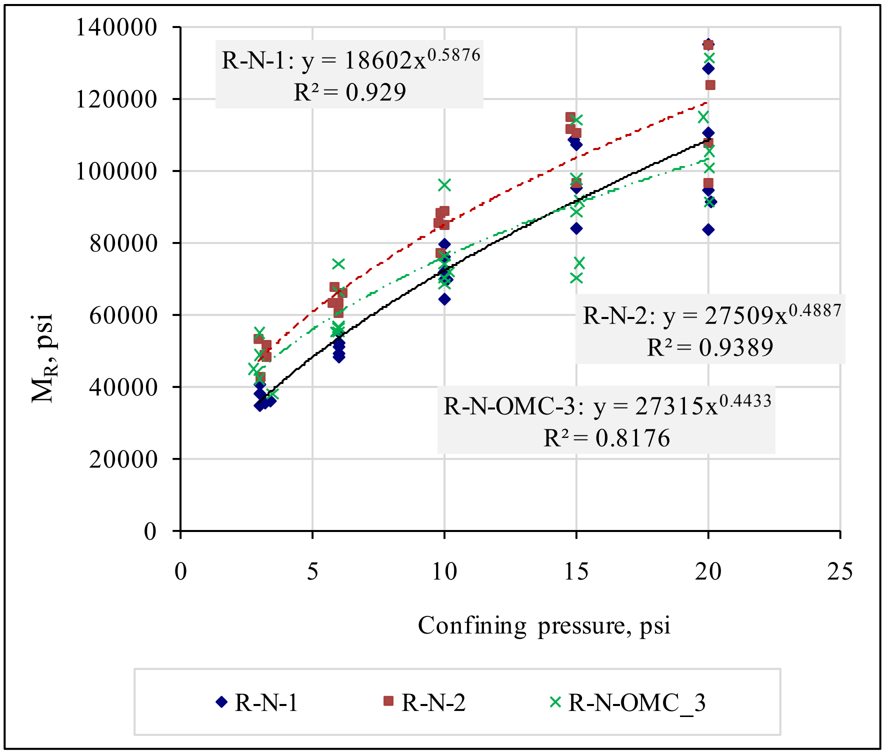

Figure D.17 M_R vs. confining pressure for 100% RAP TH 10 (OMC, 100% MDD), (one sample and 2 replicates)

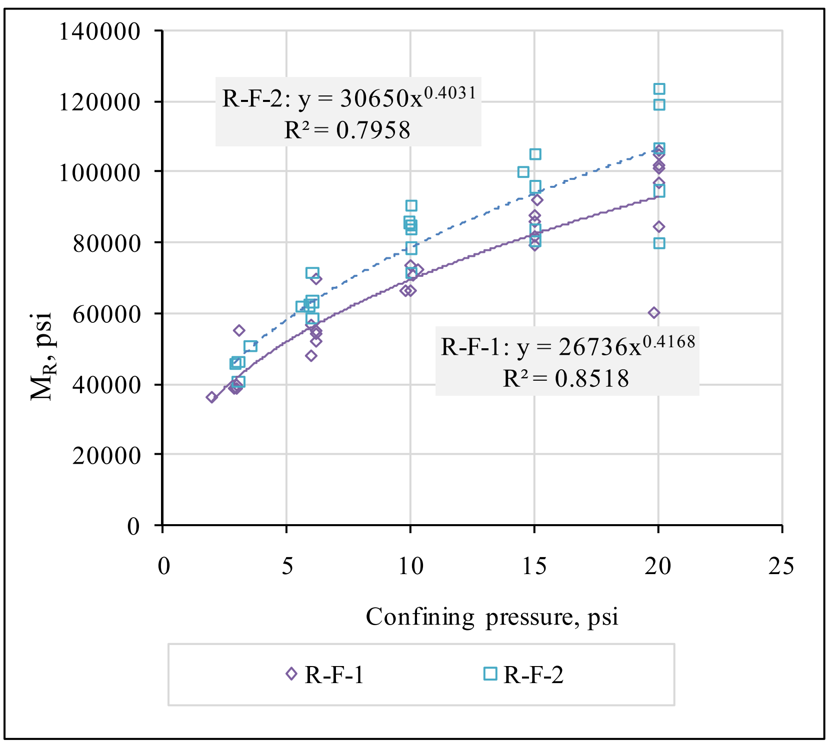

Figure D.18 M_R vs. confining pressure for 100% RAP TH 10 (OMC, 100% MDD freeze-thaw conditioned)

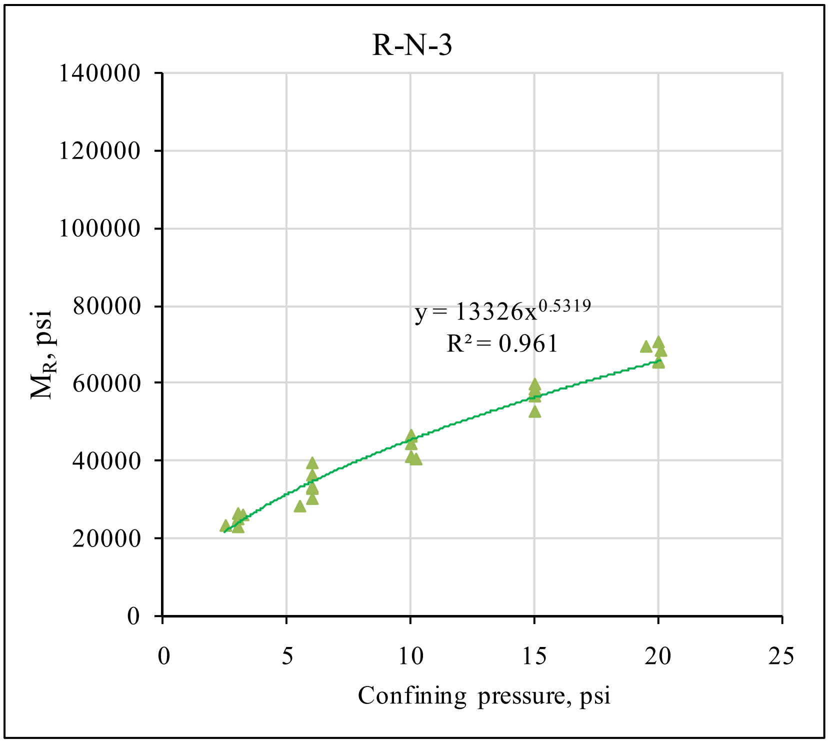

Figure D.19 M_R vs. confining pressure for 100% RAP TH 10 (OMC + 1%, 100% MDD)

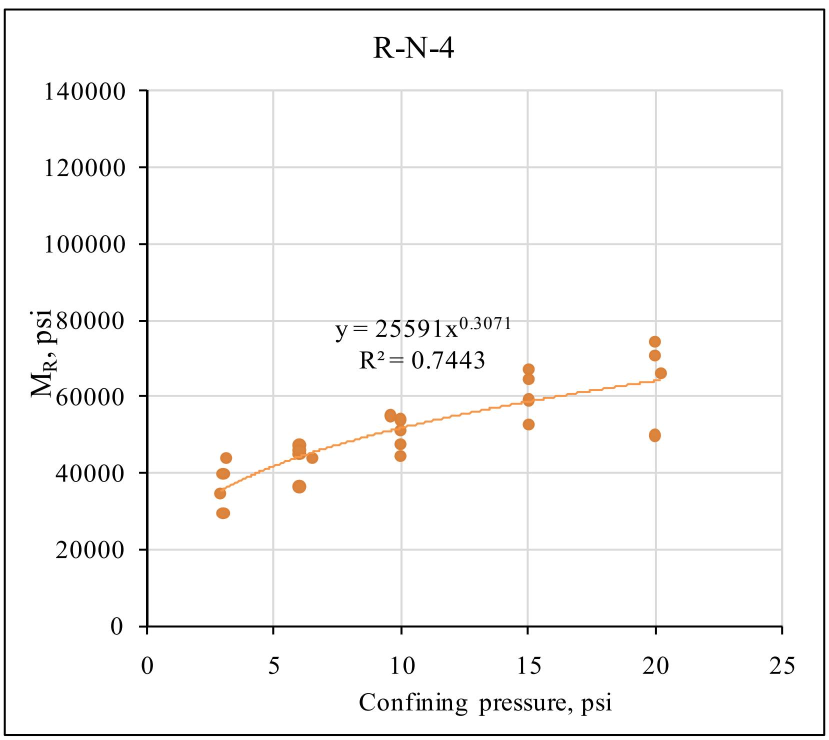

Figure D.20 M_R vs. confining pressure for 100% RAP TH 10 (OMC + 2%, 97.5% MDD)

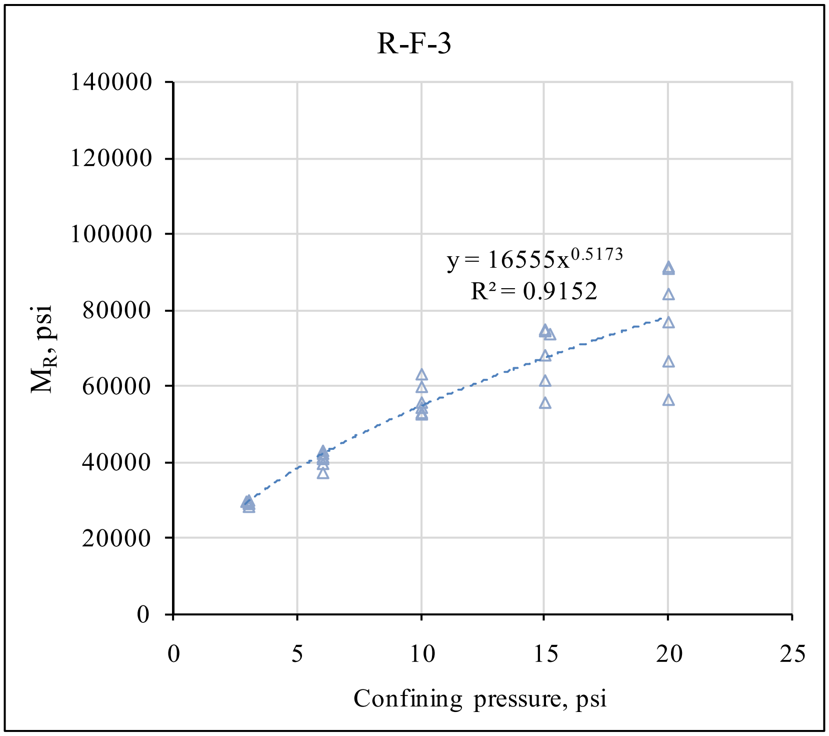

Figure D.21 M_R vs. confining pressure for 100% RAP TH 10 (OMC + 1%, 100% MDD, 2 F-T)

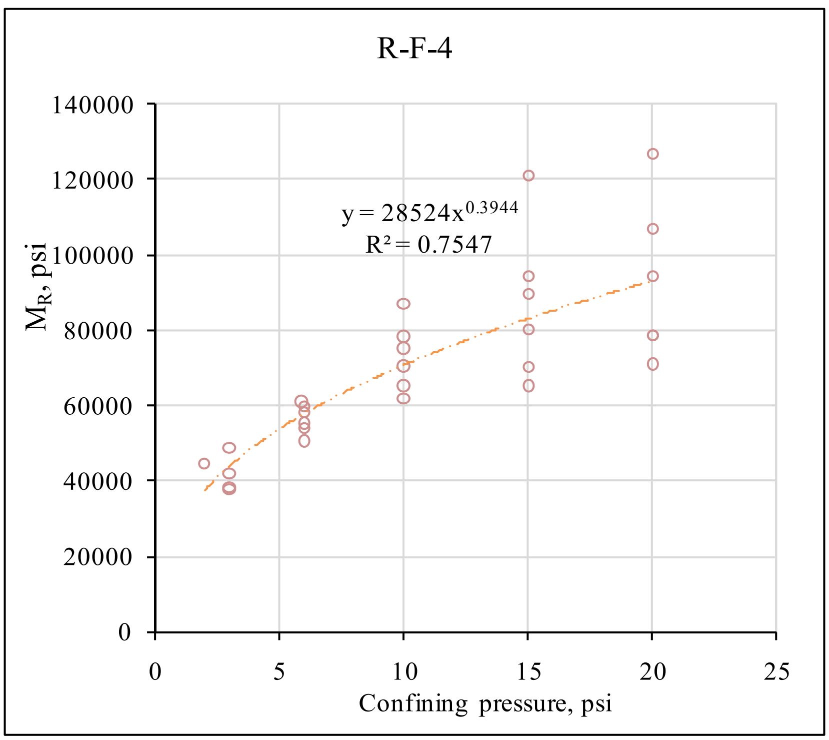

Figure D.22 M_R vs. confining pressure for 100% RAP TH 10 (OMC + 2%, 98% MDD, 2 F-T)

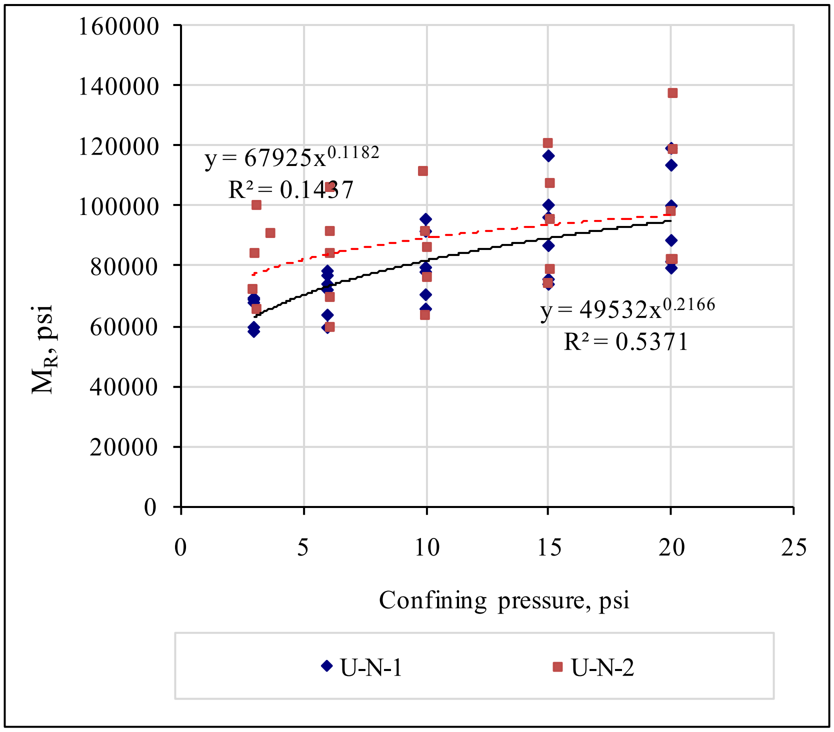

Figure D.23 M_R vs. confining pressure for RAP TH 19-101 (OMC, 100% MDD), one sample and a replicate

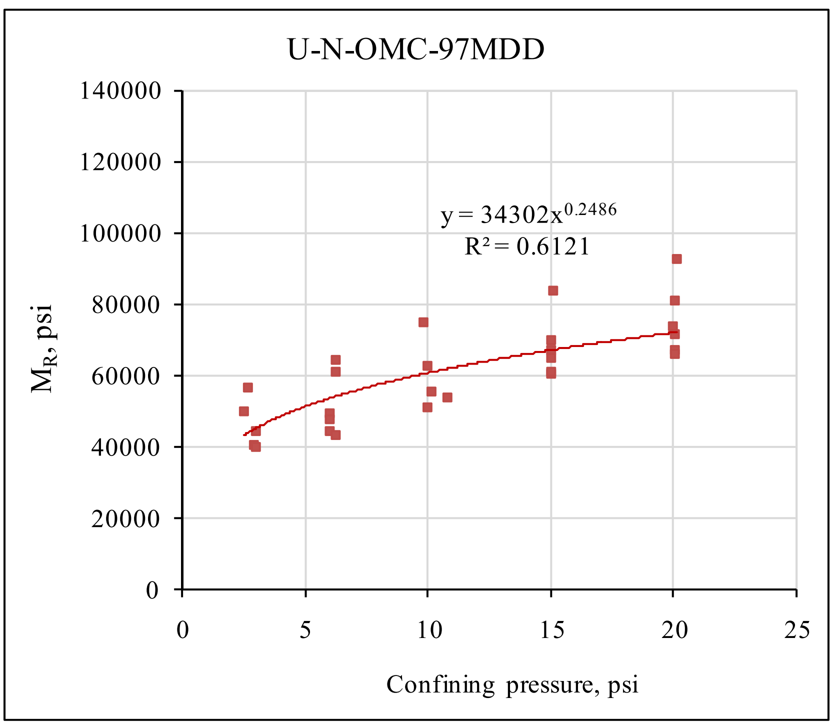

Figure D.24 M_R vs. confining pressure for RAP TH 19-101 (OMC, 97.5% MDD)

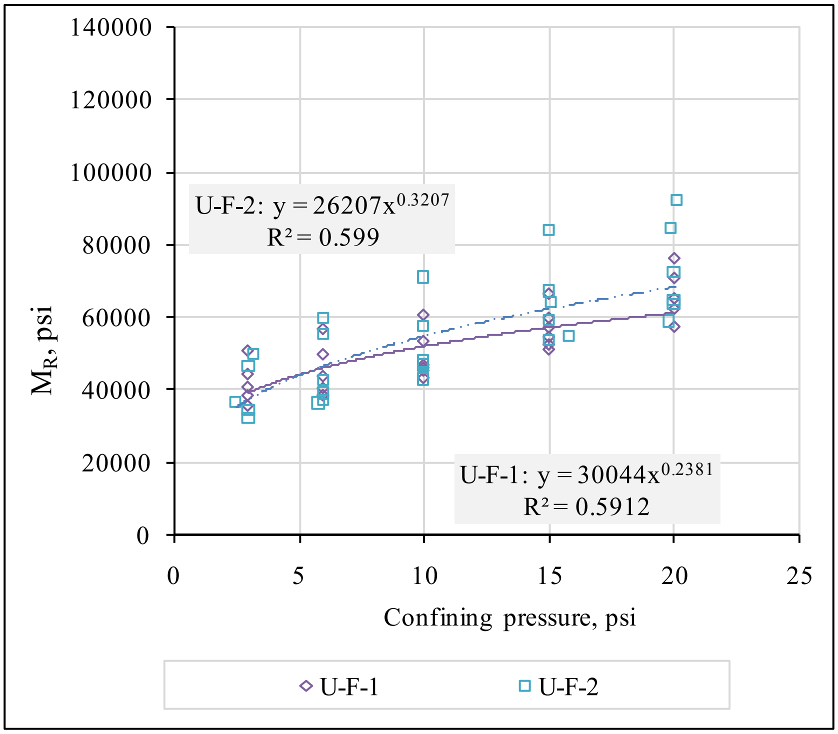

Figure D.25 M_R vs. confining pressure for RAP TH 19-101 (OMC, 100% MDD, freeze-thaw conditioned), (one sample and a replicate)

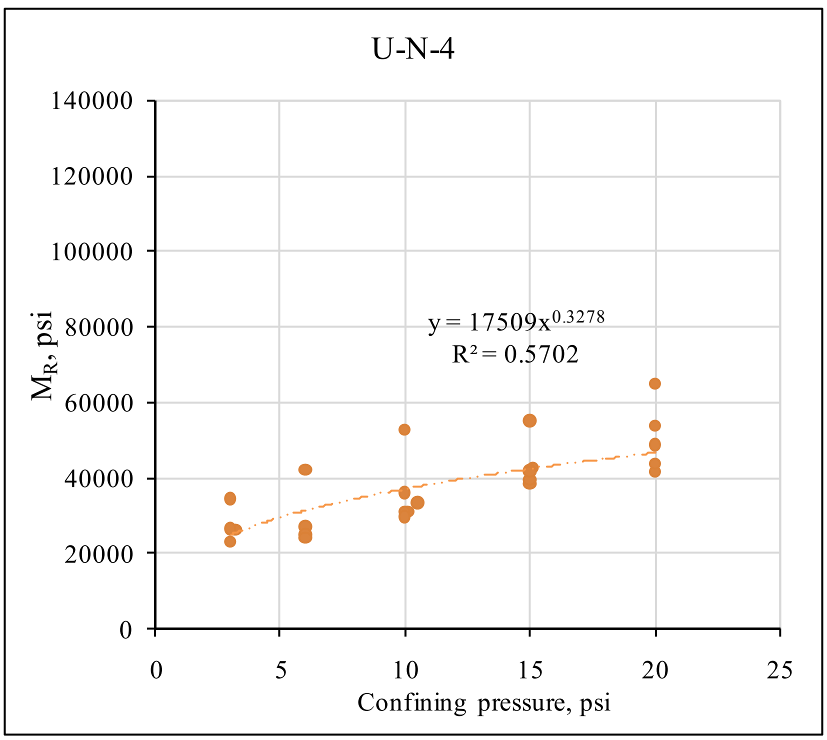

Figure D.26 M_R vs. confining pressure for RAP TH 19-101 (OMC + 2%, 100% MDD)

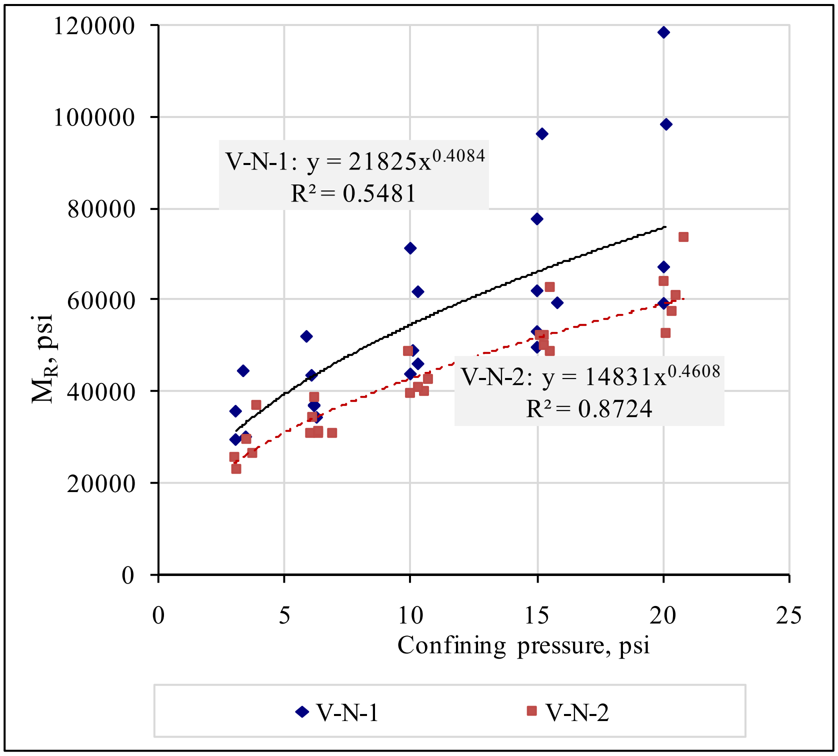

Figure D.27 M_R vs. confining pressure for RAP TH 19-104 (OMC, 100% MDD), (one sample and a replicate)

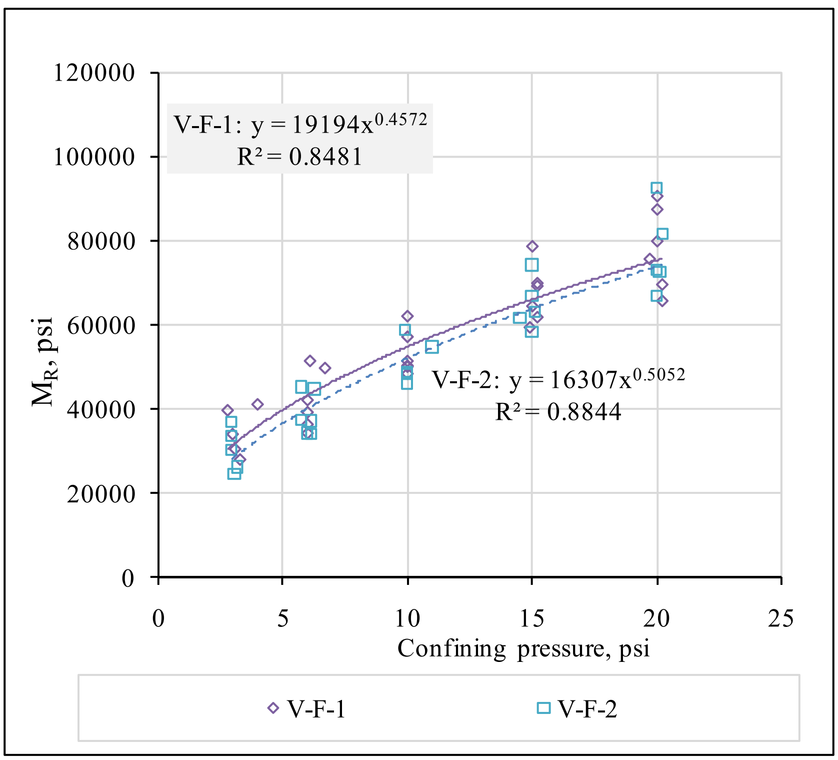

Figure D.28 M_R vs. confining pressure for RAP TH 19-104 (OMC, 100% MDD, 2 F-T)

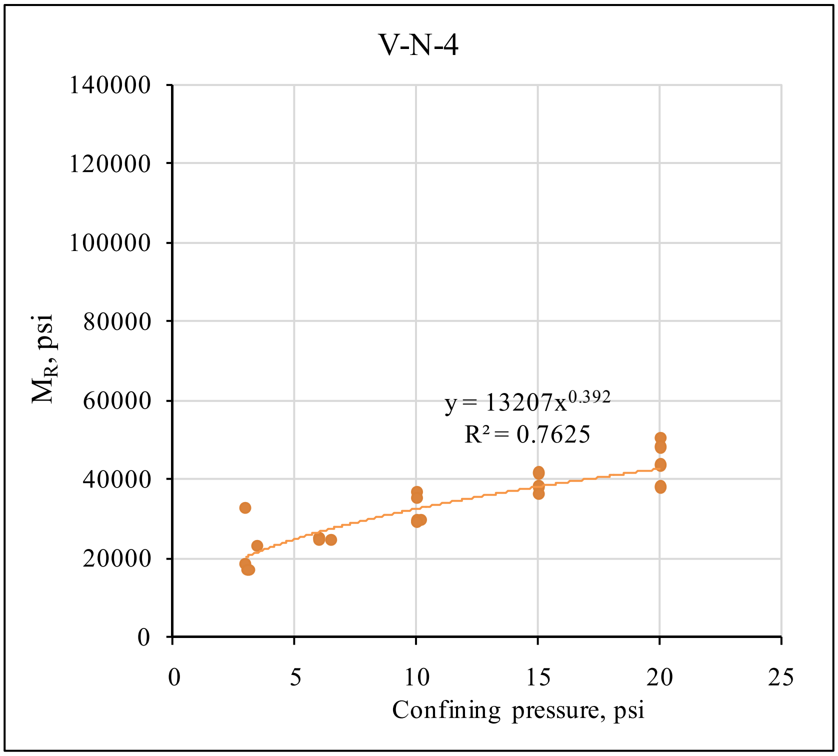

Figure D.29 M_R vs. confining pressure for RAP TH 19-104 (OMC + 2%, 97% MDD)

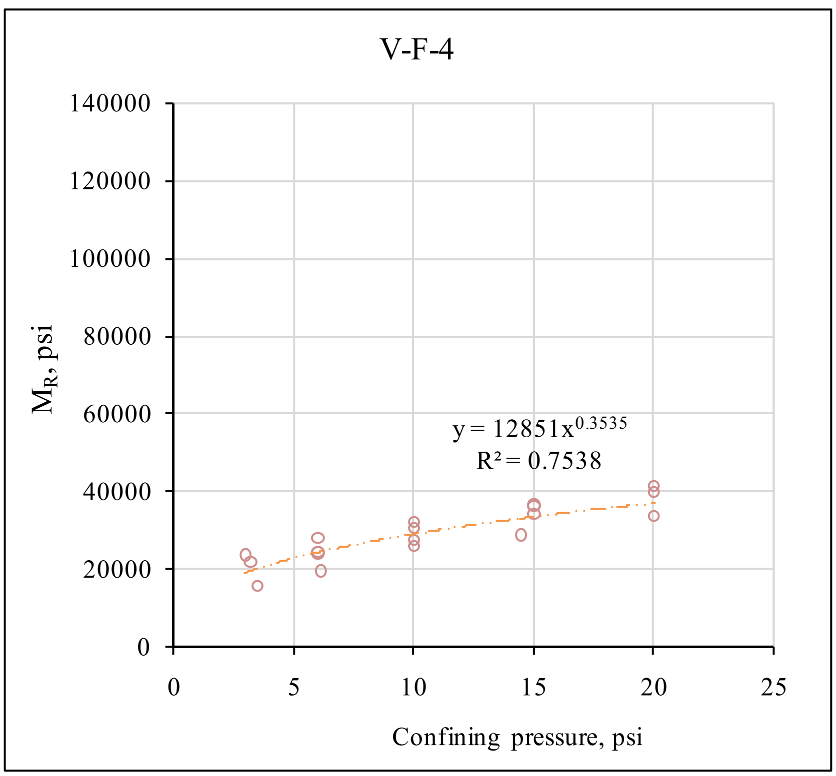

Figure D.30 M_R vs. confining pressure for RAP TH 19-104 (OMC + 2%, 97% MDD, 2 F-T)

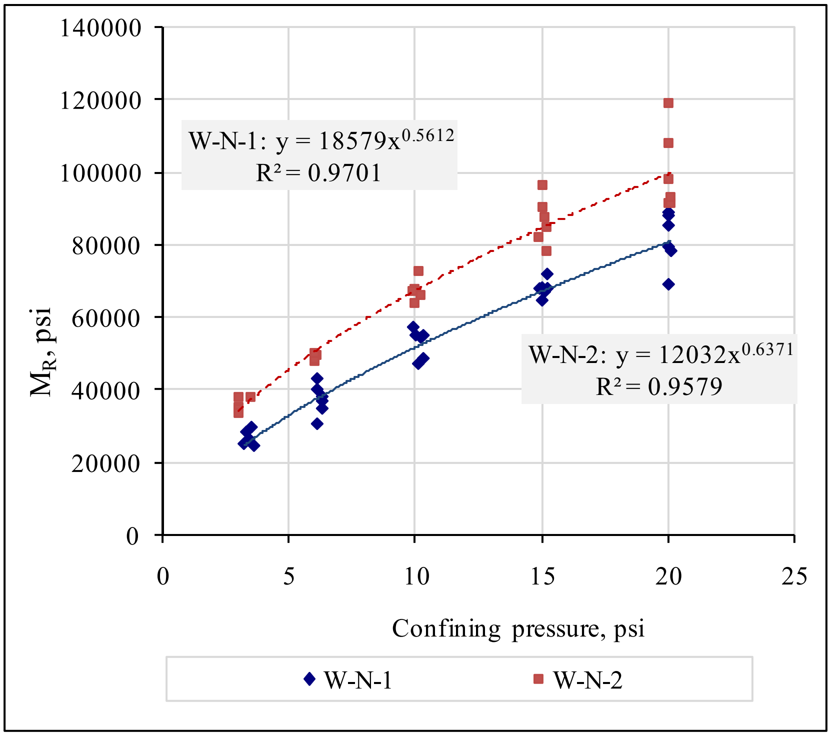

Figure D.31 M_R vs. confining pressure for RAP TH 22 (OMC, 100% MDD), (one sample and a replicate)

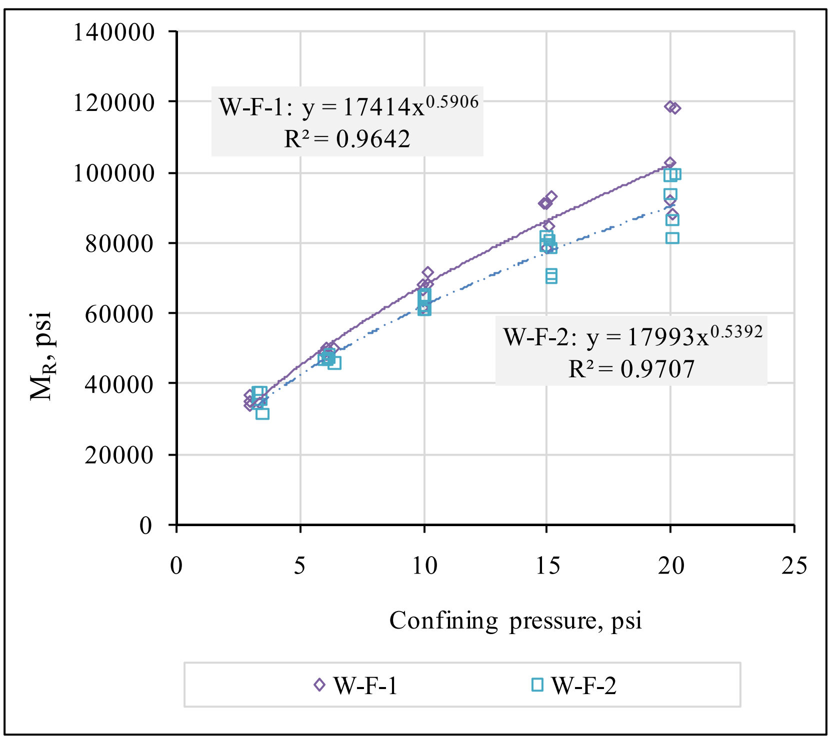

Figure D.32 M_R vs. confining pressure for RAP TH 22 (OMC, 100% MDD, 2 F-T), (one sample and a replicate)

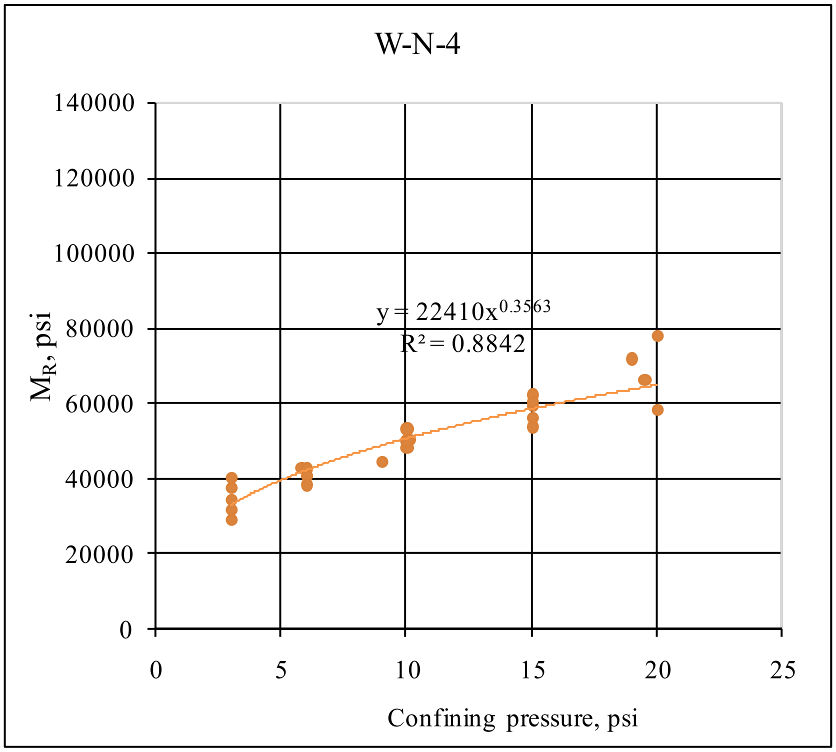

Figure D.33 M_R vs. confining pressure for RAP TH 22 (OMC + 2%, 98% MDD)

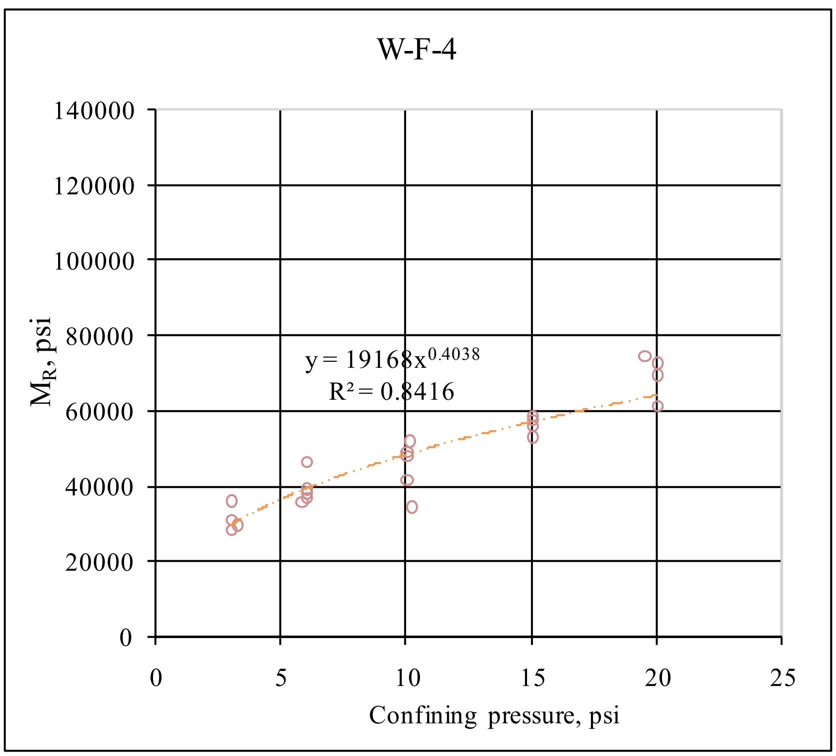

Figure D.34 M_R vs. confining pressure for RAP TH 22 (OMC + 2%, 98% MDD, 2 F-T)

Appendix E

Relation between Bulk Stress and Resilient Modulus

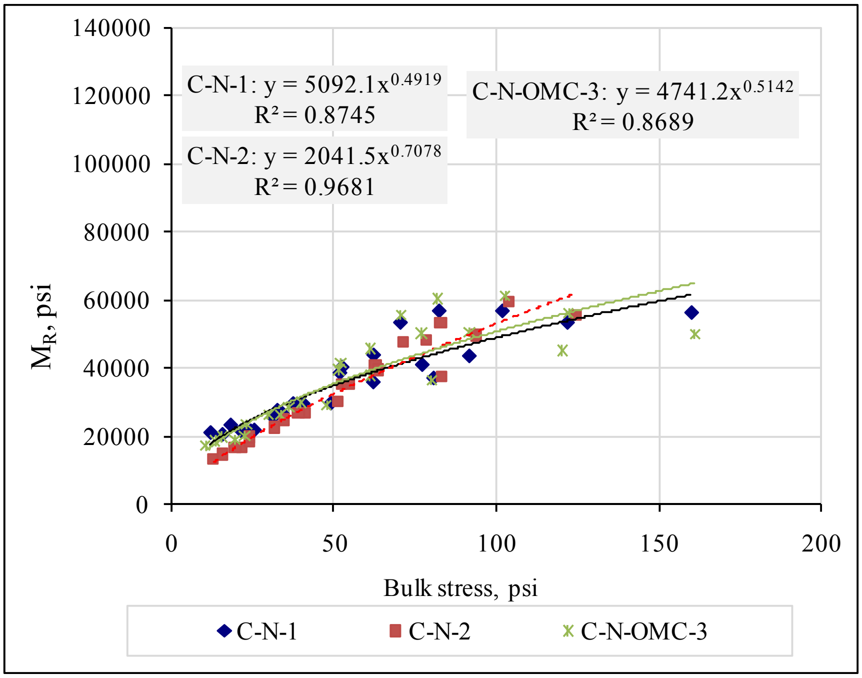

Figure E.1 M_R vs. bulk stress for Class 5 (OMC, 100% MDD, one sample and 2 replicates)

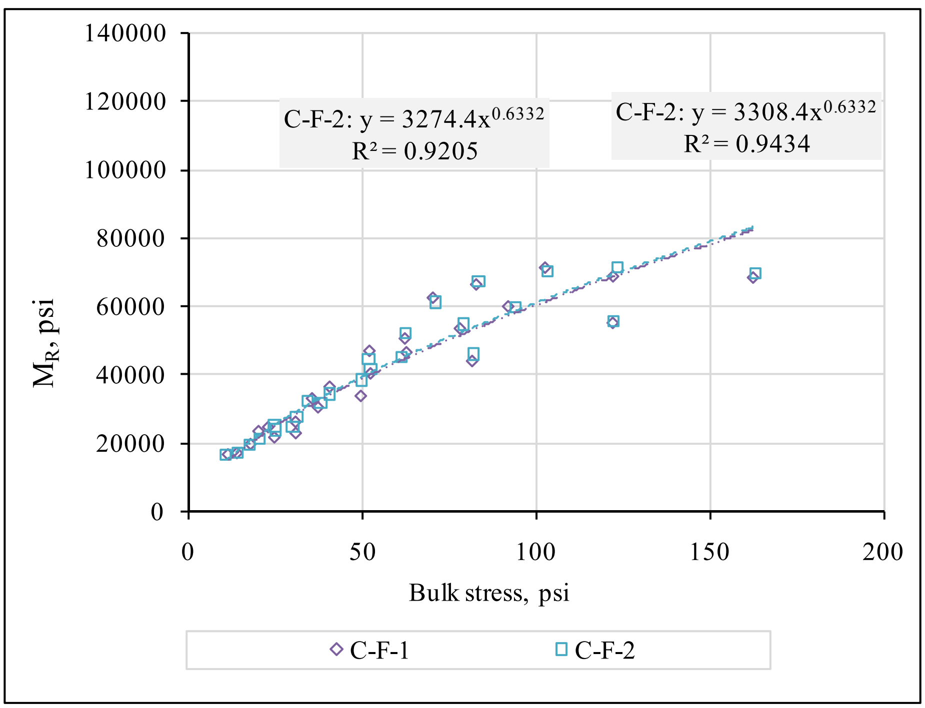

Figure E.2 M_R vs. bulk stress for Class 5 (OMC, 100% MDD, 2 F-T), (one sample and a replicate)

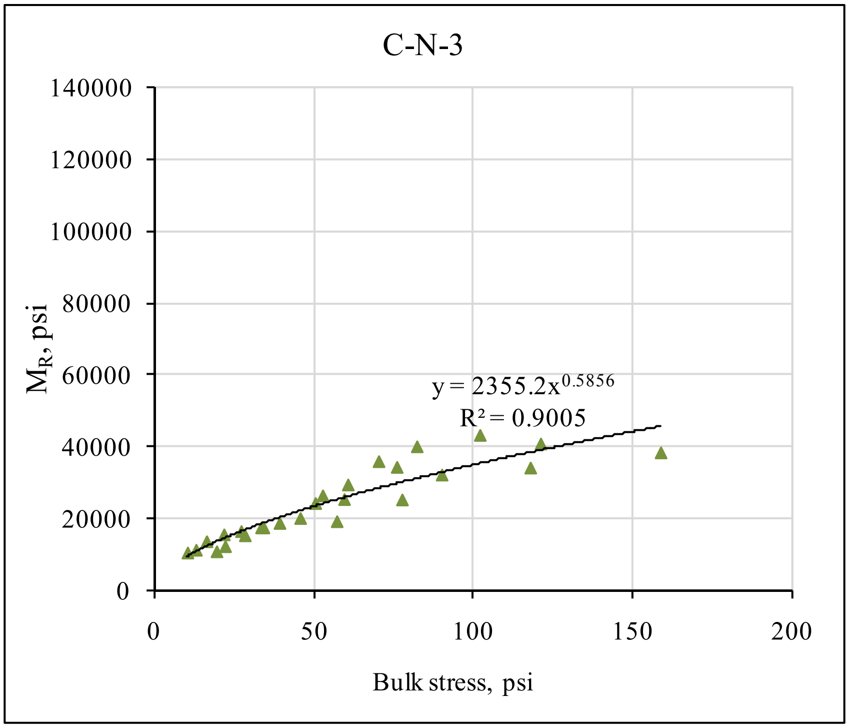

Figure E.3 M_R vs. bulk stress for Class 5 (OMC + 1%, 99% MDD)

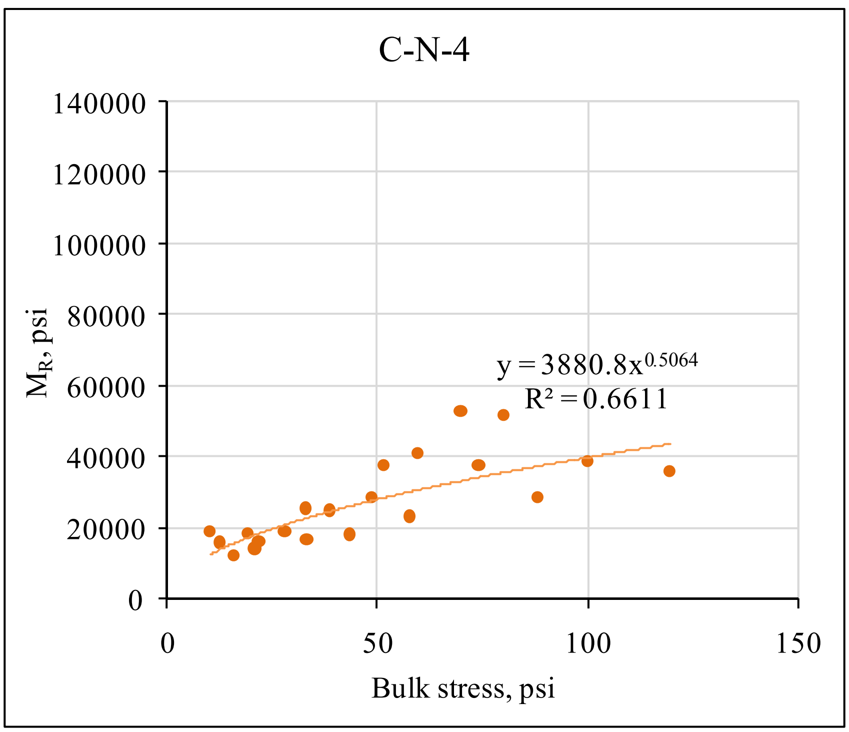

Figure E.4 M_R vs. bulk stress for Class 5 (OMC + 2%, 99% MDD)

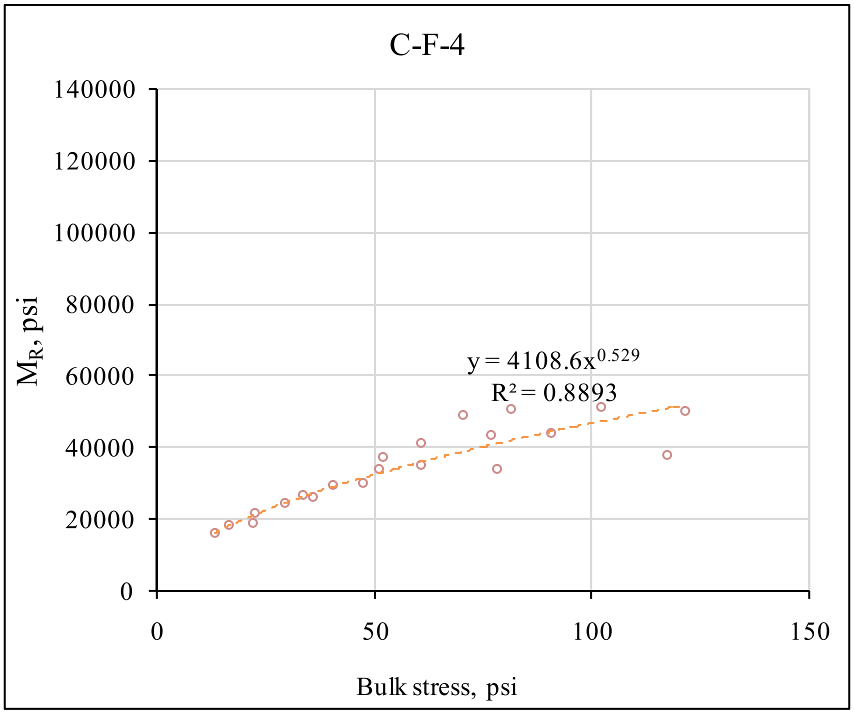

Figure E.5 M_R vs. bulk stress for Class 5 (OMC + 2%, 2 F-T)

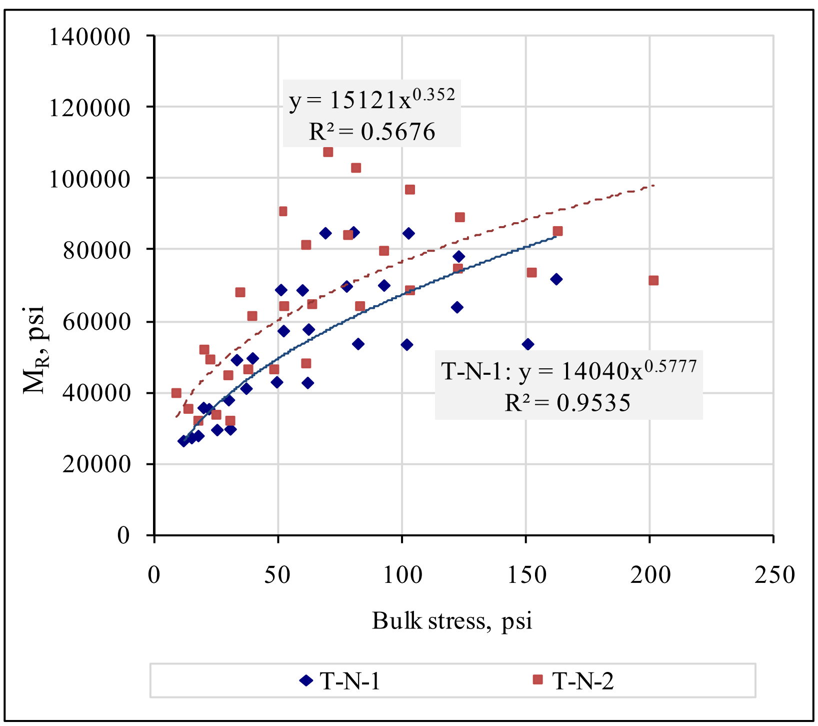

Figure E.6 M_R vs. bulk stress for 50% Class 5 + 50% RAP TH 10 (OMC, 100% MDD), (one sample and a replicate)

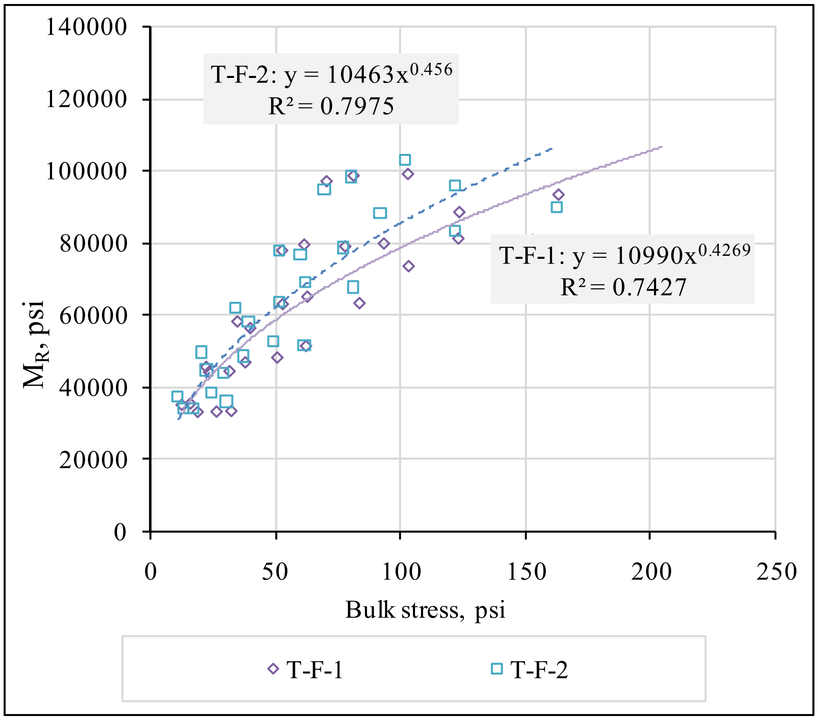

Figure E.7 M_R vs. bulk stress for 50% Class 5 + 50% RAP TH 10 (OMC, 100% MDD, 2 F-T), (one sample and a replicate)

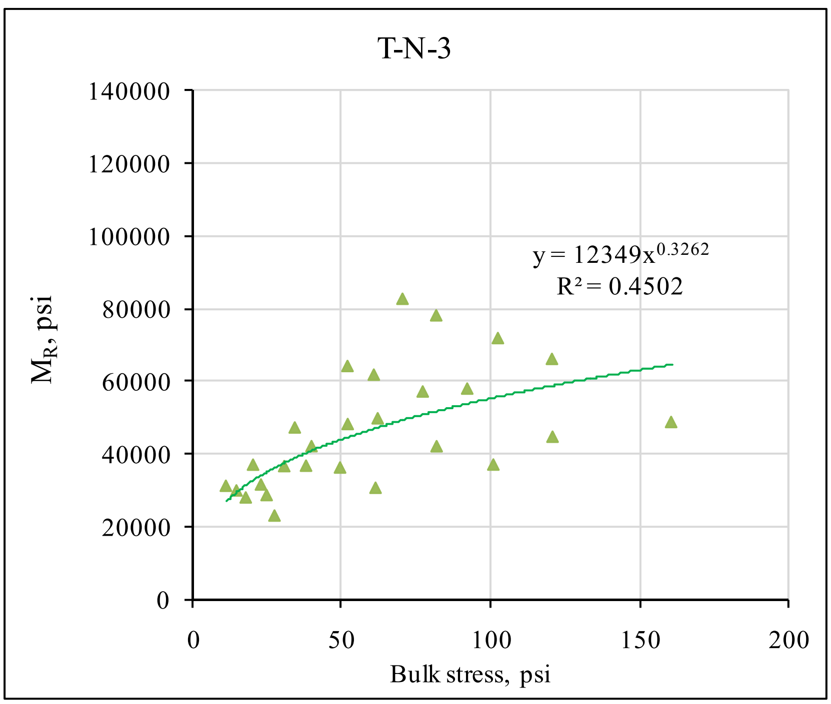

Figure E.8 M_R vs. bulk stress for 50% Class 5 + 50% RAP TH 10 (OMC + 1%, 100% MDD)

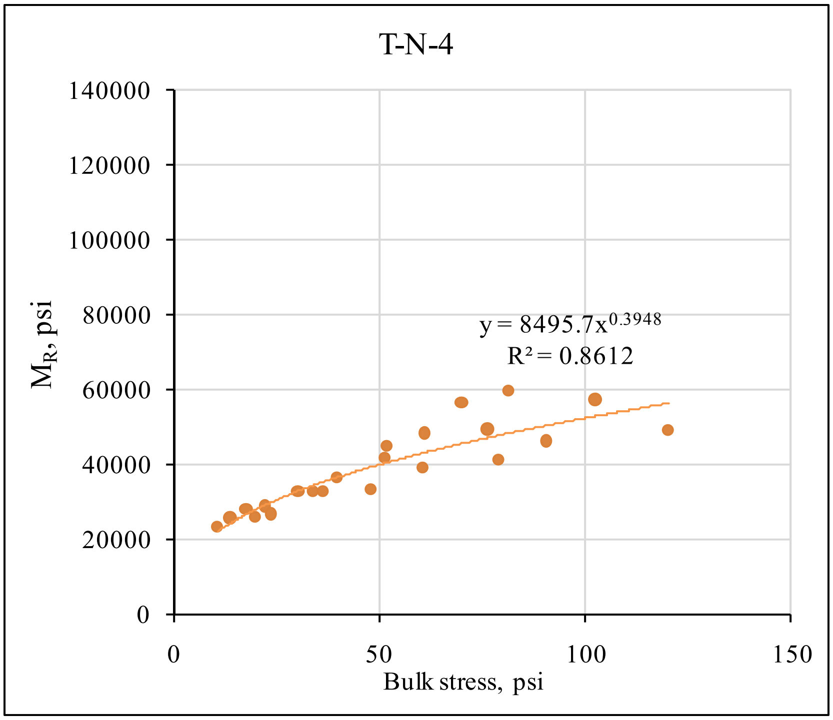

Figure E.9 M_R vs. bulk stress for 50% Class 5 + 50% RAP TH 10 (OMC + 2%, 98.5% MDD)

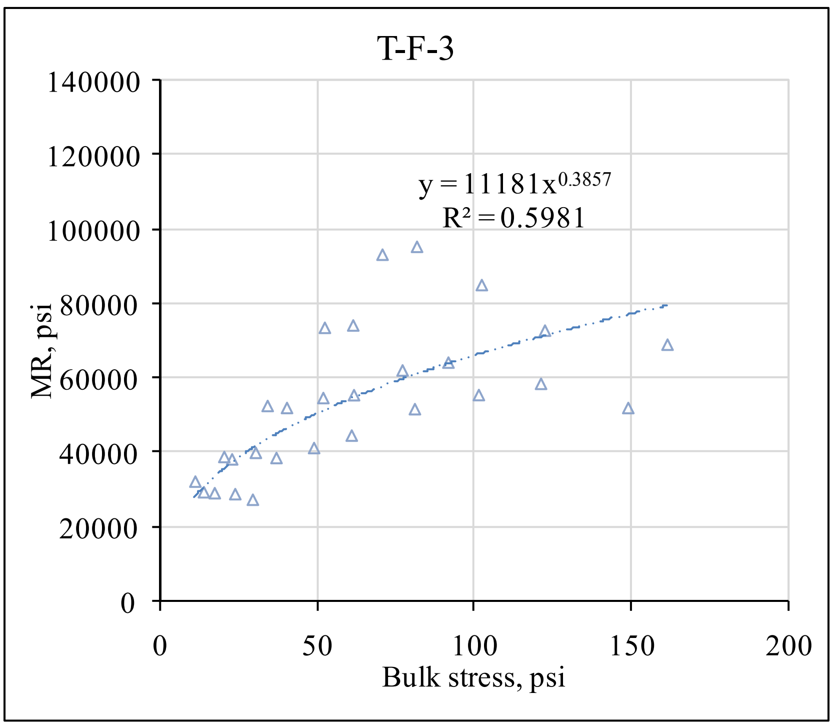

Figure E.10 M_R vs. bulk stress for 50% Class 5 + 50% RAP TH 10 (OMC + 1%, 100% MDD, 2 F-T)

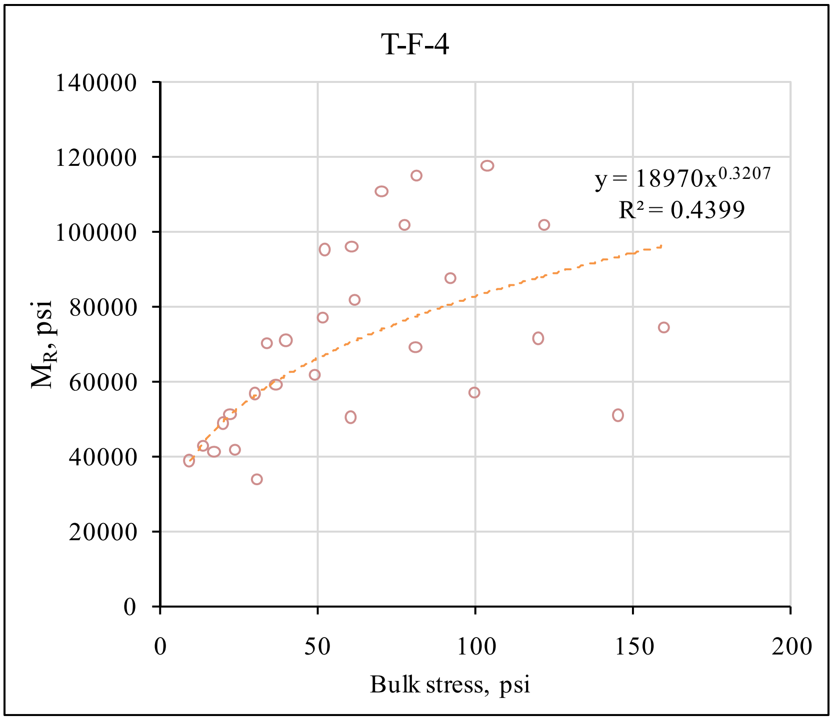

Figure E.11 M_R vs. bulk stress for 50% Class 5 + 50% RAP TH 10 (OMC + 2%, 98% MDD, 2 F-T)

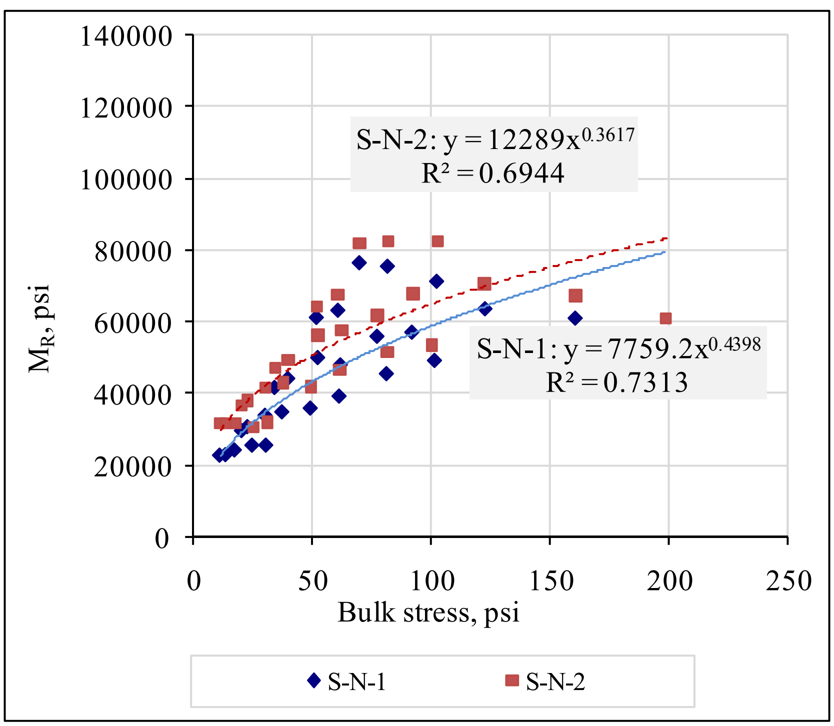

Figure E.12 M_R vs. bulk stress for 25% Class 5 + 75% RAP TH 10 (OMC, 100% MDD), (one sample and a replicate)

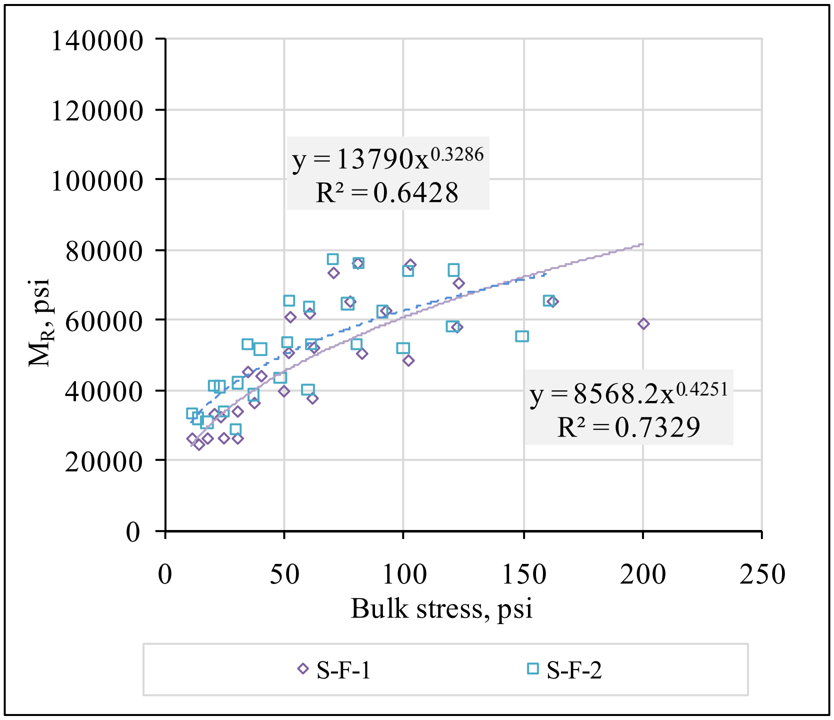

Figure E.13 M_R vs. bulk stress for 25% Class 5 + 75% RAP TH 10 (OMC, 100% MDD, 2 F-T), (one sample and a replicate)

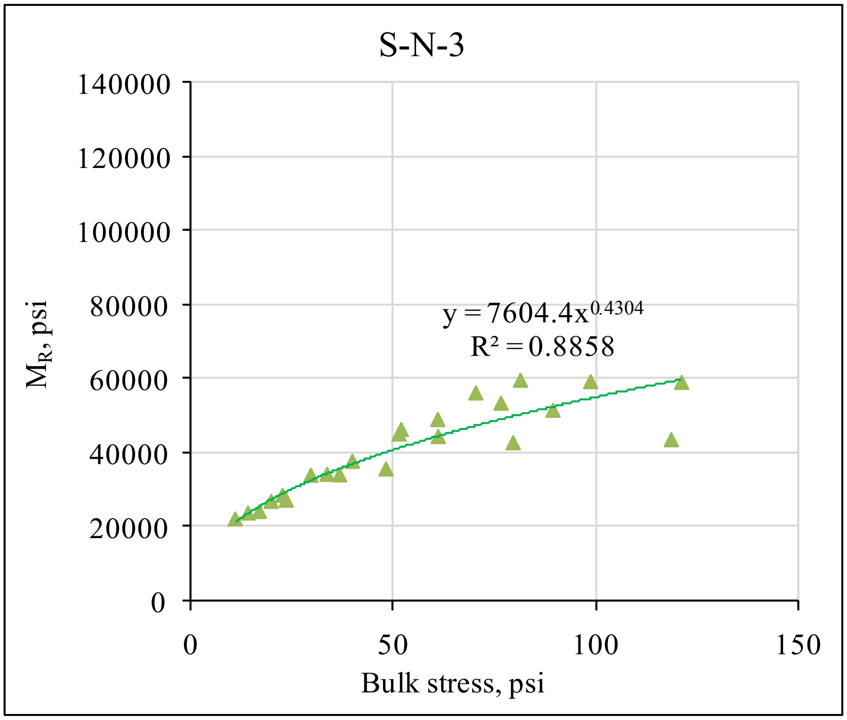

Figure E.14 M_R vs. bulk stress for 25% Class 5 + 75% RAP TH 10 (OMC + 1%, 97.6% MDD)

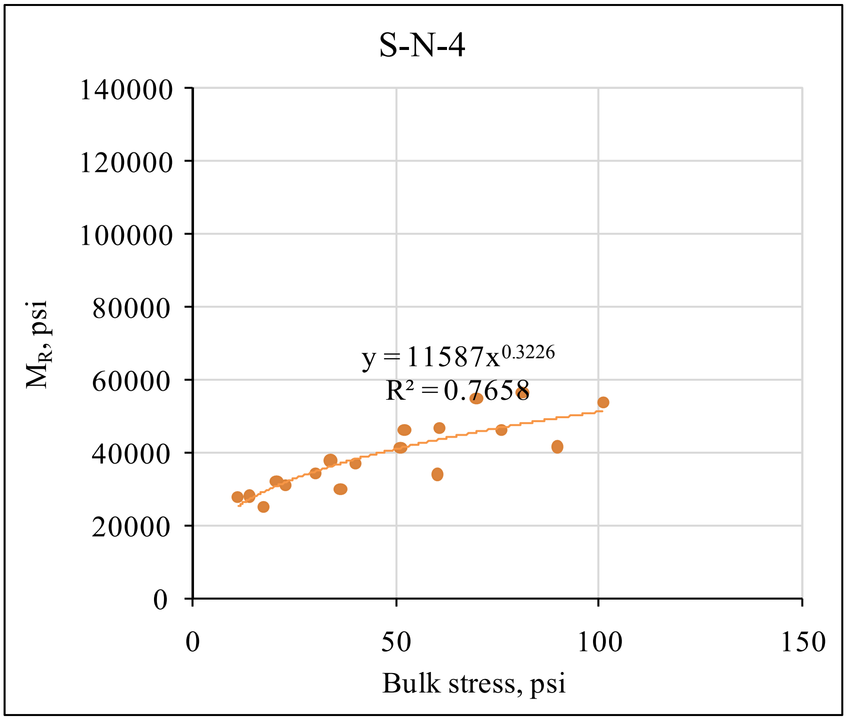

Figure E.15 M_R vs. bulk stress for 25% Class 5 + 75% RAP TH 10 (OMC + 2%, 97% MDD)

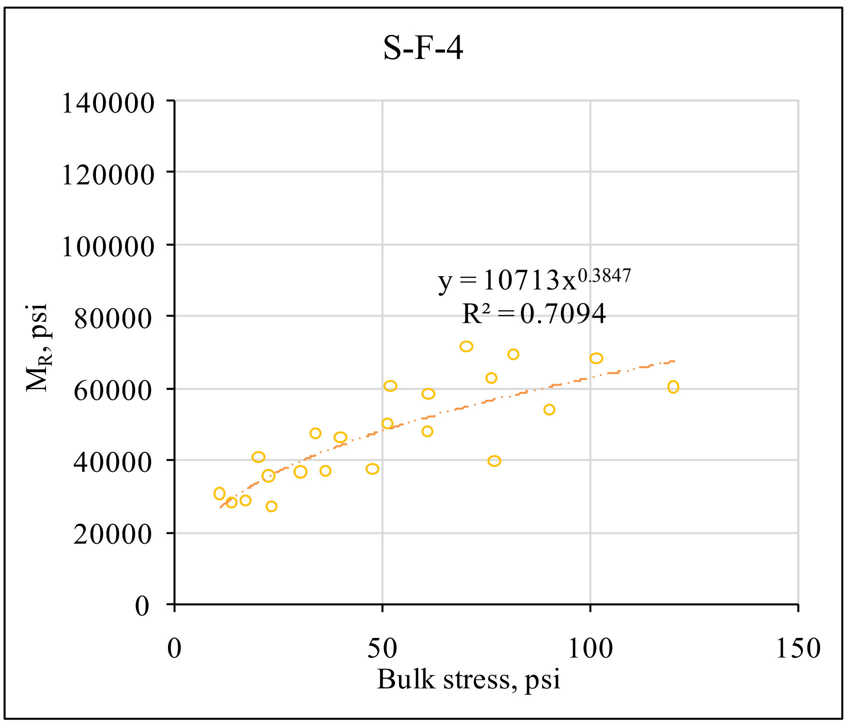

Figure E.16 M_R vs. bulk stress for 25% Class 5 + 75% RAP TH 10 (OMC + 2%, 96% MDD, 2 F-T)

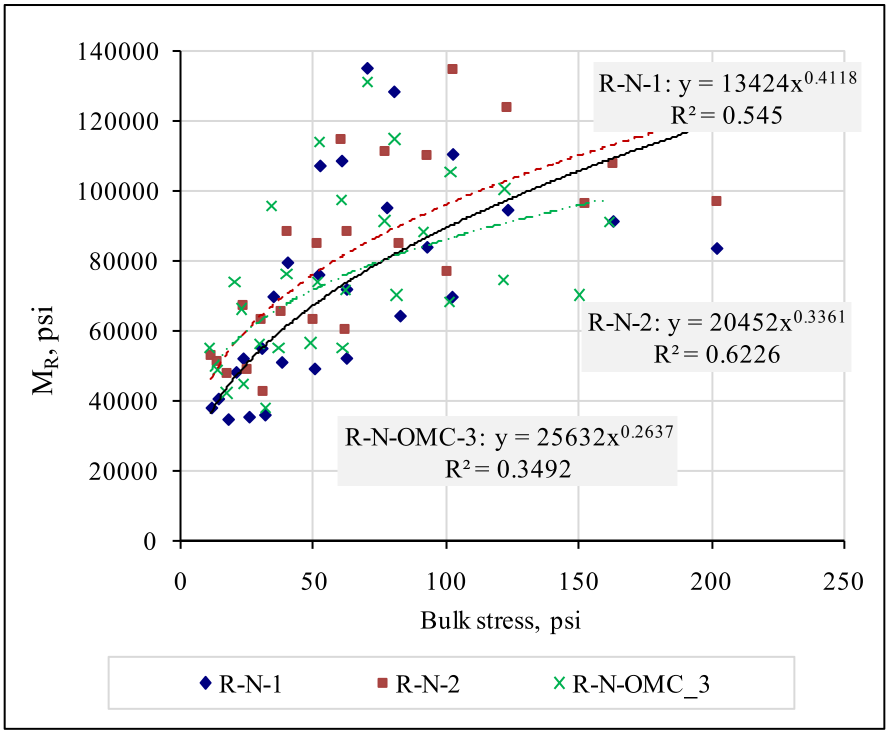

Figure E.17 M_R vs. bulk stress for 100% RAP TH 10 (OMC, 100% MDD), (one sample and 2 replicates)

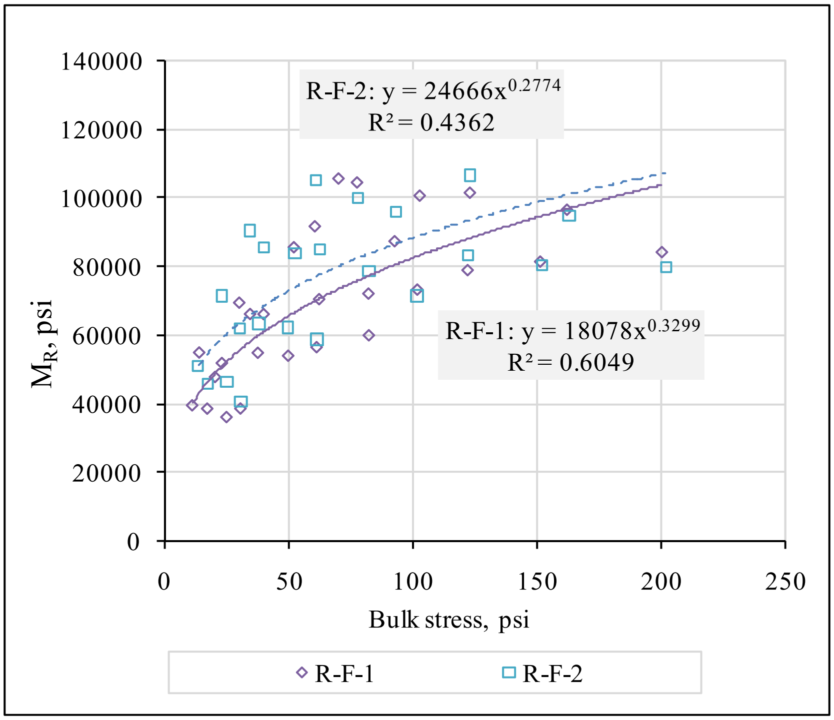

Figure E.18 M_R vs. bulk stress for 100% RAP TH 10 (OMC, 100% MDD, 2 F-T)

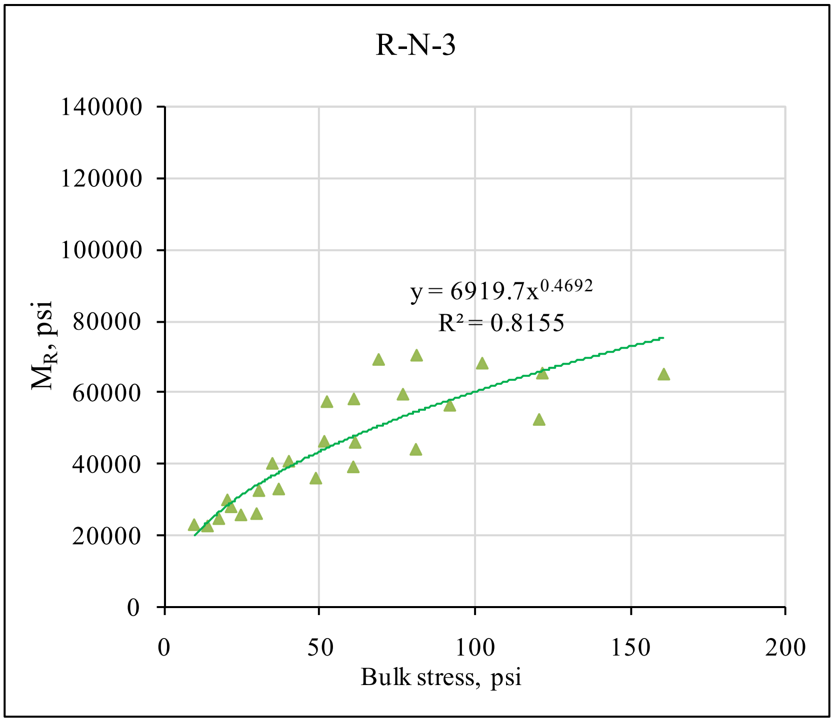

Figure E.19 M_R vs. bulk stress for 100% RAP TH 10 (OMC + 1%, 100% MDD)

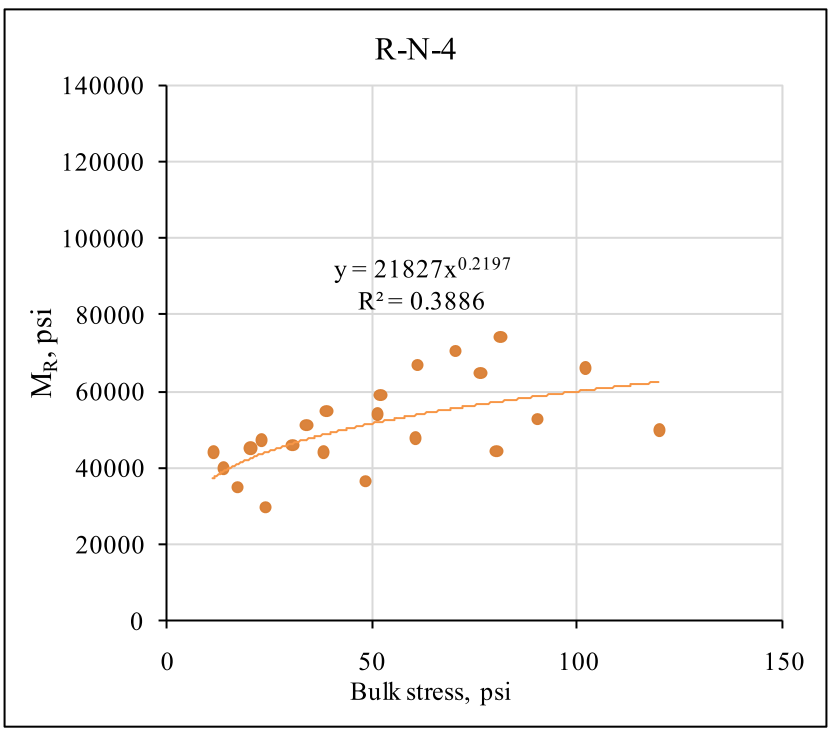

Figure E.20 M_R vs. bulk stress for 100% RAP TH 10 (OMC + 2%, 97.5% MDD)

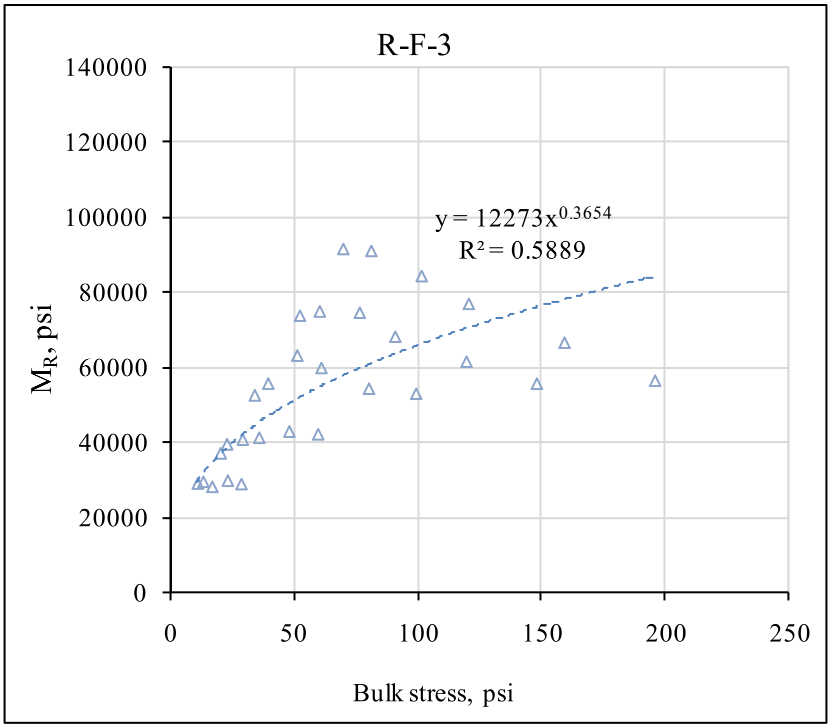

Figure E.21 M_R vs. bulk stress for 100% RAP TH 10 (OMC + 1%, 100% MDD, 2 F-T)

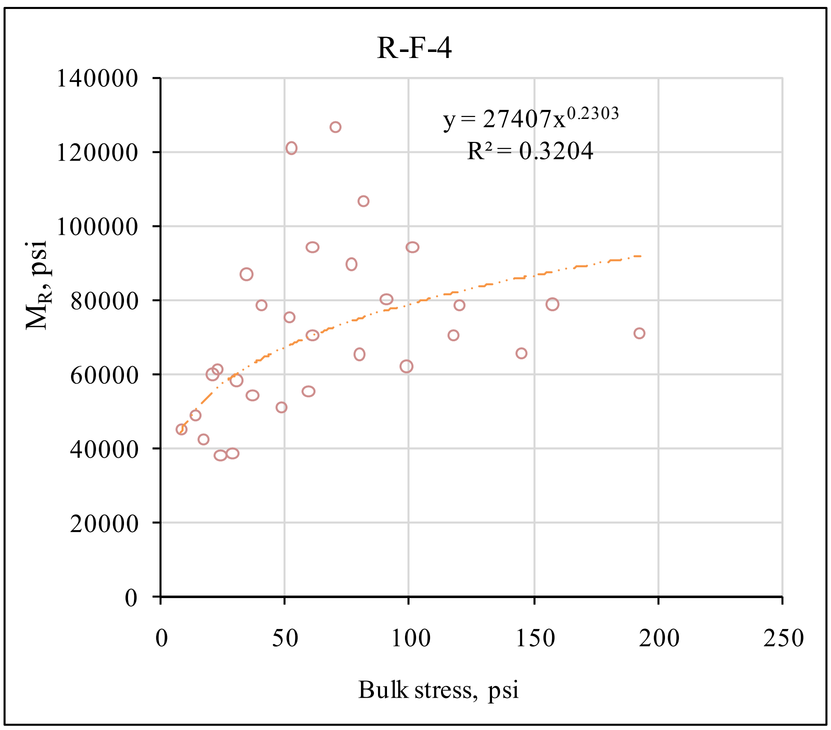

Figure E.22 M_R vs. bulk stress for 100% RAP TH 10 (OMC + 2%, 98% MDD, 2 F-T)

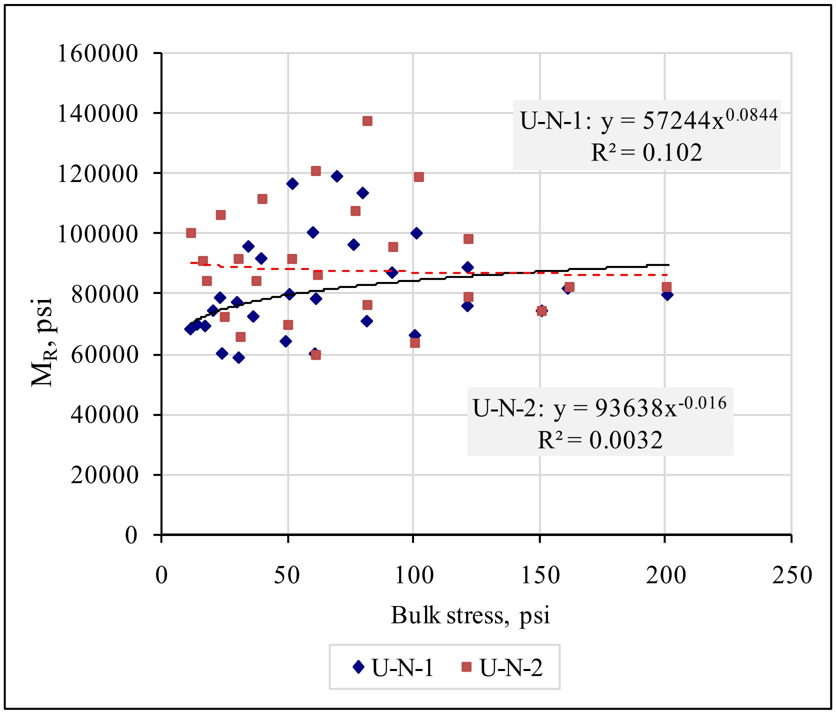

Figure E.23 M_R vs. bulk stress for RAP TH 19-101 (OMC, 100% MDD), one sample and a replicate

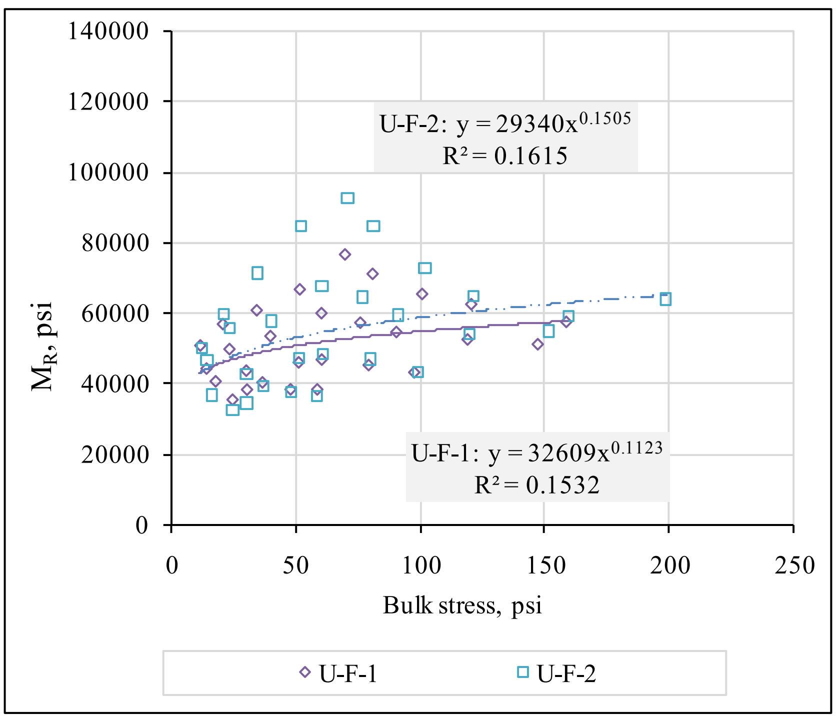

Figure E.24 M_R vs. bulk stress for RAP TH 19-101 (OMC, 100% MDD, 2 F-T), (one sample and a replicate)

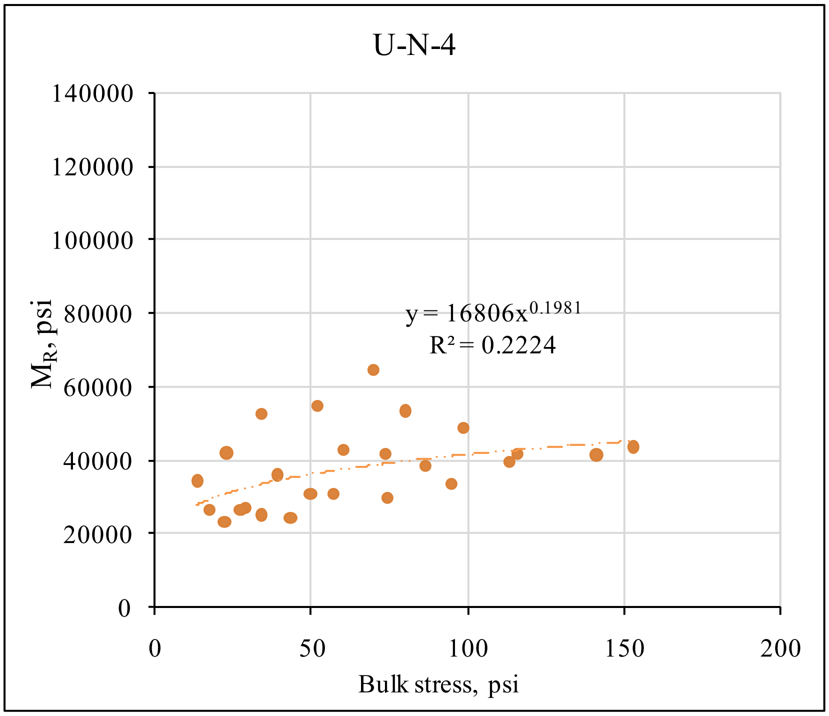

Figure E.25 M_R vs. bulk stress for RAP TH 19-101 (OMC + 2%, 100% MDD)

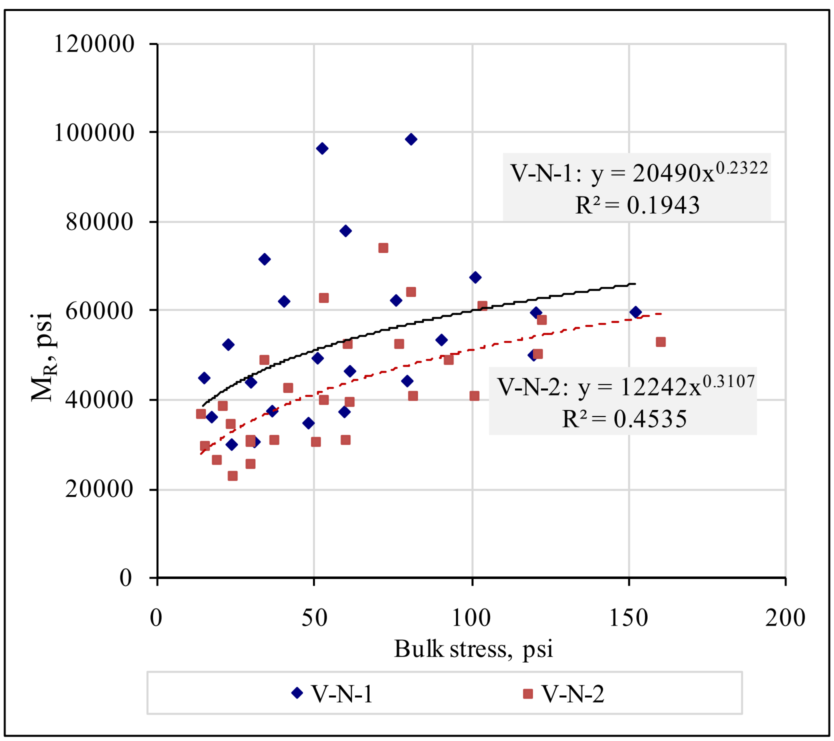

Figure E.26 M_R vs. bulk stress for RAP TH 19-104 (OMC, 100% MDD), (one sample and a replicate)

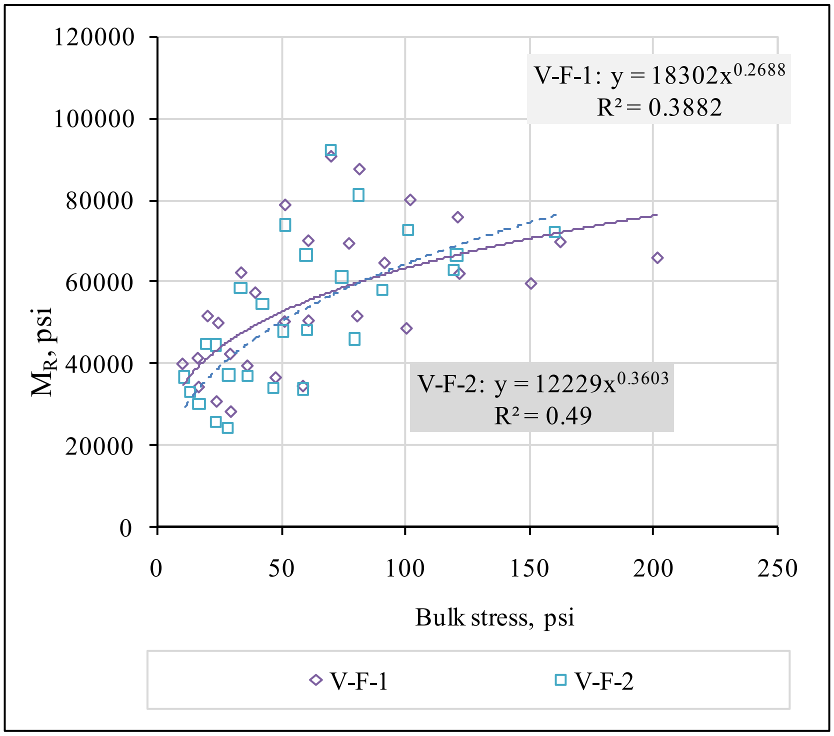

Figure E.27 M_R vs. bulk stress for RAP TH 19-104 (OMC, 100% MDD, 2 F-T)

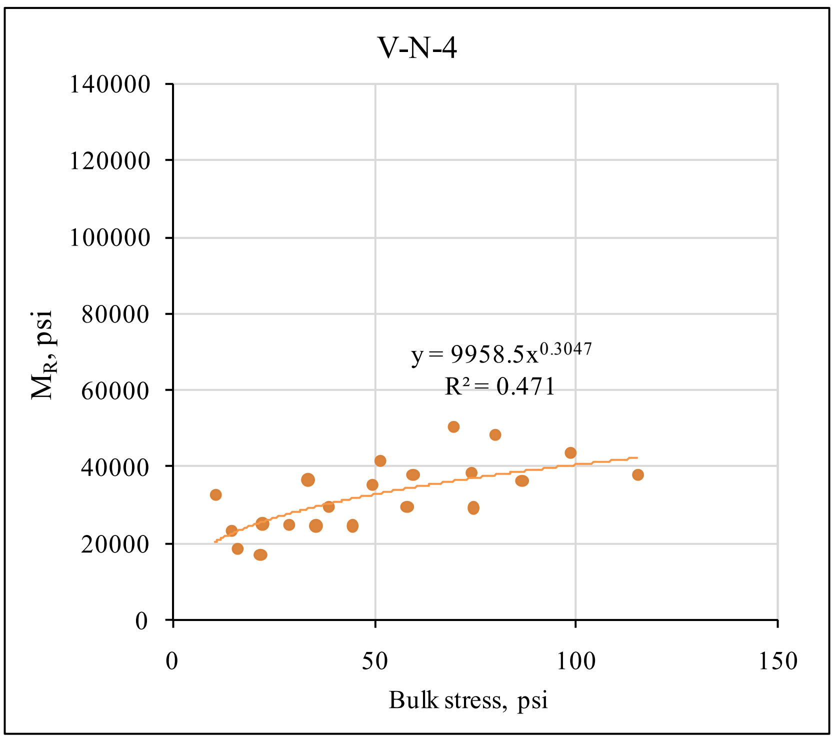

Figure E.28 M_R vs. bulk stress for RAP TH 19-104 (OMC + 2%, 97% MDD)

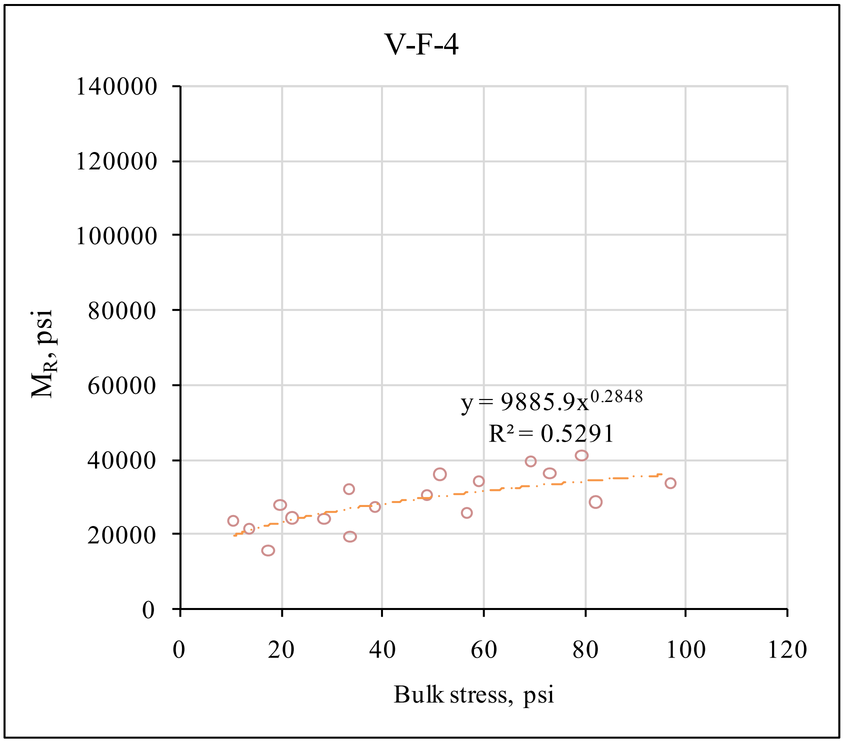

Figure E.29 M_R vs. bulk stress for RAP TH 19-104 (OMC + 2%, 97% MDD, 2 F-T)

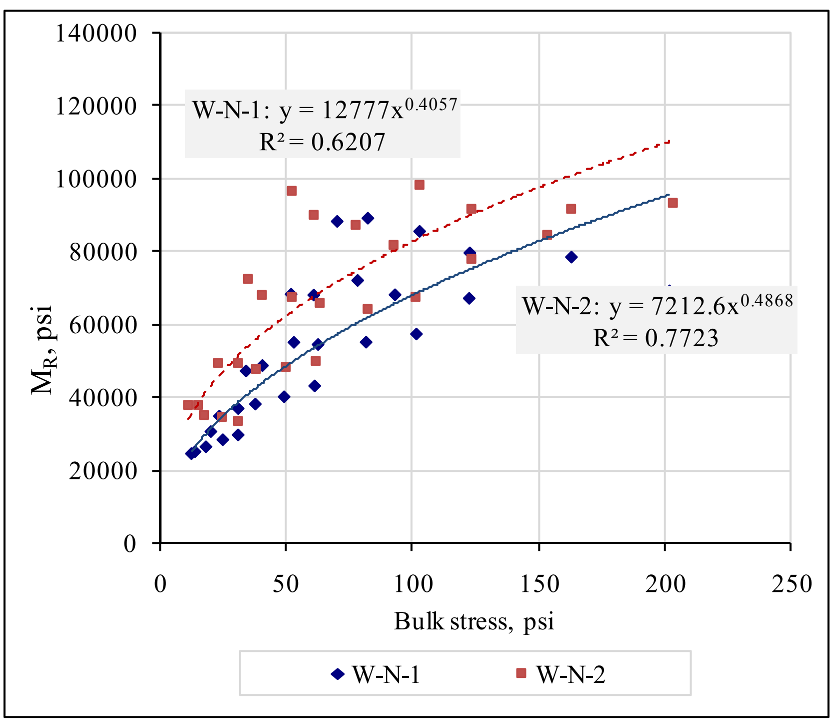

Figure E.30 M_R vs. bulk stress for RAP TH 22 (OMC, 100% MDD), (one sample and a replicate)

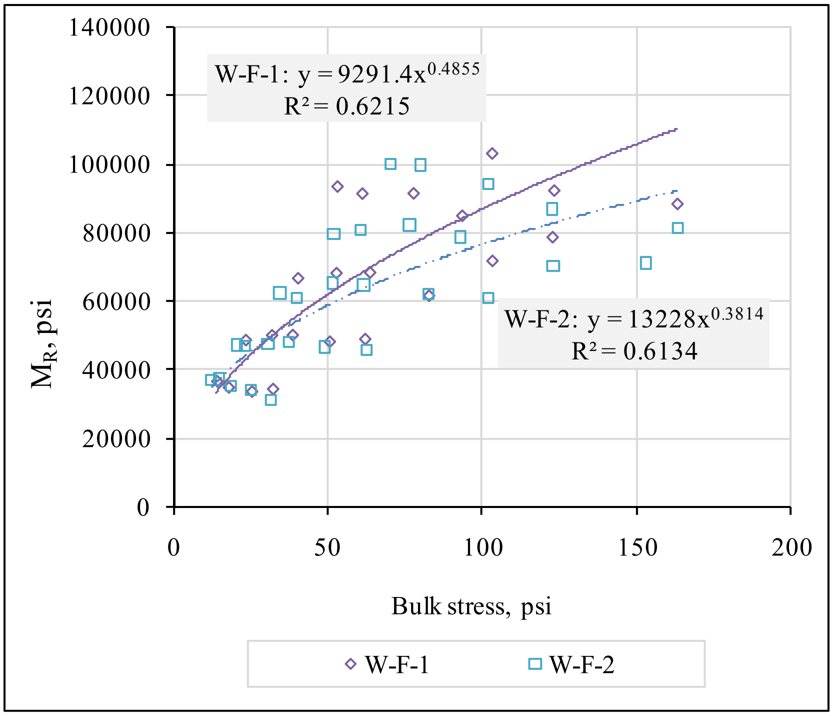

Figure E.31 M_R vs. bulk stress for RAP TH 22 (OMC, 100% MDD, 2 F-T), (one sample and a replicate)

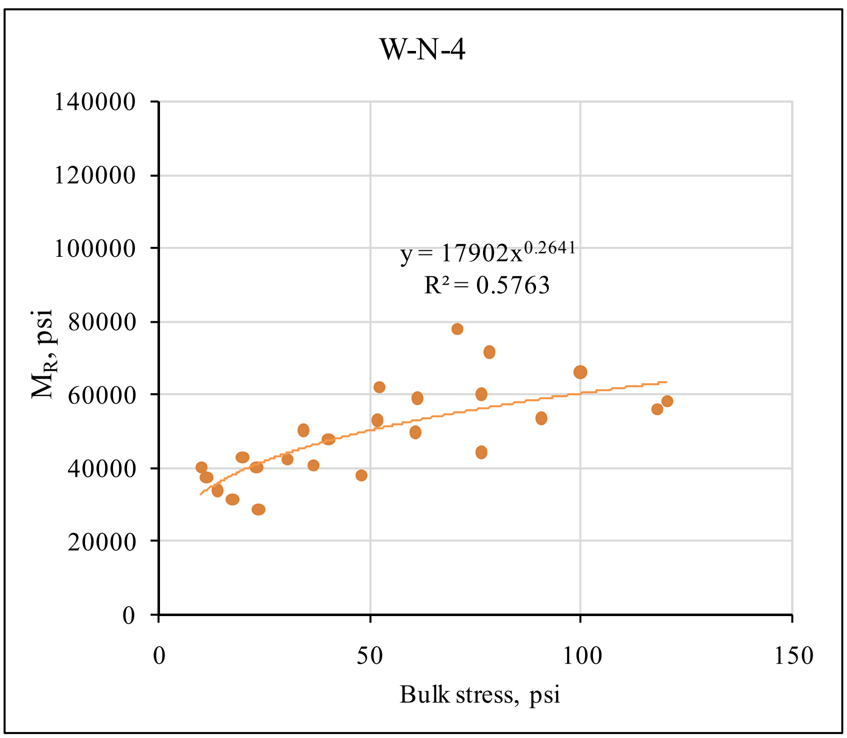

Figure E.32 M_R vs. bulk stress for RAP TH 22 (OMC + 2%, 98% MDD)

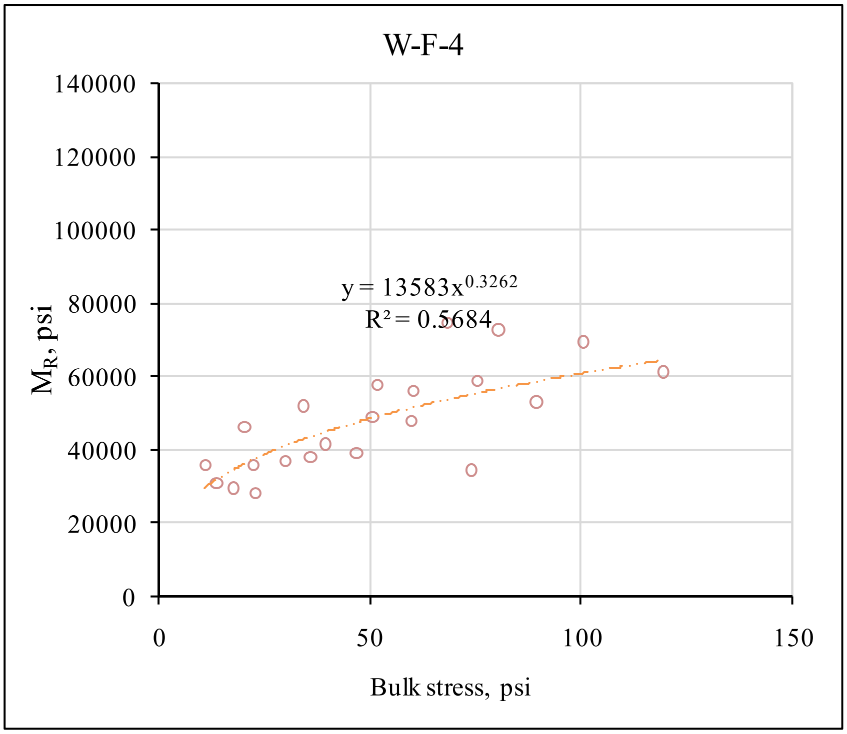

Figure E.33 M_R vs. bulk stress for RAP TH 22 (OMC + 2%, 98% MDD, 2 F-T)

Appendix F

Effect of Confining Pressure and Deviator Stress on Resilient Modulus

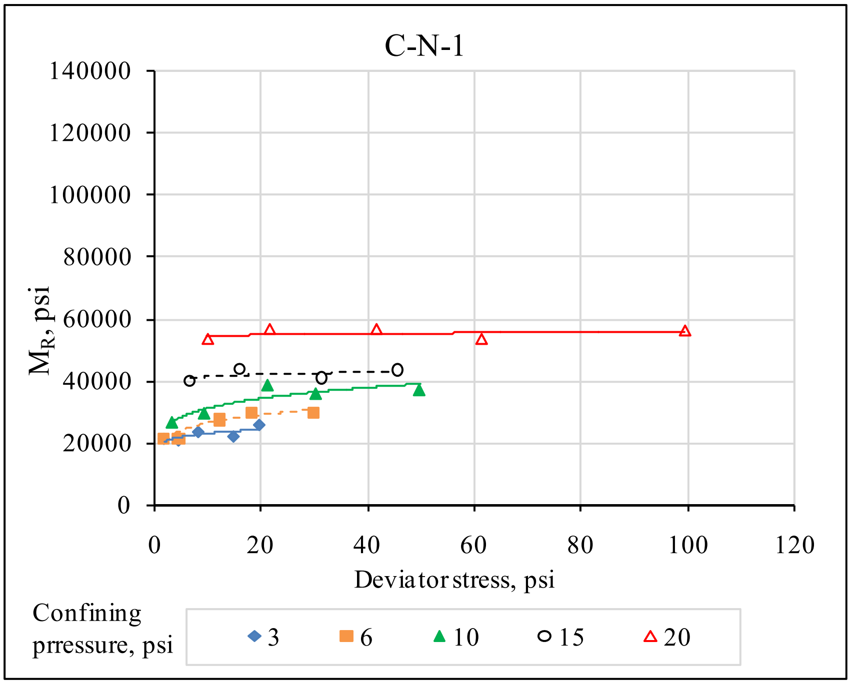

Figure F.1 M_R vs. deviator stress at different confining pressures for Class 5 (OMC, 100% MDD)

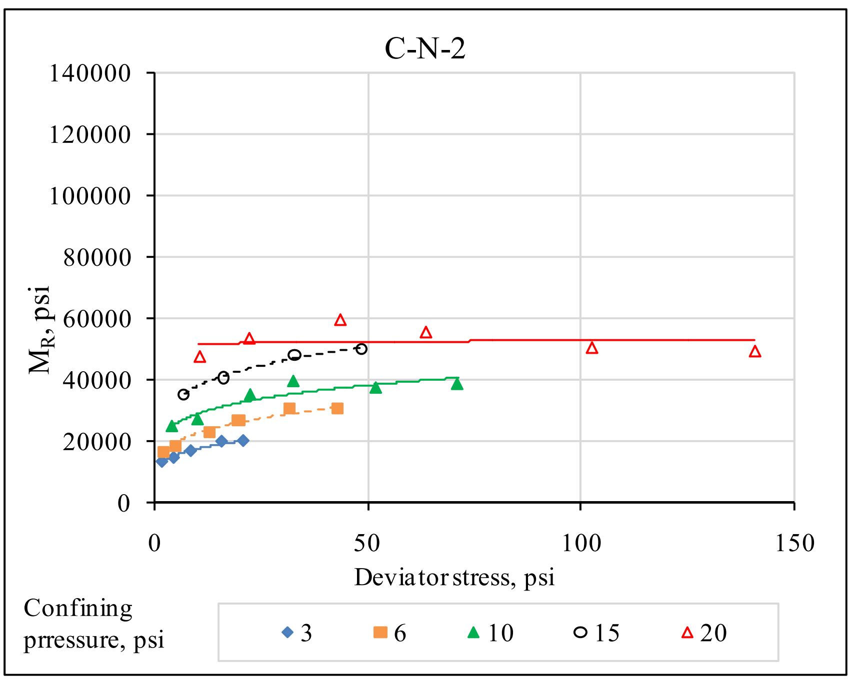

Figure F.2 M_R vs. deviator stress at different confining pressures for Class 5 (OMC, 100% MDD, replicate)

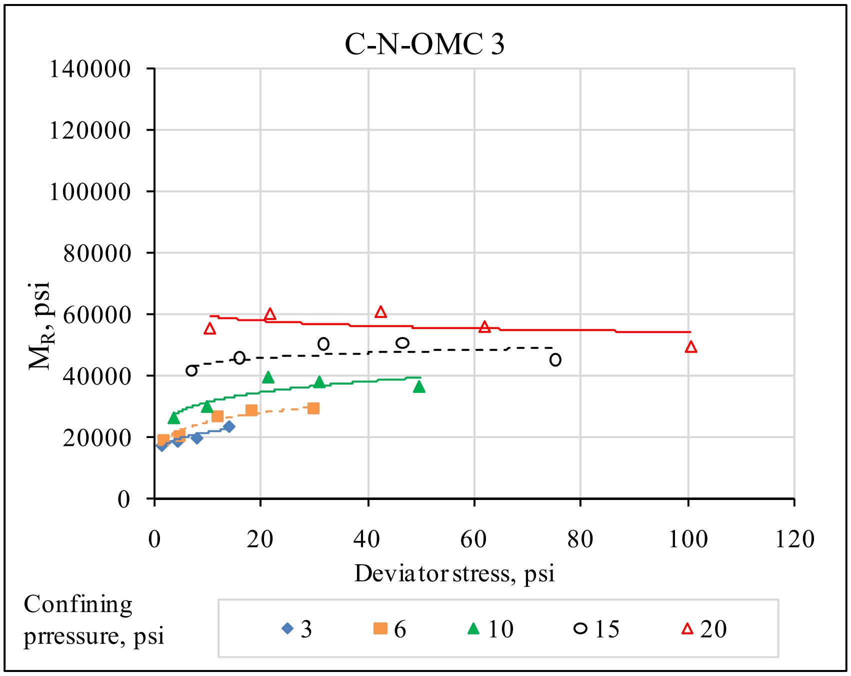

Figure F.3 M_R vs. deviator stress at different confining pressures for Class 5 (OMC, 100% MDD, 2nd replicate)

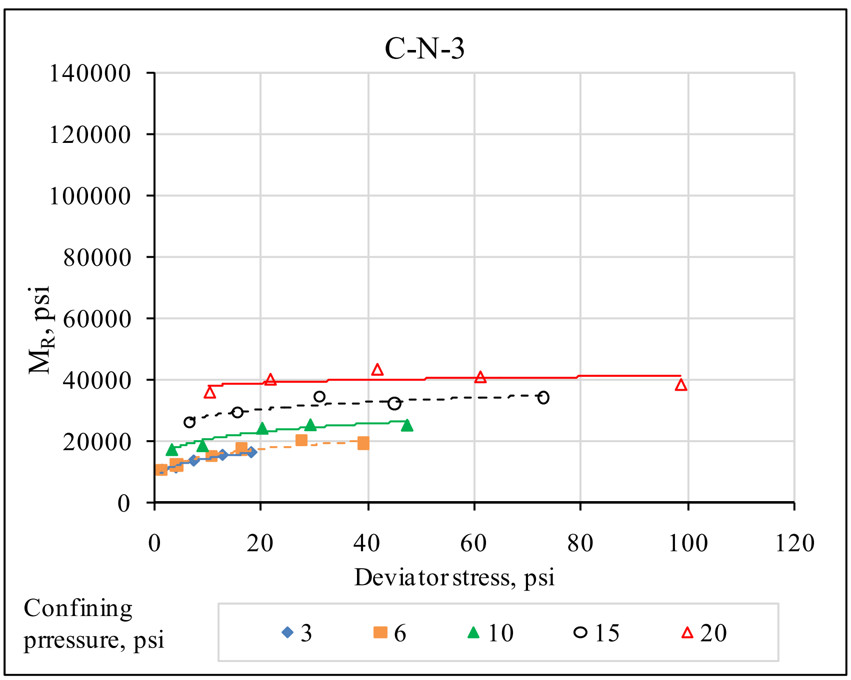

Figure F.4 M_R vs. deviator stress at different confining pressures for Class 5 (OMC + 1%, 99% MDD)

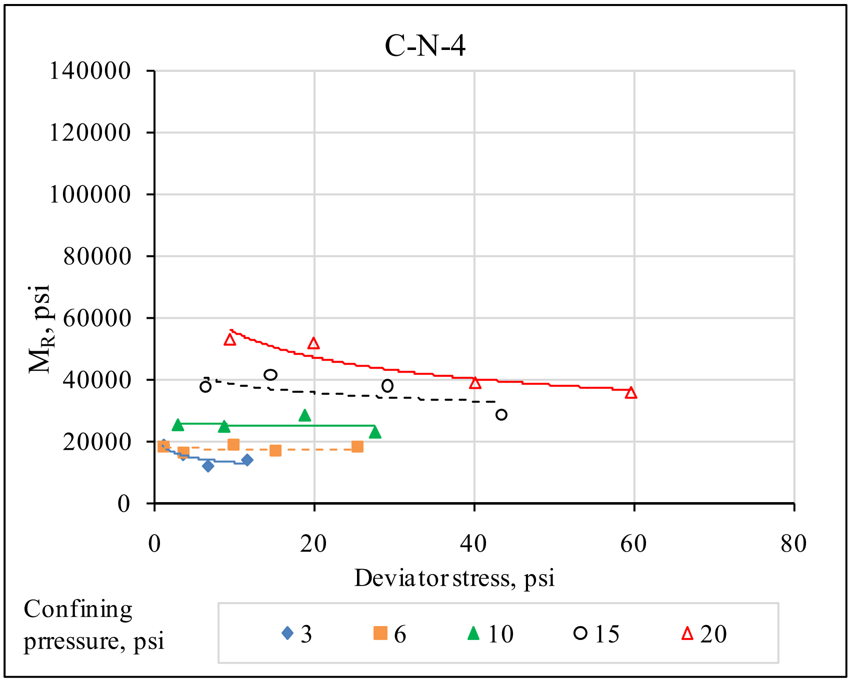

Figure F.5 M_R vs. deviator stress at different confining pressures for Class 5 (OMC + 2%, 99% MDD)

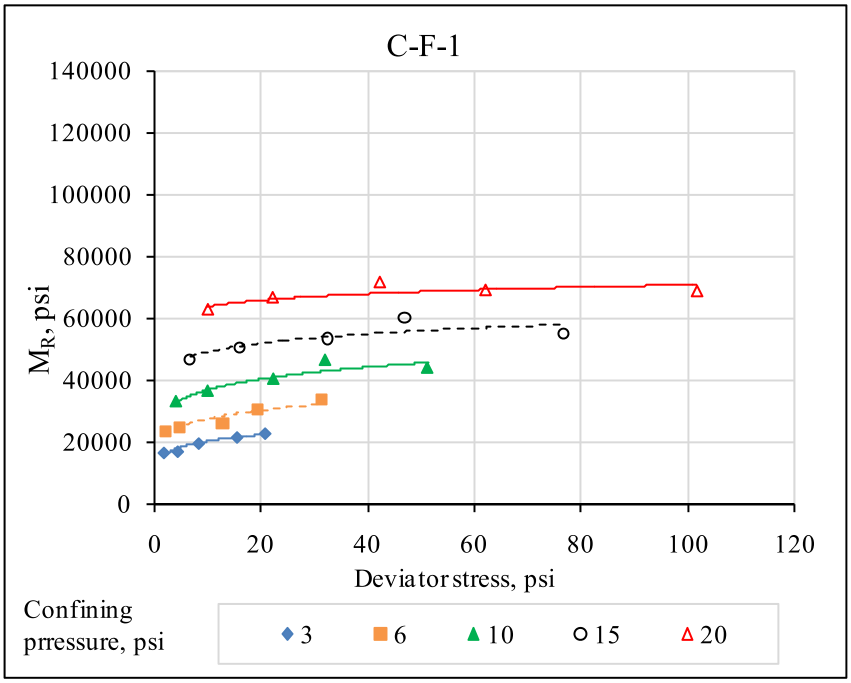

Figure F.6 M_R vs. deviator stress at different confining pressures for Class 5 (OMC, 100% MDD, 2 F-T)

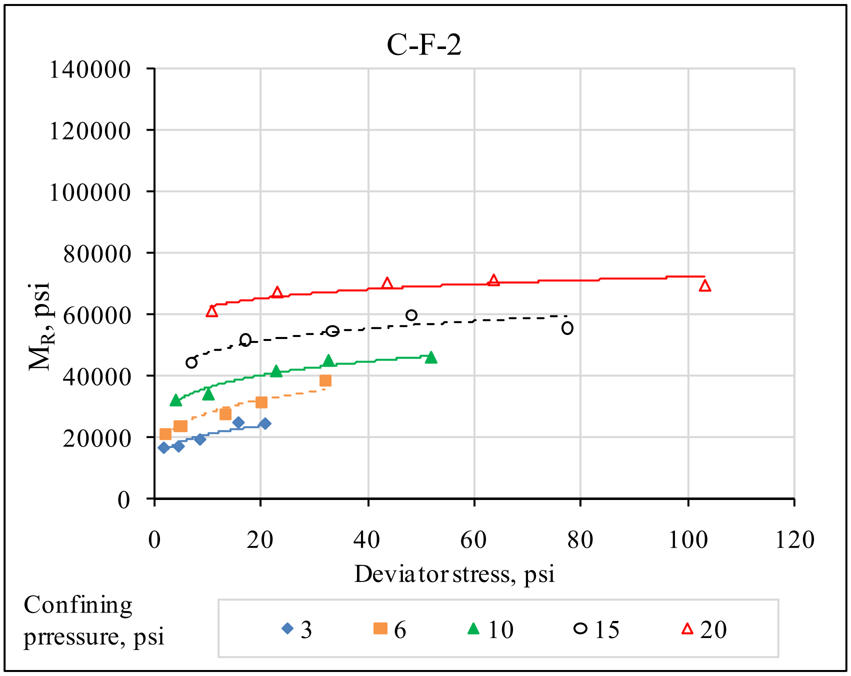

Figure F.7 M_R vs. deviator stress at different confining pressures for Class 5 (OMC, 100% MDD, 2 F-T, replicate)

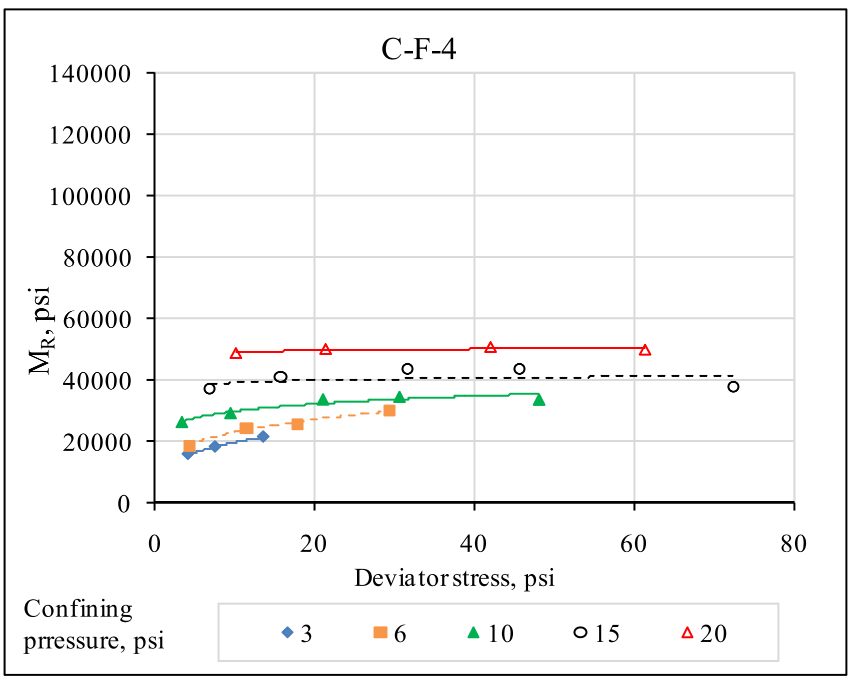

Figure F.8 M_R vs. deviator stress at different confining pressures for Class 5 (OMC + 2%, 2 F-T)

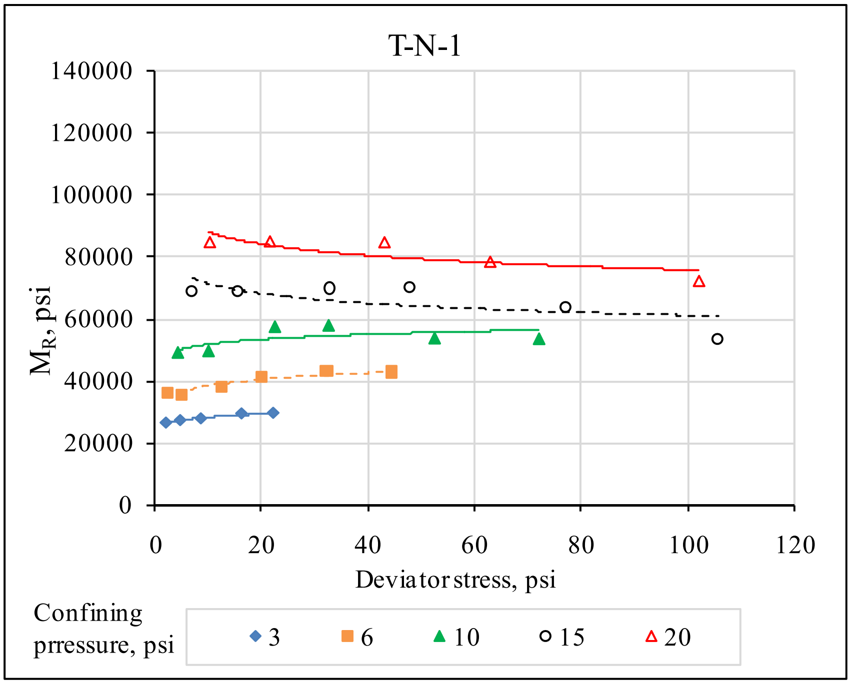

Figure F.9 M_R vs. deviator stress at different confining pressures for 50% Class 5 + 50% RAP TH 10 (OMC, 100% MDD)

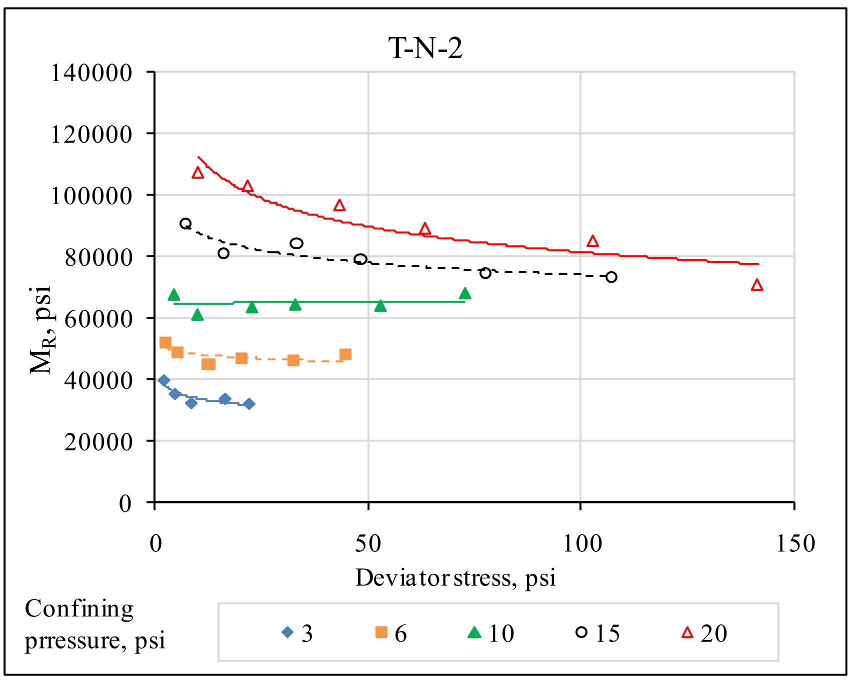

Figure F.10 M_R vs. deviator stress at different confining pressures for 50% Class 5 + 50% RAP TH 10 (OMC, 100% MDD, replicate)

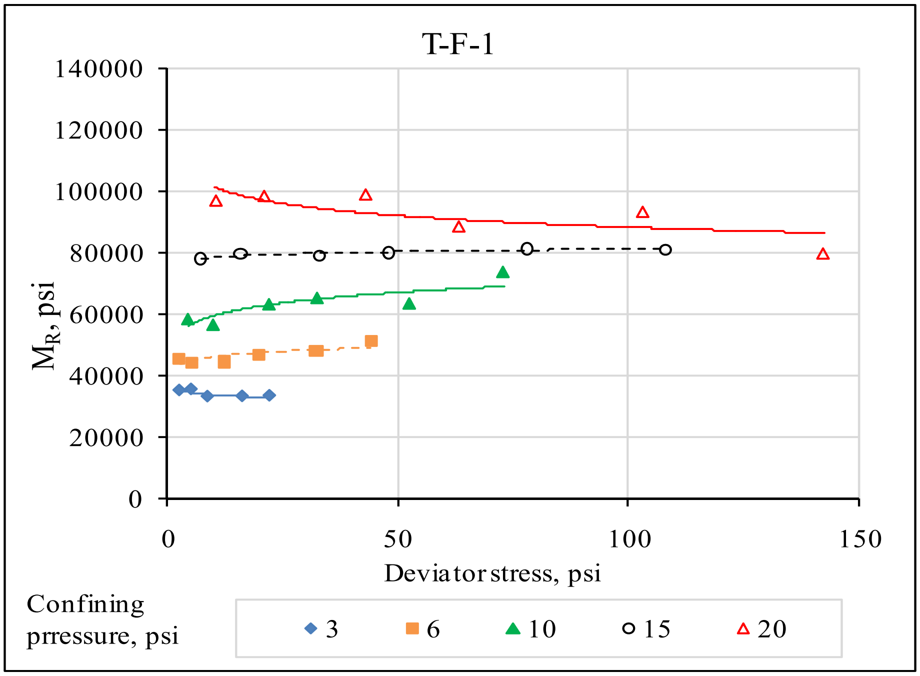

Figure F.11 M_R vs. deviator stress at different confining pressures for 50% Class 5 + 50% RAP TH 10 (OMC, 100% MDD, 2 F-T)

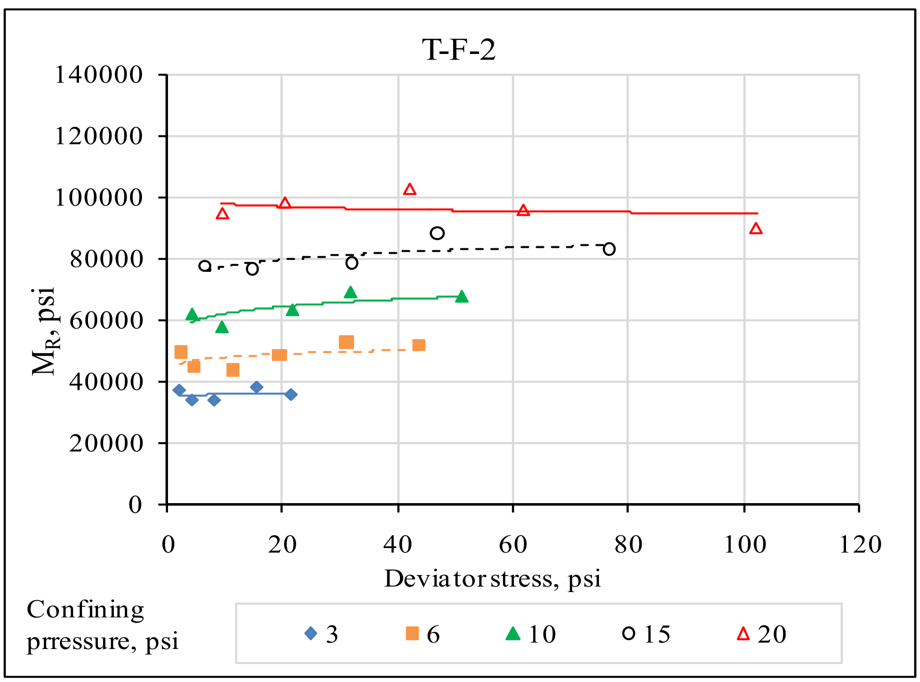

Figure F.12 M_R vs. deviator stress at different confining pressures for 50% Class 5 + 50% RAP TH 10 (OMC, 100% MDD, 2 F-T, replicate)

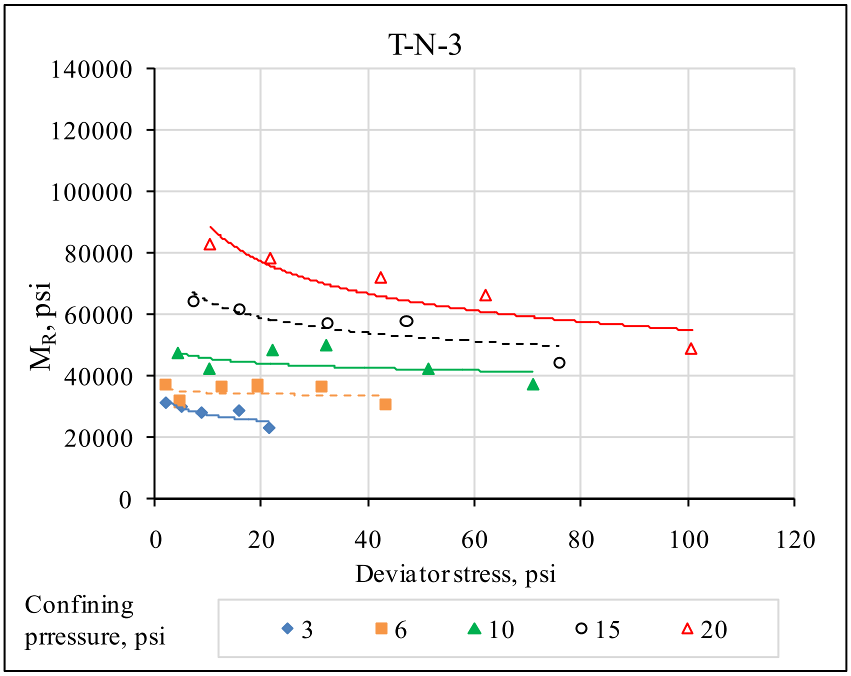

Figure F.13 M_R vs. deviator stress at different confining pressures for 50% Class 5 + 50% RAP TH 10 (OMC + 1%, 100% MDD)

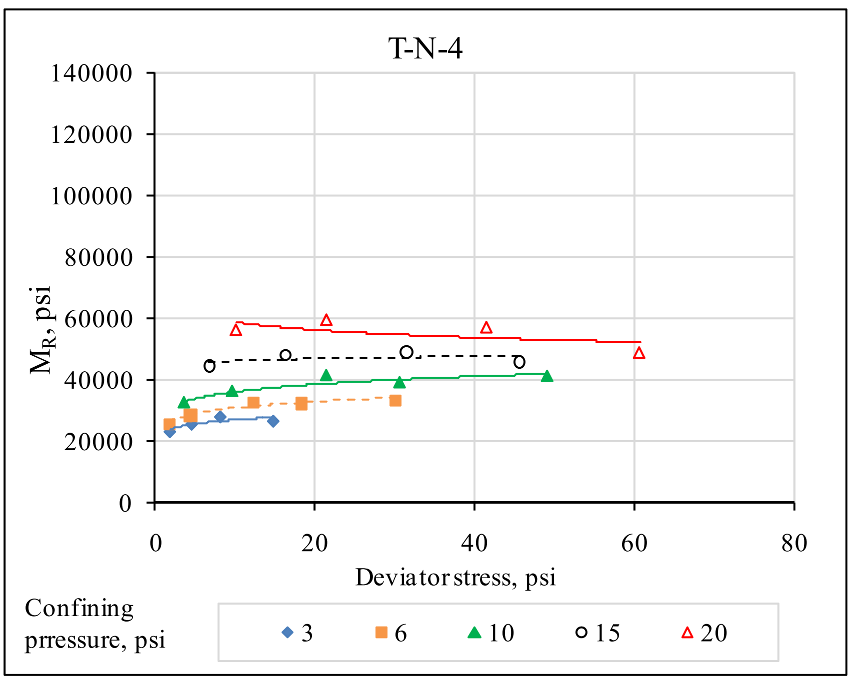

Figure F.14 M_R vs. deviator stress at different confining pressures for 50% Class 5 + 50% RAP TH 10 (OMC + 2%, 98.5% MDD)

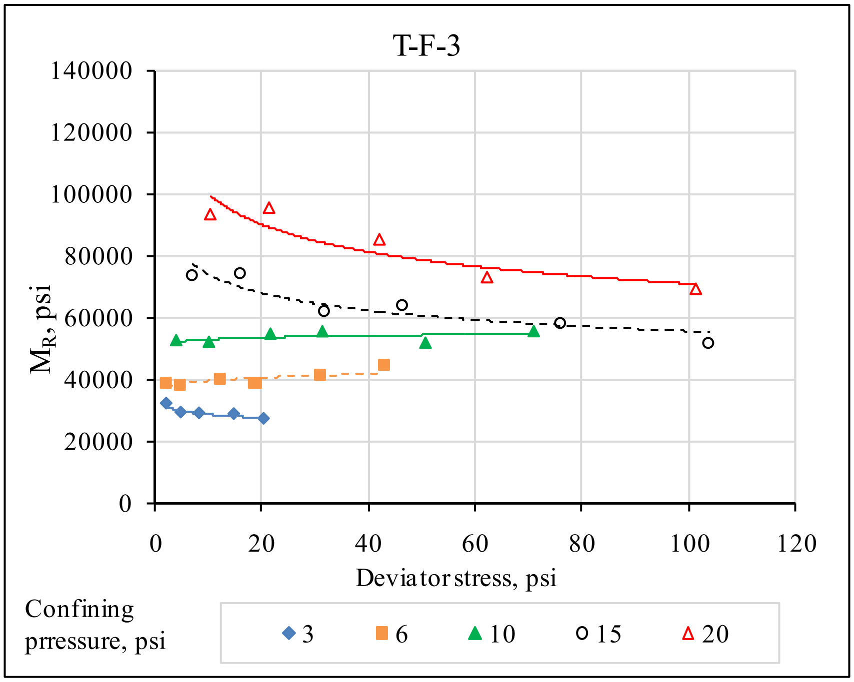

Figure F.15 M_R vs. deviator stress at different confining pressures for 50% Class 5 + 50% RAP TH 10 (OMC + 1%, 100% MDD, 2 F-T)

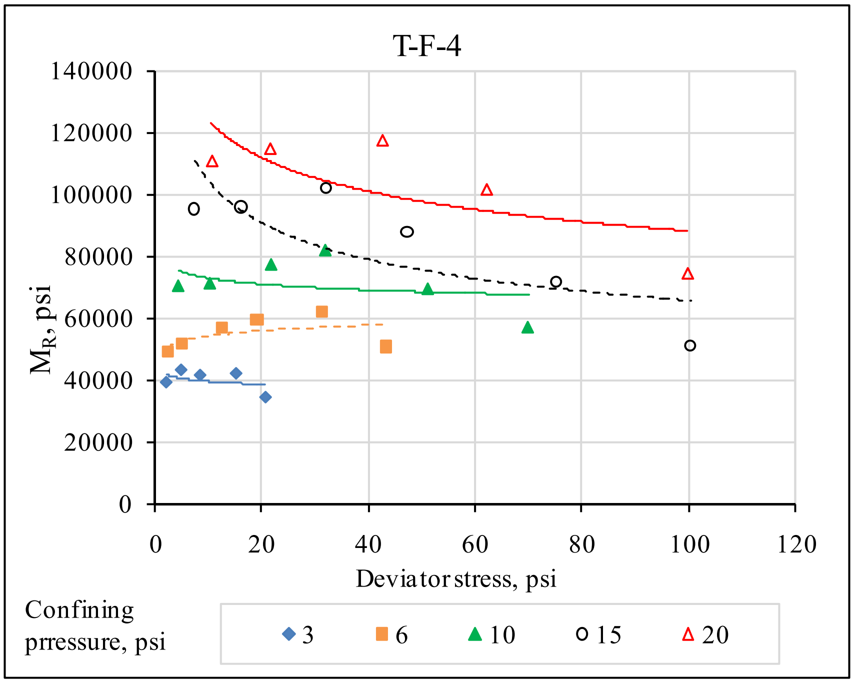

Figure F.16 M_R vs. deviator stress at different confining pressures for 50% Class 5 + 50% RAP TH 10 (OMC + 2%, 98% MDD, 2 F-T)

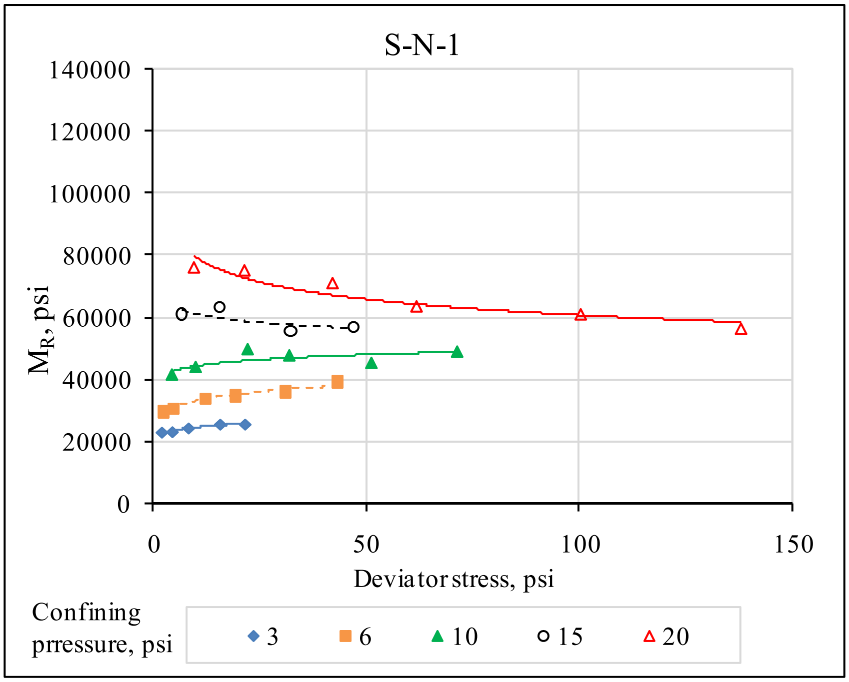

Figure F.17 M_R vs. deviator stress at different confining pressures for 25% Class 5 + 75% RAP TH 10 (OMC, 100% MDD)

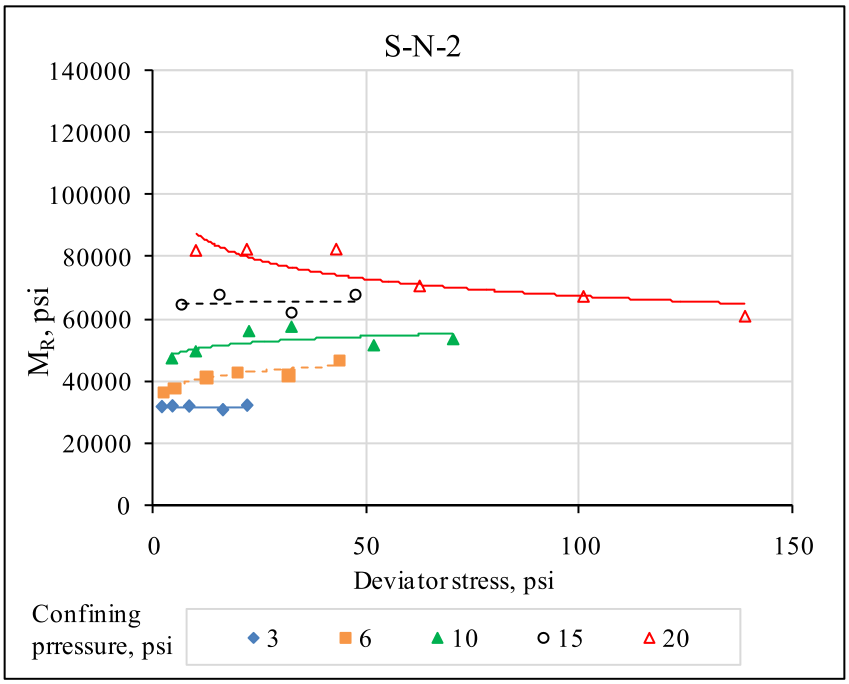

Figure F.18 M_R vs. deviator stress at different confining pressures for 25% Class 5 + 75% RAP TH 10 (OMC, 100% MDD, replicate)

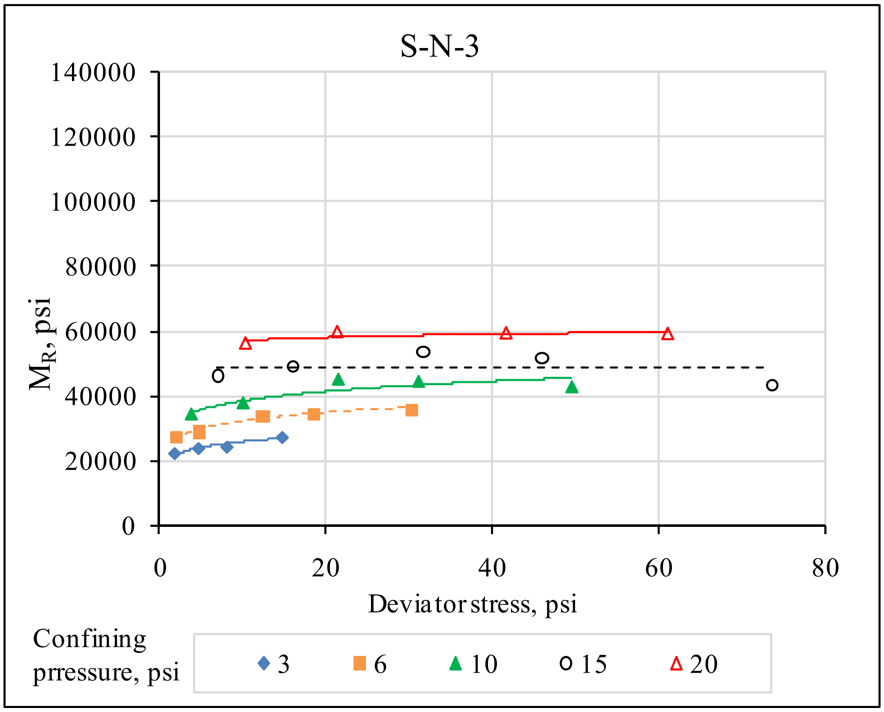

Figure F.19 M_R vs. deviator stress at different confining pressures for 25% Class 5 + 75% RAP TH 10 (OMC + 1%, 97.6% MDD)

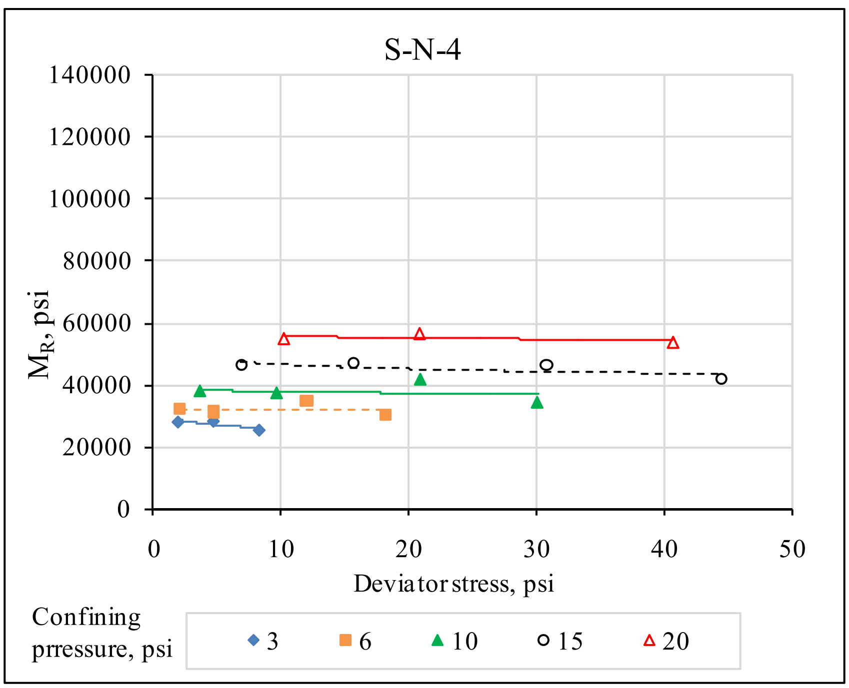

Figure F.20 M_R vs. deviator stress at different confining pressures for 25% Class 5 + 75% RAP TH 10 (OMC + 2%, 97% MDD)

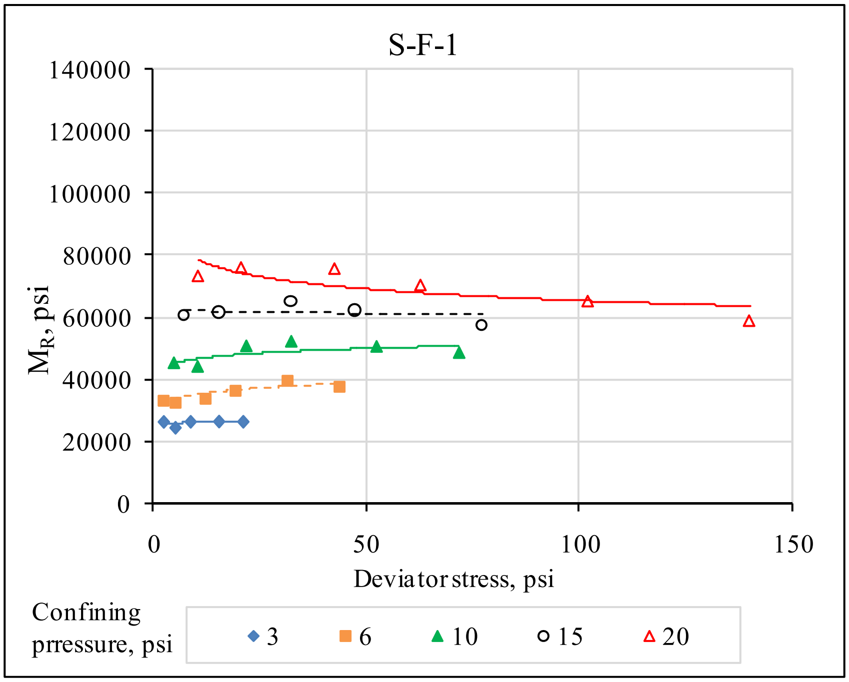

Figure F.21 M_R vs. deviator stress at different confining pressures for 25% Class 5 + 75% RAP TH 10 (OMC, 100% MDD, 2 F-T)

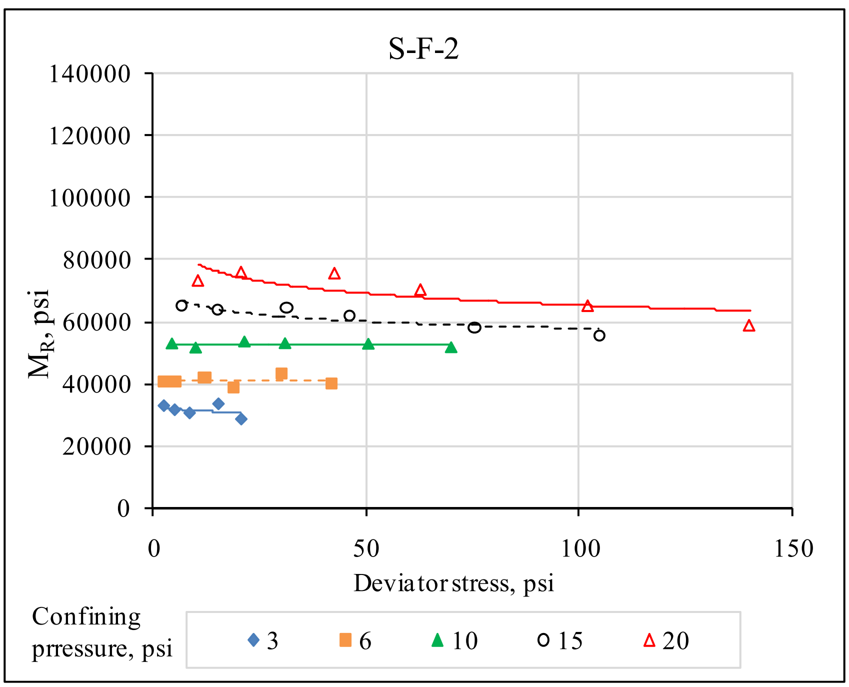

Figure F.22 M_R vs. deviator stress at different confining pressures for 25% Class 5 + 75% RAP TH 10 (OMC, 100% MDD, 2 F-T, replicate)

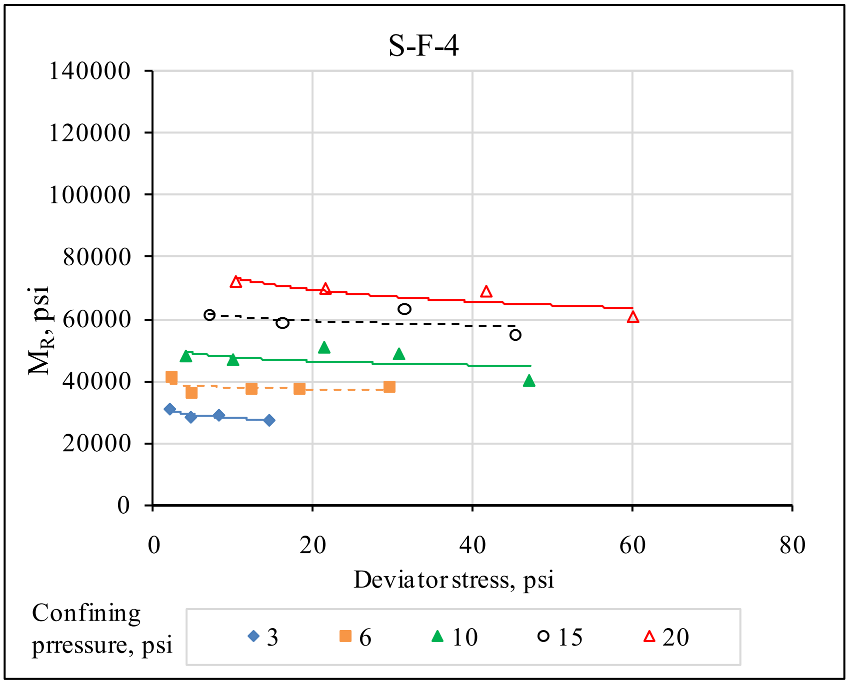

Figure F.23 M_R vs. deviator stress at different confining pressures for 25% Class 5 + 75% RAP TH 10 (OMC + 2%, 96% MDD, 2 F-T)

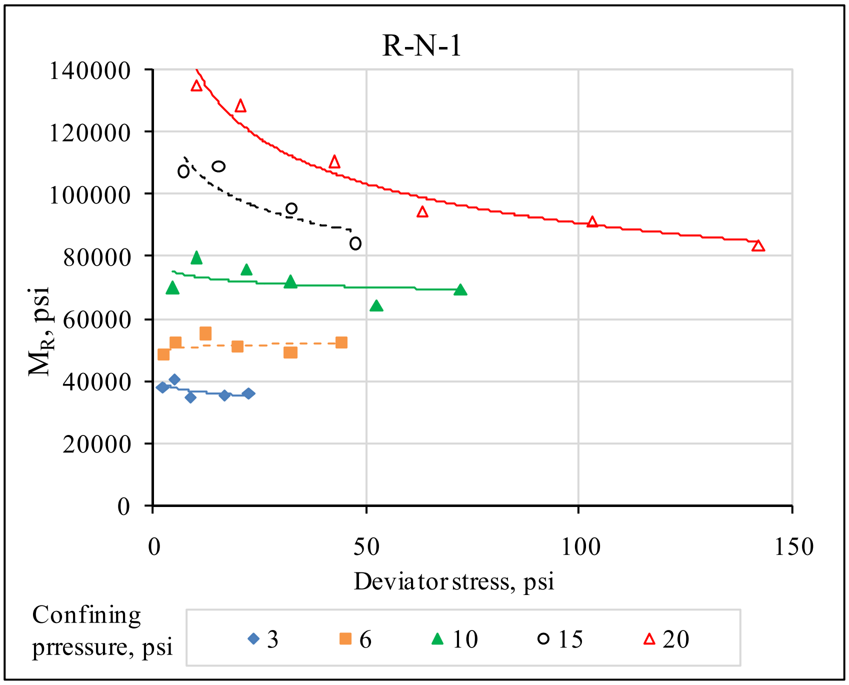

Figure F.24 M_R vs. deviator stress at different confining pressures for 100% RAP TH 10 (OMC, 100% MDD)

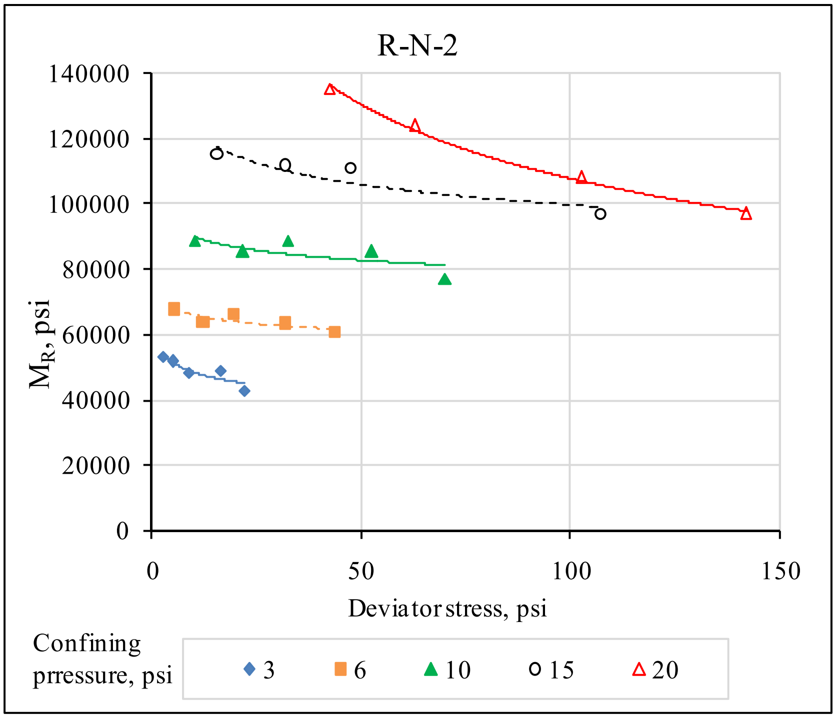

Figure F.25 M_R vs. deviator stress at different confining pressures for 100% RAP TH 10 (OMC, 100% MDD, replicate)

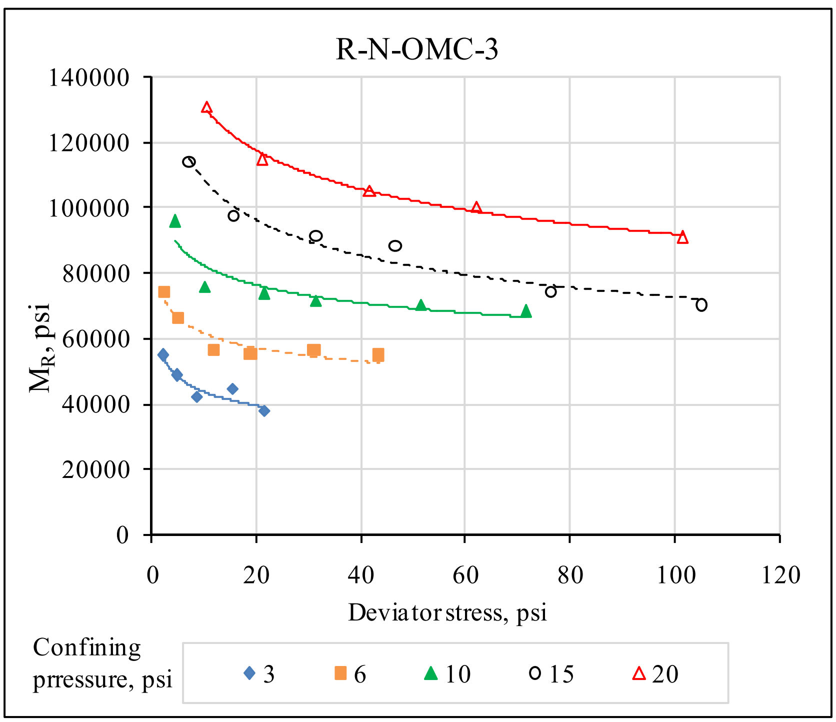

Figure F.26 M_R vs. deviator stress at different confining pressures for 100% RAP TH 10 (OMC, 100% MDD, 2nd replicate)

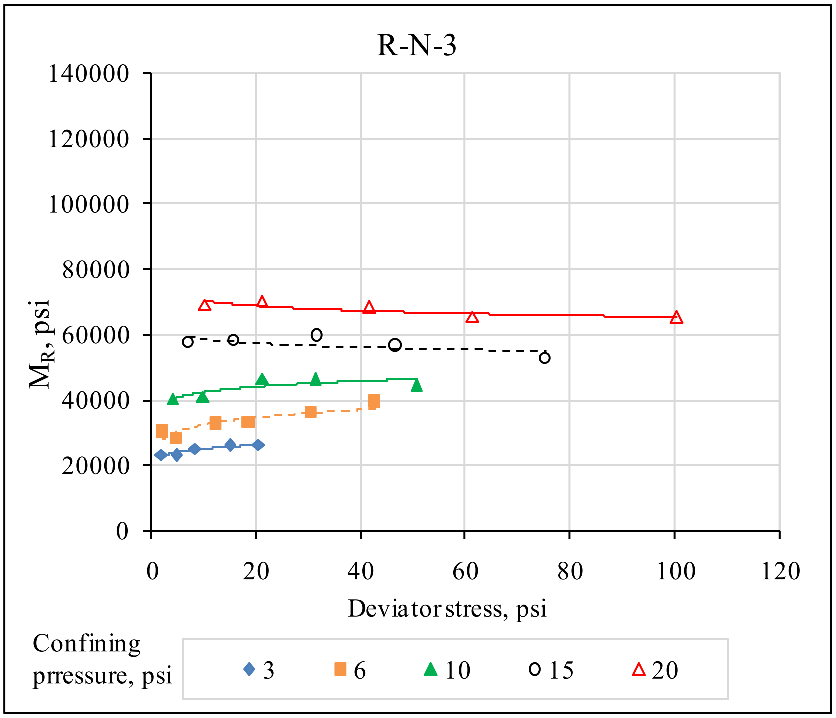

Figure F.27 M_R vs. deviator stress at different confining pressures for 100% RAP TH 10 (OMC + 1%, 100% MDD)

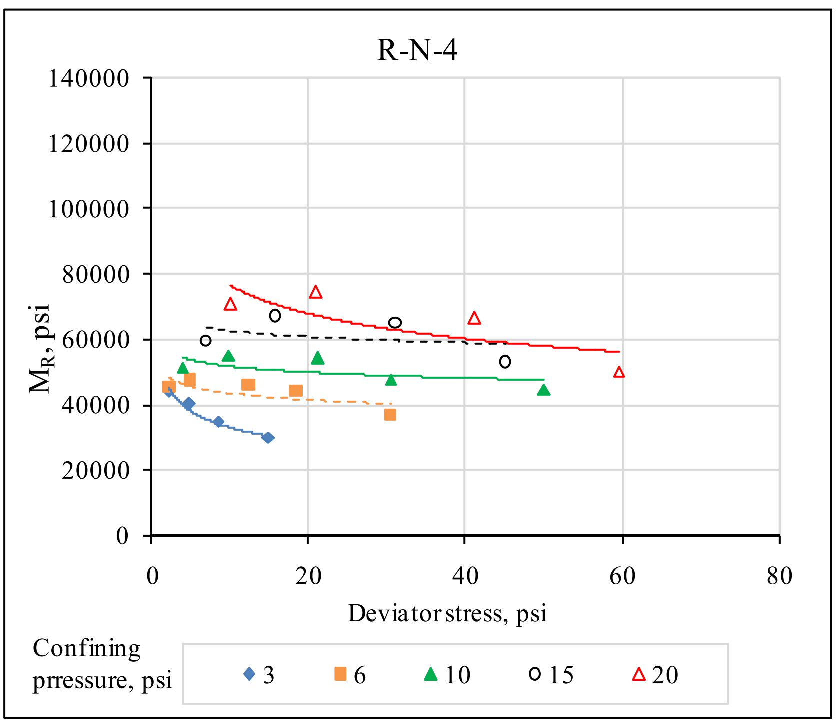

Figure F.28 M_R vs. deviator stress at different confining pressures for 100% RAP TH 10 (OMC + 2%, 97.5% MDD)

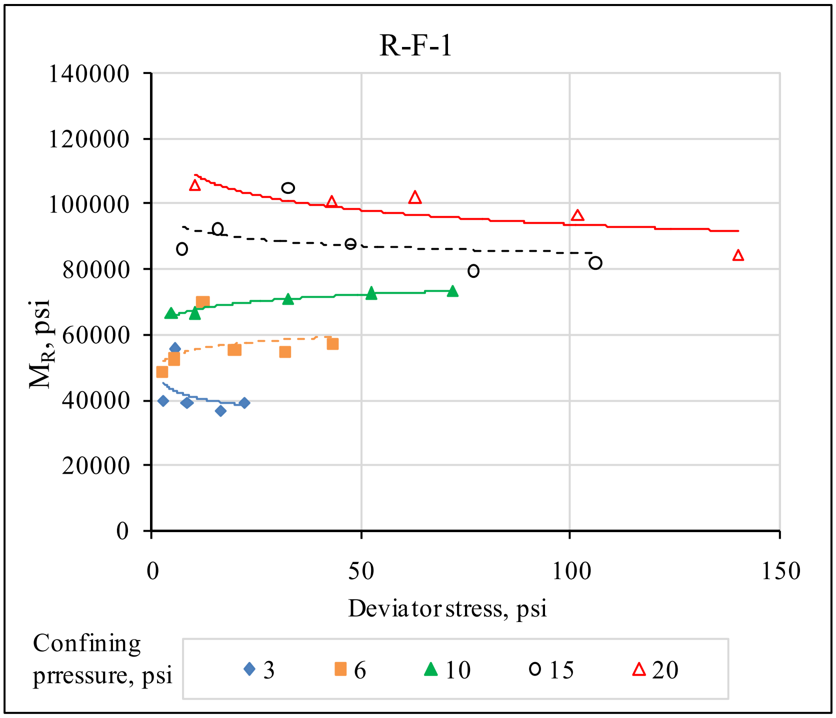

Figure F.29 M_R vs. deviator stress at different confining pressures for 100% RAP TH 10 (OMC + 1%, 100% MDD, 2 F-T)

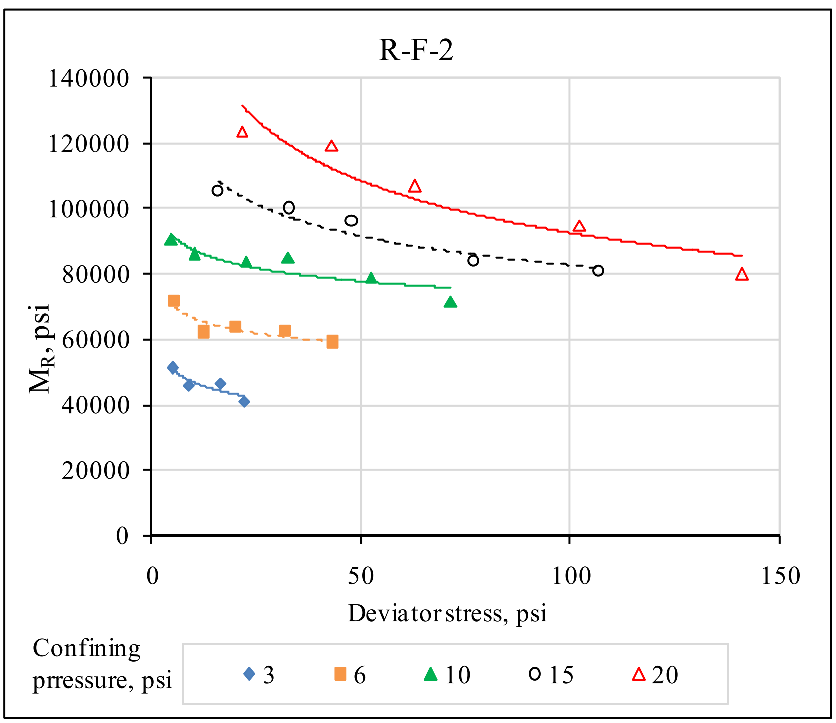

Figure F.30 M_R vs. deviator stress at different confining pressures for 100% RAP TH 10 (OMC + 1%, 100% MDD, 2 F-T, replicate)

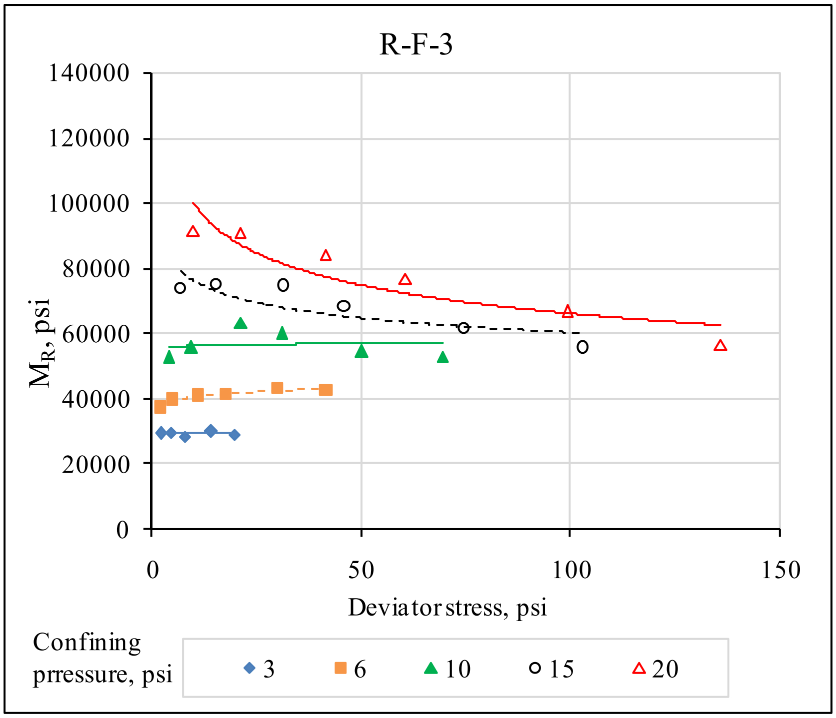

Figure F.31 M_R vs. deviator stress at different confining pressures for 100% RAP TH 10 (OMC + 1%, 100% MDD, 2 F-T)

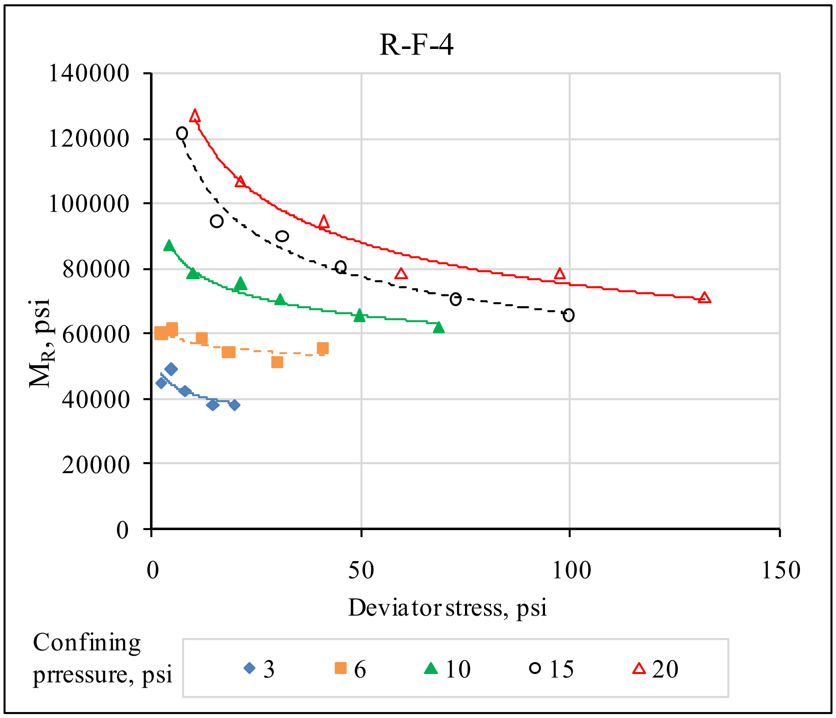

Figure F.32 M_R vs. deviator stress at different confining pressures for 100% RAP TH 10 (OMC + 2%, 98% MDD, 2 F-T)

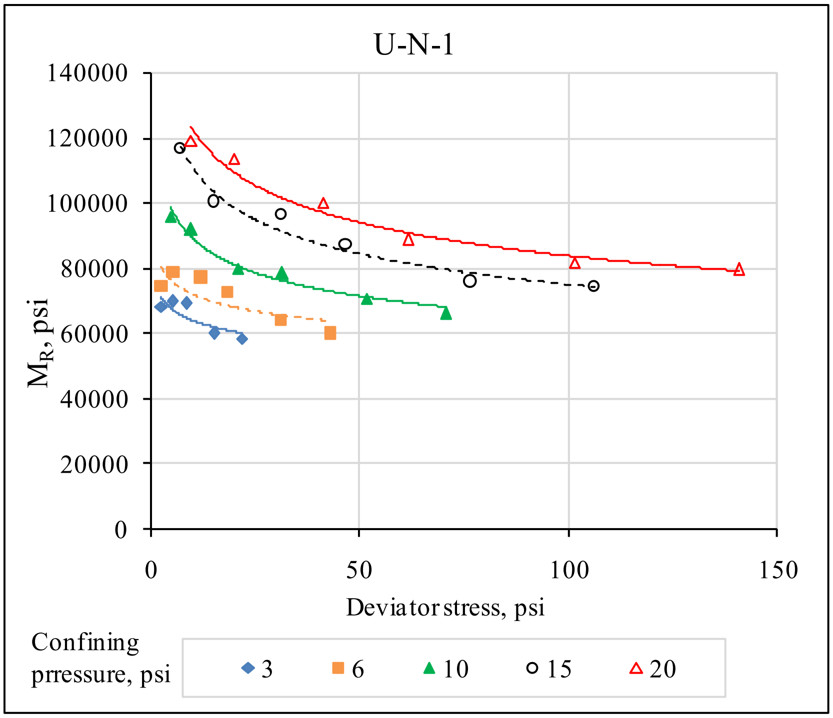

Figure F.33 M_R vs. deviator stress at different confining pressures for RAP TH 19-101 (OMC, 100% MDD)

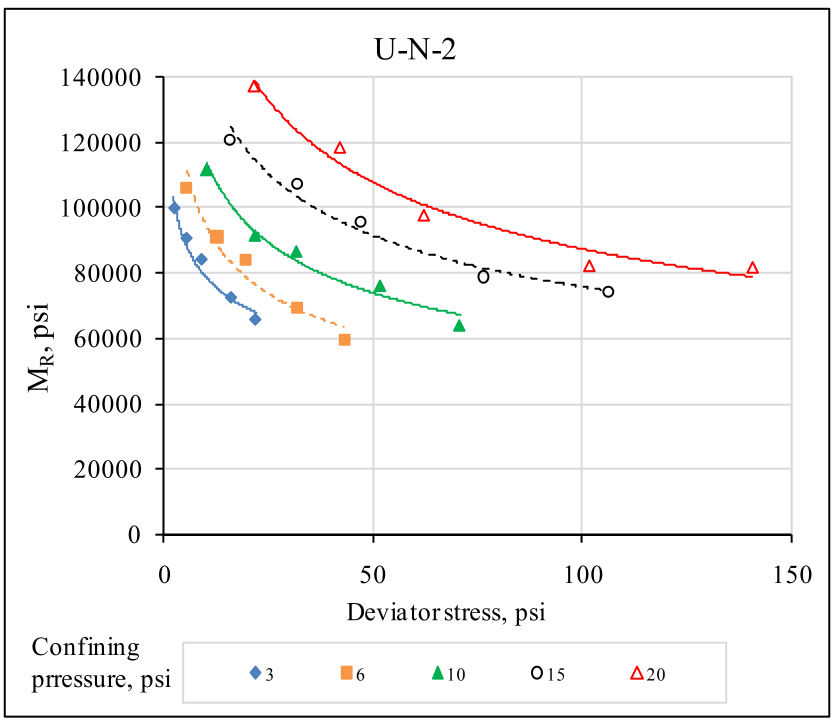

Figure F.34 M_R vs. deviator stress at different confining pressures for RAP TH 19-101 (OMC, 100% MDD, replicate)

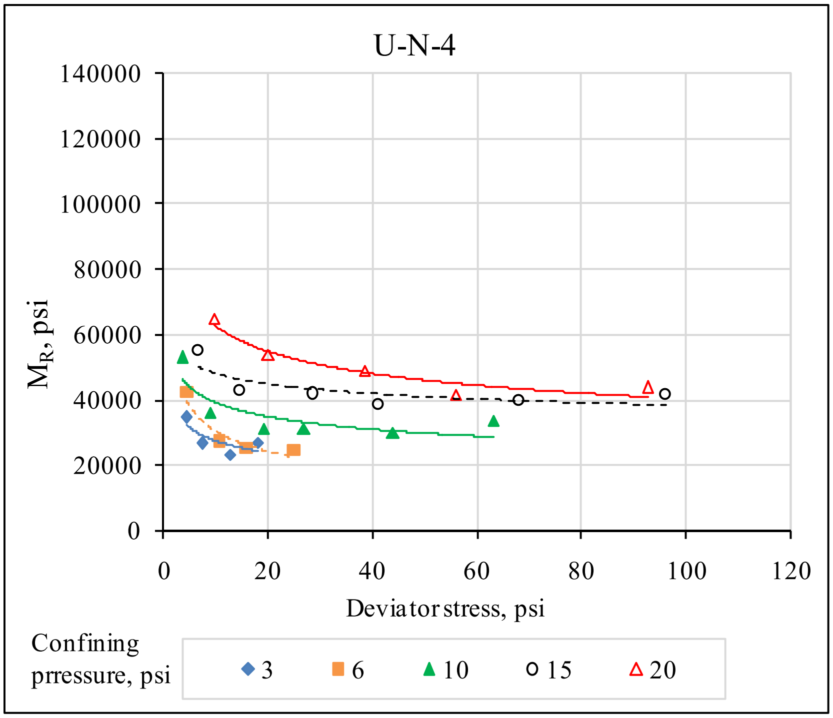

Figure F.35 M_R vs. deviator stress at different confining pressures for RAP TH 19-101 (OMC + 2%, 100% MDD)

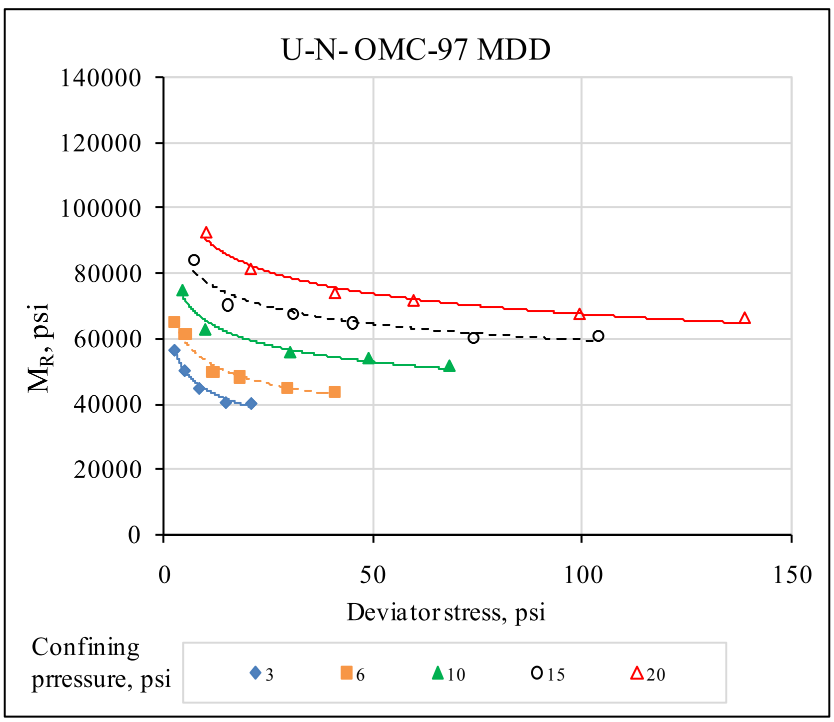

Figure F.36 M_R vs. deviator stress at different confining pressures for RAP TH 19-101 (OMC, 97.5% MDD)

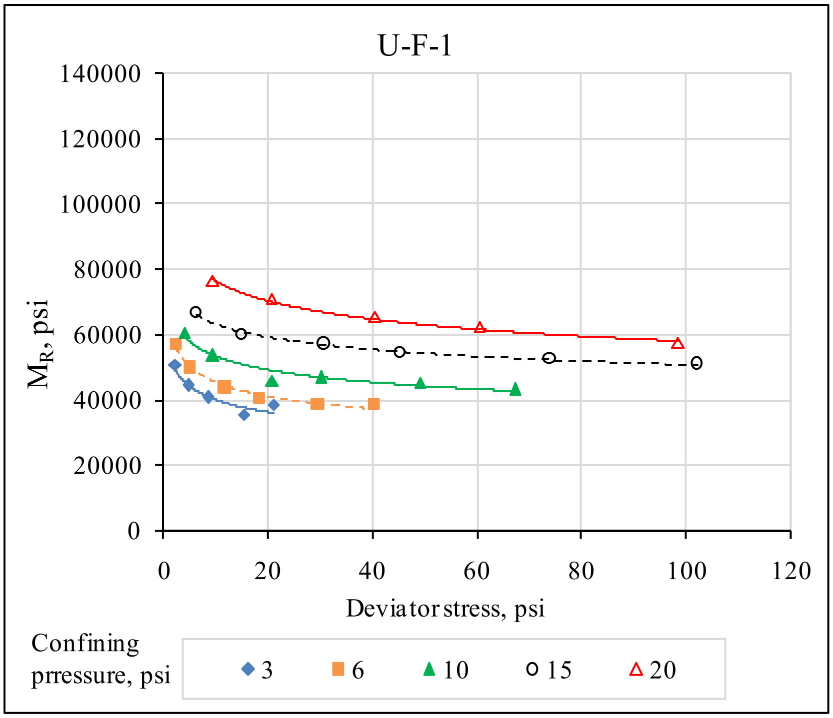

Figure F.37 M_R vs. deviator stress at different confining pressures for RAP TH 19-101 (OMC, 100% MDD, 2 F-T)

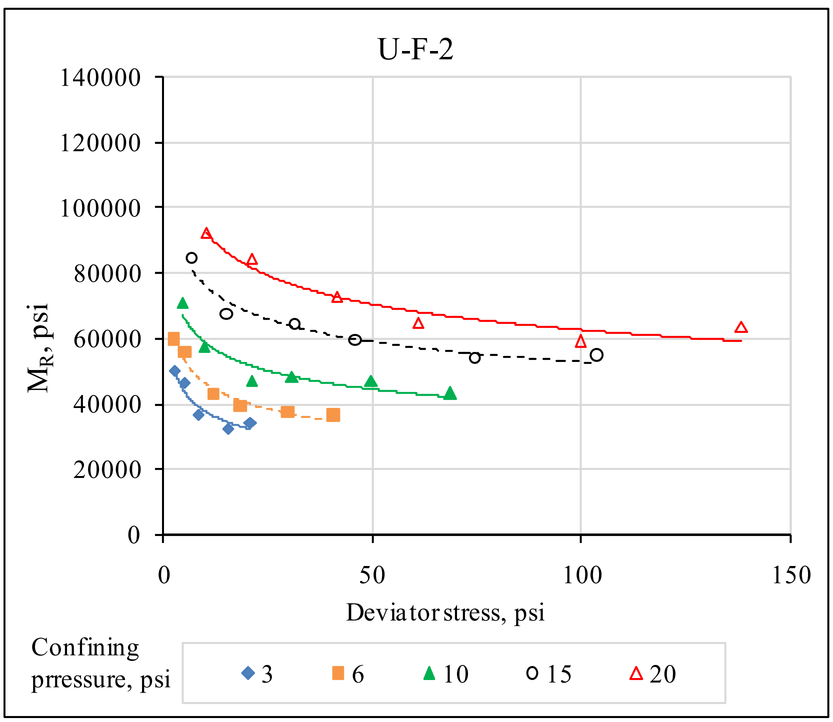

Figure F.38 M_R vs. deviator stress at different confining pressures for RAP TH 19-101 (OMC, 100% MDD, 2 F-T, replicate)

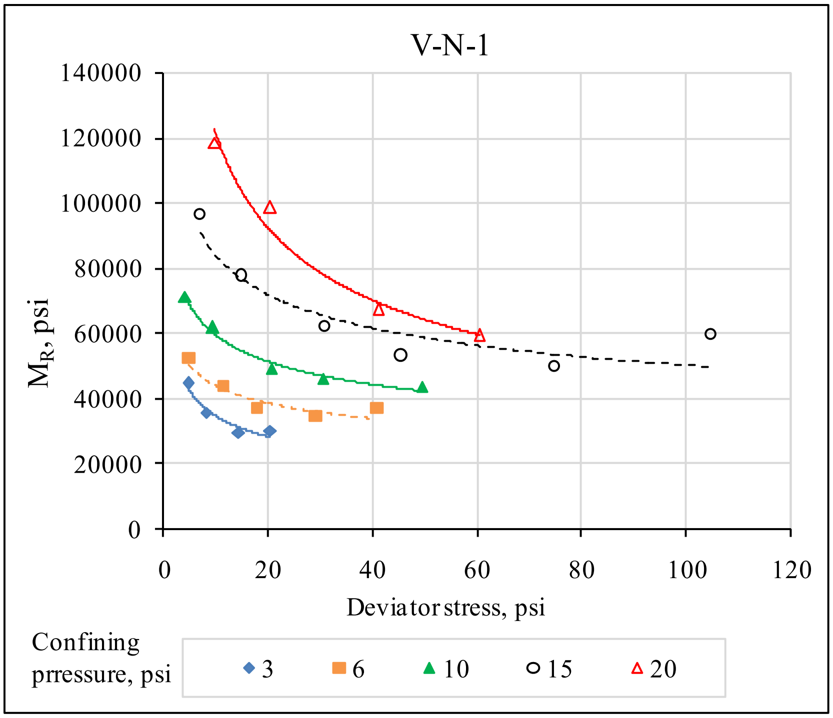

Figure F.39 M_R vs. deviator stress at different confining pressures for RAP TH 19-104 (OMC, 100% MDD)

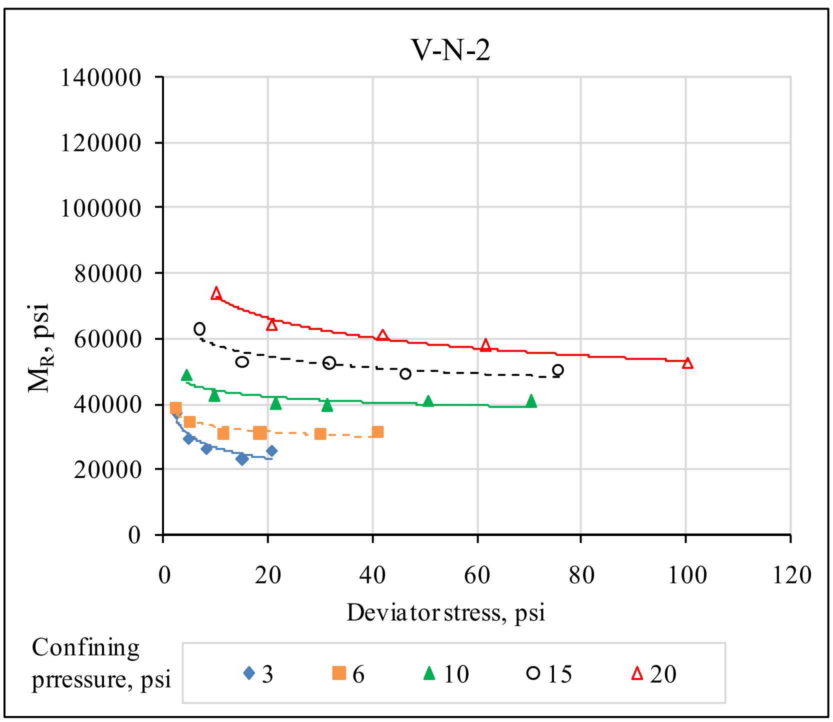

Figure F.40 M_R vs. deviator stress at different confining pressures for RAP TH 19-104 (OMC, 100% MDD, replicate)

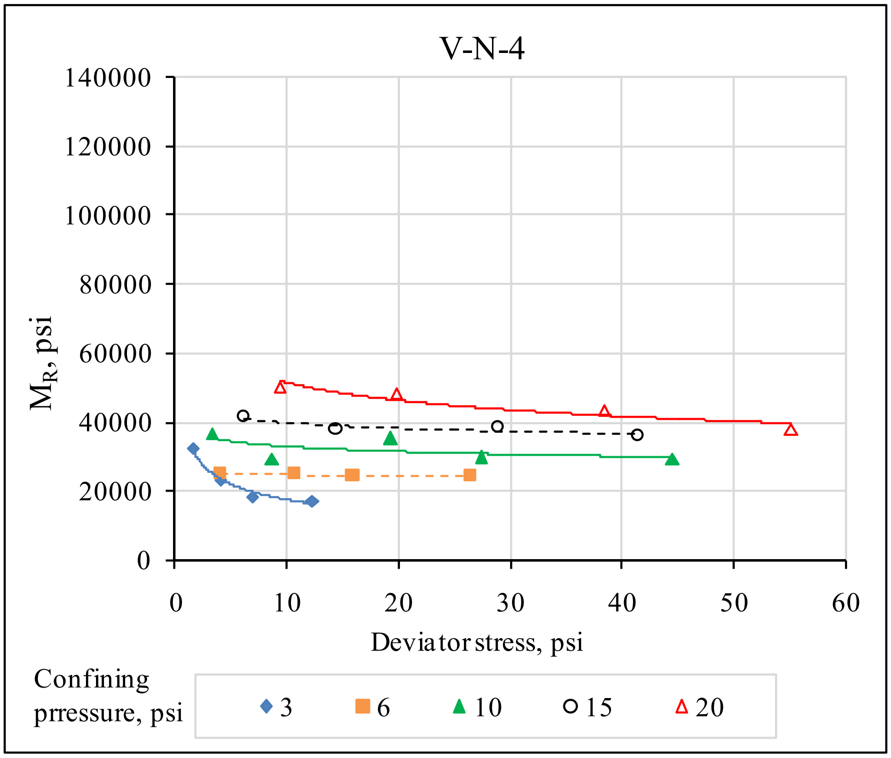

Figure F.41 M_R vs. deviator stress at different confining pressures for RAP TH 19-104 (OMC + 2%, 97% MDD)

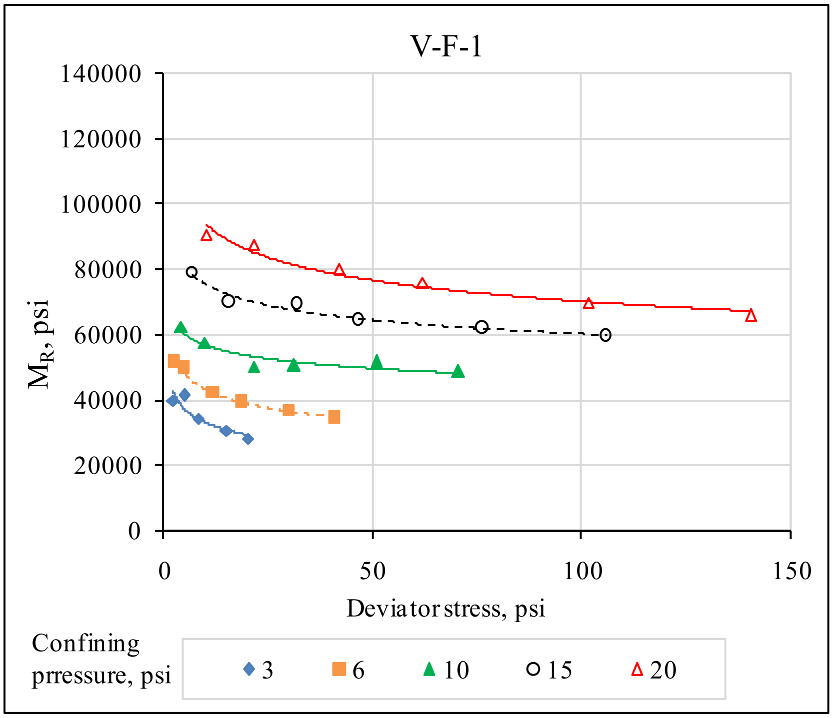

Figure F.42 M_R vs. deviator stress at different confining pressures for RAP TH 19-104 (OMC, 100% MDD, 2 F-T)

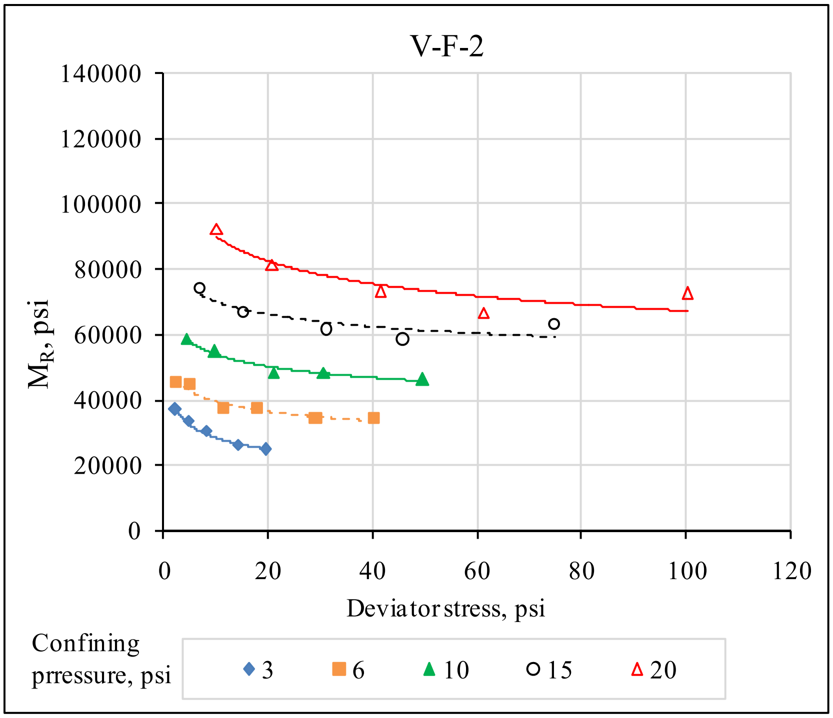

Figure F.43 M_R vs. deviator stress at different confining pressures for RAP TH 19-104 (OMC, 100% MDD, 2 F-T, replicate)

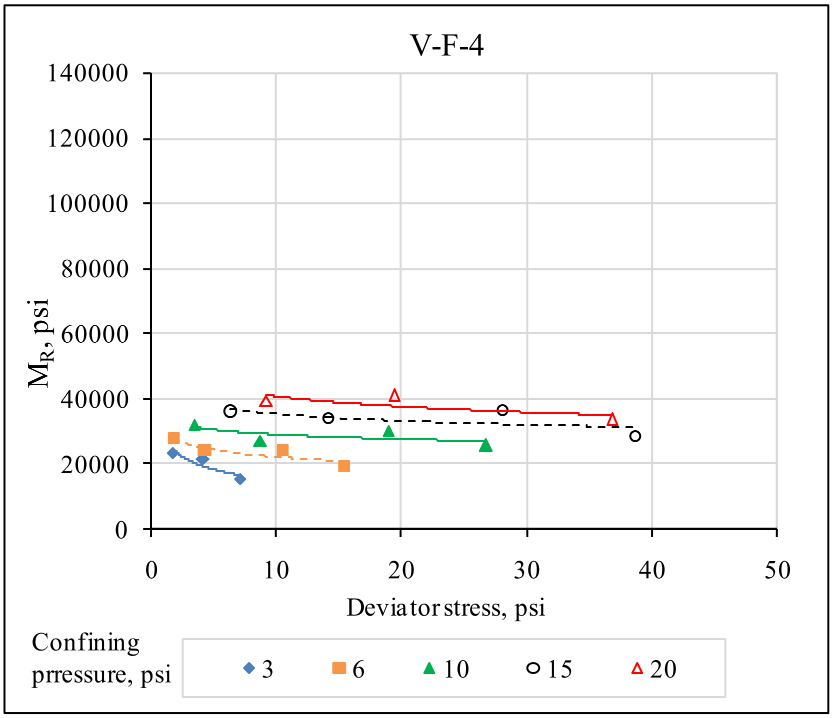

Figure F.44 M_R vs. deviator stress at different confining pressures for RAP TH 19-104 (OMC + 2%, 97% MDD, 2 F-T)

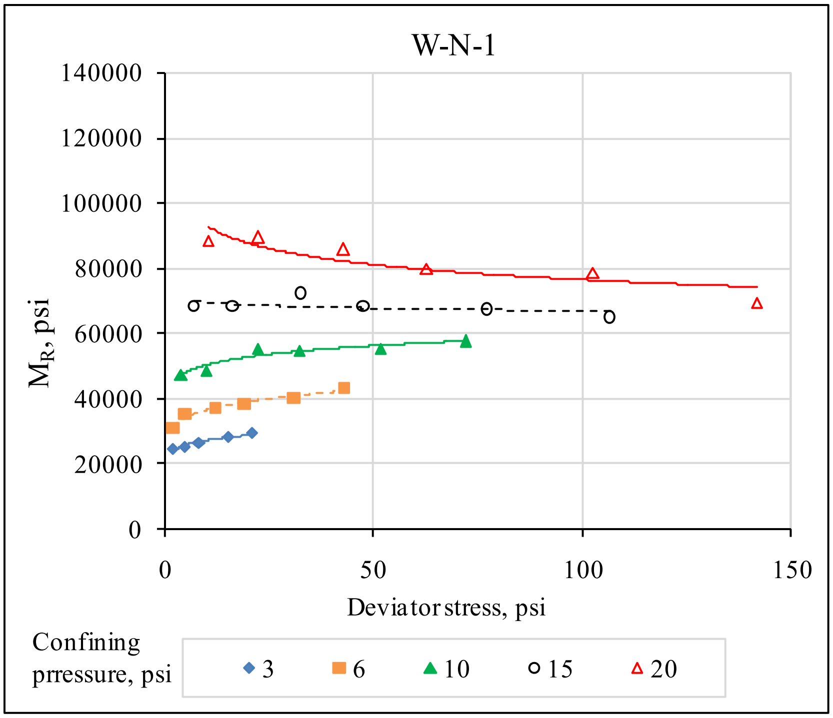

Figure F.45 M_R vs. deviator stress at different confining pressures for RAP TH 22 (OMC, 100% MDD)

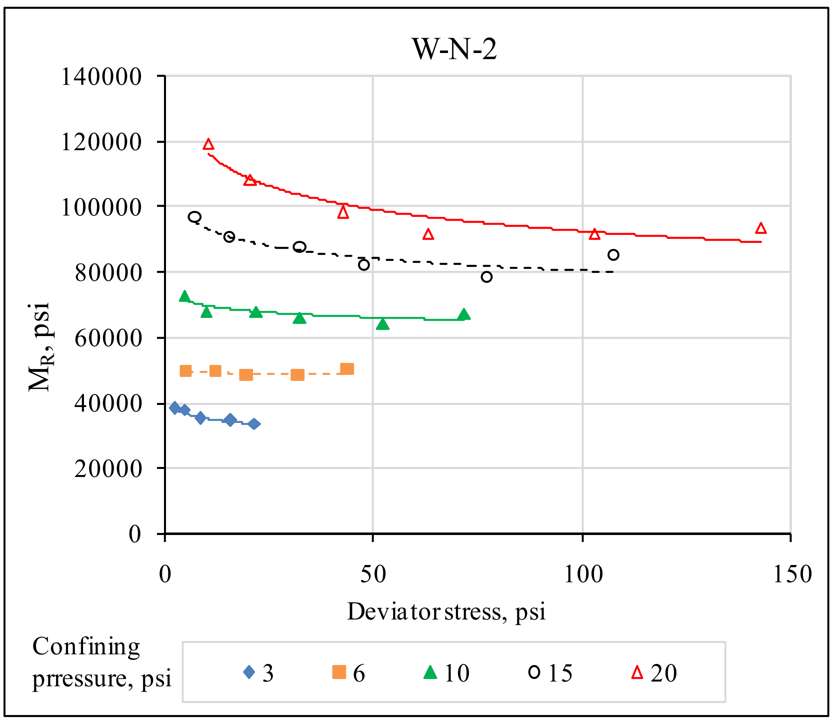

Figure F.46 M_R vs. deviator stress at different confining pressures for RAP TH 22 (OMC, 100% MDD, replicate)

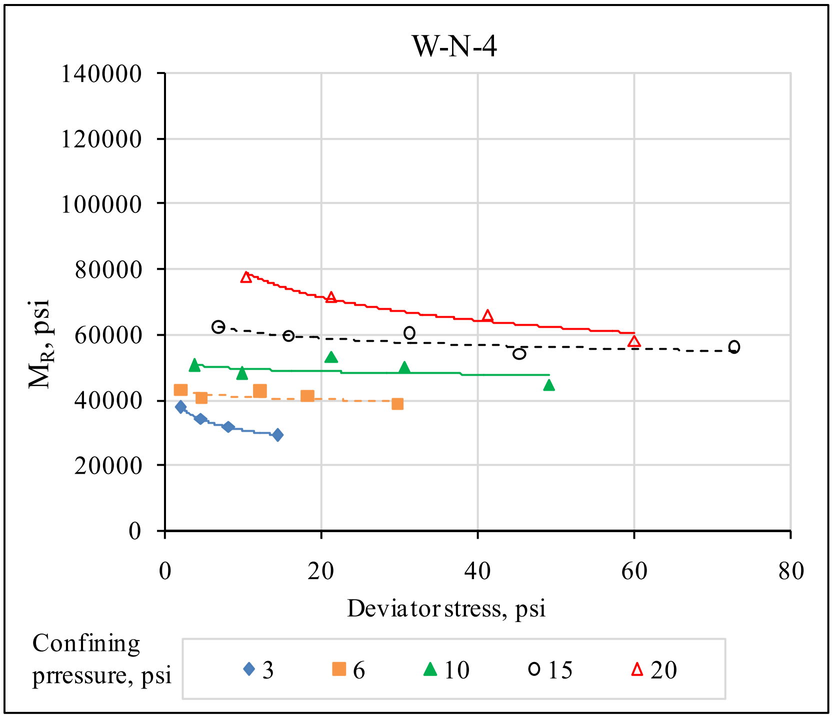

Figure F.47 M_R vs. deviator stress at different confining pressures for RAP TH 22 (OMC + 2%, 98% MDD)

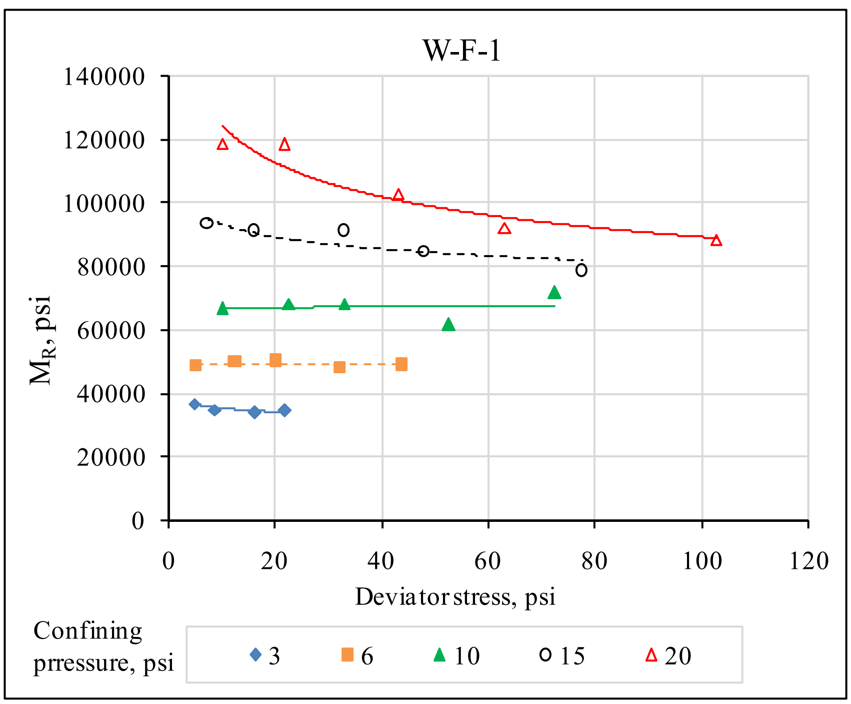

Figure F.48 M_R vs. deviator stress at different confining pressures for RAP TH 22 (OMC, 100% MDD, 2 F-T)

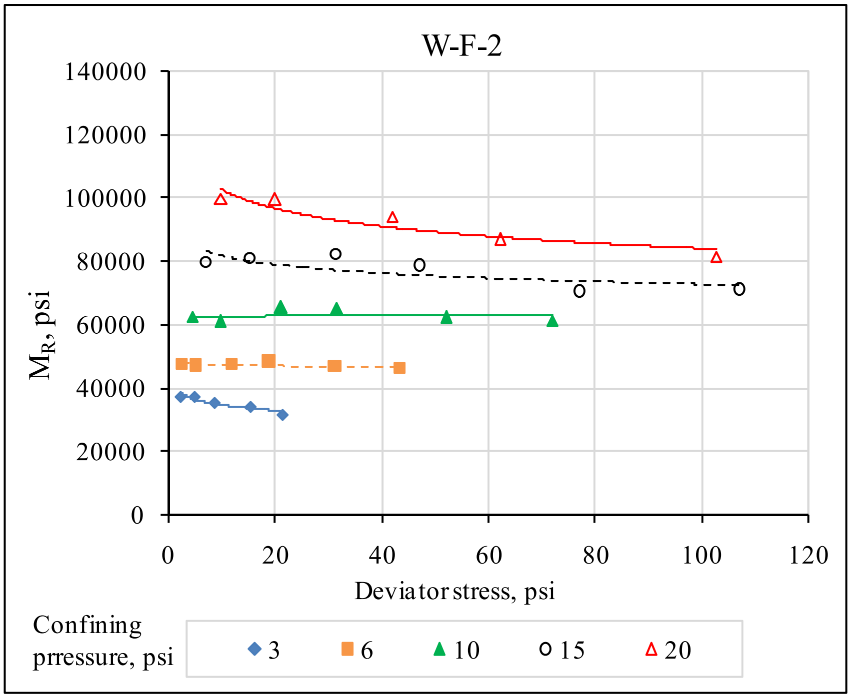

Figure F.49 M_R vs. deviator stress at different confining pressures for RAP TH 22 (OMC, 100% MDD, 2 F-T, replicate)

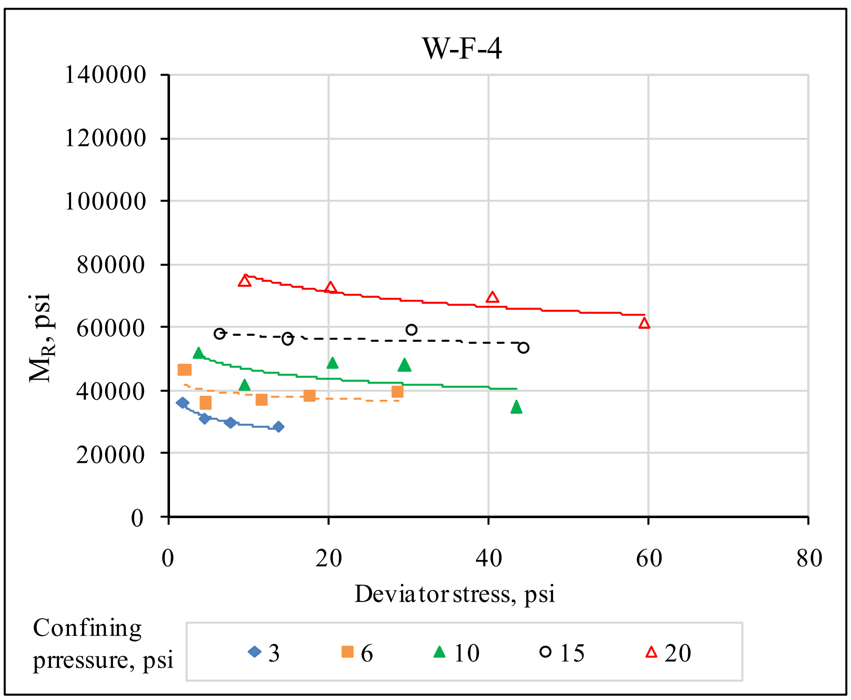

Figure F.50 M_R vs. deviator stress at different confining pressures for RAP TH 22 (OMC + 2%, 98% MDD, 2 F-T)

Appendix G

Dynamic Cone Penetration Results

Table G.1 Dynamic Cone Penetration Results for RAP TH 19-101

RAP TH 19-101			
	DCP#1	DCP#2	DCP#3
No. of blows	mm/blow	mm/blow	mm/blow
0	311	314	313
1	335	337	335
2	353	349	347
3	370	365	360
4	381	380	372
5	392	389	382
6	402	400	393
7	412	410	404
8	421	419	412
9	432	424	420
10	442	432	428
11	455	440	437
12	465	446	445
13	479	451	452
14	493	460	460
15	510	470	467
16	519	480	475
17	528	490	483
18	537	499	493
19	546	508	503
20	559	517	512
21	566	524	525
22	580	530	533
23	604	538	540
24	630	544	545
25		548	551
26		554	560
27		563	569
28		570	582
29		580	595
30		595	610
31		611	632

Table G.2 Dynamic Cone Penetration Results for RAP TH 19-104

RAP - TH 19-104				
	DCP#4-1	DCP#4-2	DCP#5	DCP#6
No. of blows	mm/blow	mm/blow	mm/blow	mm/blow
0	315	305	304	305
1	342	330	330	327
2	356	352	352	342
3	370	365	369	357
4	382	379	382	370
5	390	387	390	380
6	397	395	398	388
7	402	402	404	395
8	409	408	410	401
9	414	416	416	405
10		422	422	410
11		429	428	416
12		437	433	424
13		442	438	430
14		446	444	435
15		450	449	442
16		458	457	447
17		465	465	452
18		470	473	457
19		476	482	462
20		483	490	470
21		489	497	475
22		495	506	481
23		501	512	488
24		507	521	493
25		514	523	502
26		520	535	509
27		525	545	515
28		532	560	520
29		538	592	527
30		543	628	533
31		550		536
32		558		545
33		566		552
34		575		559
35		587		569
36		605		579
37		632		597
38				626

Table G.3 Dynamic Cone Penetration Results for RAP TH 22

TH 22			
	DCP#1	DCP#2	DCP#3
No. of blows	mm/blow	mm/blow	mm/blow
0	305	305	308
1	338	329	332
2	349	344	347
3	364	360	359
4	375	370	372
5	386	383	385
6	398	393	399
7	408	403	414
8	418	414	429
9	429	426	442
10	438	436	454
11	447	448	464
12	455	457	474
13	463	467	481
14	472	472	490
15	483	479	497
16	492	485	504
17	504	490	512
18	509	496	518
19		503	
20		507	
21		513	
22		518	