

EVALUATION OF HIGH PERCENTAGE RECYCLED ASPHALT PAVEMENT AS BASE
COURSE MATERIALS

By

MENGQI WU

A thesis submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

WASHINGTON STATE UNIVERSITY
Department of Civil and Environmental Engineering

August 2011

To the Faculty of Washington State University:

The members of the Committee appointed to examine the thesis of MENGQI WU find it satisfactory and recommend that it be accepted.

Haifang Wen, Ph.D., Chair

Balasingam Muhunthan, Ph.D.

Shihui Shen, Ph.D.

ACKNOWLEDGMENT

I would like to express my deepest gratitude to my advisor, Dr. Haifang Wen, who has offered me the great opportunity pursuing my master degree in Washington State University. I would never have been able to finish this thesis without all his support with guidance, patience, and encouragement. I would like to thanks Dr. Balasingam Muhunthan. Every time I came across difficulties in my research and turned to him, he always supported me with his patience and guidance. I also would like to thanks Dr. Shihui Shen, who led me to the road of pavement engineering. I would never been able to start the graduate study in WSU without her recommendation.

Special thanks go to Kalehiwot Nega for his help with air void study. As a friend, he was always willing to help and give his best suggestions. I would like to thank Jingan Wang, Huanan Yu and Junyan Yi for their help during lab testing. The lab assistance from undergraduates, Mr. Kelvin Daratha and Mr. Vincent Wen, is appreciated.

I would like to thank my husband, Xin Li, he was always supporting and encouraging me through my graduate study.

Finally, I would like to thank Transportation Northwest (TransNOW) and the Federal Highway Administration for the financial support of my research project.

EVALUATE HIGH PERCENTAGE RECYCLED ASPHALT PAVEMENT AS BASE MATERIALS

Abstract

by Mengqi Wu, M.S.
Washington State University
August 2011

Chair: Haifang Wen

The use of recycled materials for construction is beneficial to both the environment and the economy. Recycled asphalt pavement (RAP) is one of the most commonly used recycled materials. Different state departments of transportation allow the use of RAP in base materials at different percentages. Evaluation of engineering performance of base materials with RAP is important for proper pavement design. This study evaluated the potential use of high percentage recycled asphalt pavement as base course material without compromising the pavement performance in terms of stiffness, permanent deformation and permeability.

RAP from two different sources were collected for lab testing. Resilient modulus (M_r) was selected to represent the stiffness of base course material and the models that account for the effects of moisture content on the resilient modulus of unbound materials were evaluated on crushed aggregates with RAP. In addition, models were proposed to account for the effects of temperature on the resilient modulus of base materials with RAP.

Based on M_r testing results, permanent deformation was compared for specimens containing different percentages of RAP to evaluate the rutting potential. It was found adding RAP to virgin aggregate increased resilient modulus, but also increased rutting potential under certain conditions, such as 60 °C (140 °F), OMC-4 or OMC-2; and OMC at 20 °C for RAP1. Repeated load triaxial test was conducted in order to evaluate the effect of RAP percentage on permanent strain of base

course material. Tseng and Lytton introduced a permanent deformation prediction model in 1989 for granular base course material, and the model was modified by adding RAP percentage as a parameter for base course materials containing RAP.

Constant head permeability tests were conducted for samples containing different percentages of RAP, and the results suggested that coefficient of permeability decreased with the increase of RAP percentage. In addition, freeze-thaw conditioning was applied to specimens to investigate the effect on M_r and permeability.

X-Ray Computed Tomography scanning was conducted for specimens containing different percentages of RAP. Lower air void was detected for specimens containing higher RAP percentage, which might be one of the reasons leading to higher M_r and lower permeability.

TABLE OF CONTENTS

ACKNOWLEDGMENT	III
ABSTRACT	IV
LIST OF TABLES	IX
LIST OF FIGURES	X
CHAPTER1: INTRODUCTION	1
1.1 PROBLEM STATEMENT	1
1.2 BACKGROUND	2
1.3 OBJECTIVES.....	3
1.4 ORGANIZATION OF THESIS	3
CHAPTER 2: LITERATURE REVIEW	5
2.1 INTRODUCTION.....	5
2.2 CURRENT USE OF RAP AS BASE COURSE	5
2.3 PAST STUDIES ON RESILIENT MODULUS OF RAP	7
2.4 PAST STUDIES ON OTHER ENGINEERING PROPERTIES OF RAP	9
2.4.1 Moisture-density relationship	9
2.4.2 Permanent deformation.....	10
2.4.3 Permeability	11
2.4.4 Moisture damage.....	12
CHAPTER 3: MATERIAL AND EXPERIMENTS.....	14
3.1 CHARACTERIZATION OF BASE COURSE MATERIAL CONTAINING RAP	14

3.1.1 Sampling	14
3.1.2 Gradation	14
3.1.3 Asphalt content determination.....	16
3.1.4 Specific gravity	17
3.1.5 Moisture-density relationship	17
3.1.6 Stiffness	19
3.1.7 Permanent deformation.....	23
3.1.8 Permeability	25
3.1.9 Moisture damage.....	27
3.2 X-RAY COMPUTED TOMOGRAPHY SCANNING FOR SPECIMENS CONTAINING RAP..	28
3.2.1 Introduction	28
3.2.2 X-Ray CT scanning methods for specimens containing RAP.....	29
CHAPTER 4: ANALYSIS AND RESULTS	31
4.1 ASPHALT CONTENT DETERMINATION.....	31
4.2 BULK SPECIFIC GRAVITY AND MOISTURE-DENSITY RELATIONSHIP.....	31
4.3 STIFFNESS.....	34
4.3.1 Modeling of resilient modulus	34
4.3.2 Effect of RAP percentage on resilient modulus	37
4.3.3 Modeling the effect of moisture content on Mr	39
4.3.4 Effect of temperature on resilient modulus	43
4.3.5 Effect of state of stress on resilient modulus.....	50
4.4 PERMANENT DEFORMATION	55
4.4.1 Permanent deformation determined by resilient modulus test method	55
4.4.2 Permanent deformation determined by repeated load triaxial compression test method	61
4.5 PERMEABILITY	67
4.6 MOISTURE DAMAGE.....	68
4.6.1 Effect of freeze-thaw on resilient modulus	68
4.6.2 Effect of freeze-thaw on permeability	70
4.7 X-RAY CT SCANNING FOR SPECIMENS CONTAINING RAP	71
4.8 SUMMARY	75

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS.....	77
5.1 CONCLUSIONS.....	77
5.2 RECOMMENDATIONS.....	79
REFERENCES	80
APPENDIX DETAILED TESTING RESULT	83

LIST OF TABLES

Table 1 State DOTs Survey Result [McGarrah 2007]	6
Table 2 Gradation for evaluated samples and required gradation in WSDOT specifications	15
Table 3 Test variables of RAP percentage, temperature and moisture content	21
Table 4 Test Sequence for Base/Subbase Materials [Witczak 2004]	23
Table 5 Asphalt content corresponding to RAP percentage.....	31
Table 6 Compaction Characteristics before and after Correction	32
Table 7 Coefficients and R ² for Different Samples Based on NCHRP 1-28A Model.....	35
Table 8 Model coefficients P-value and R ² for determining the effect of moisture content on Mr	41
Table 9 Model efficient, R ² and P-value for evaluating the effects of temperature on Mr.....	48
Table 10 Permanent Strain for RAP1 and RAP2 mixtures	56
Table 11 Cyclic stress and confining pressure applied to RAP2 samples.....	61
Table 12 Model coefficients, P-value and R ² for Permanent Deformation Characterization	62
Table 13 Permanent deformation data for base material [Tseng et al. 1989]	65
Table 14 Coefficient of permeability for RAP2 mixtures	67
Table 15 Moisture Content of Specimens before and after Mr Test	70
Table 16 Resilient Modulus at Confining Pressure of 41kPa (5.95psi) and Deviator Stress of 103kPa (14.94psi).....	75

LIST OF FIGURES

Figure 1 Witczak (2004) Definition of Resilient Modulus Terms	8
Figure 2 Gradation for evaluated samples and required gradation in WSDOT specifications	16
Figure 3 Resilient Modulus Sample during Testing in GCTS	22
Figure 4 LVDTs used for measuring the permanent deformation	24
Figure 5 Constant-head Permeability Test Equipment	27
Figure 6 Moisture-density relationship for (a) RAP1 mixtures (b) RAP2 mixtures	33
Figure 7 Relation of OMC, Bulk Specific Gravity and RAP Percentage	33
Figure 8 Relation between Predicted Mr and Measured Mr for (a) 0% RAP1 with OMC tested at 20 °C (b) 0% RAP1 with OMC tested at 60 °C (c) 0% RAP1 with OMC-4% tested at 20 °C.....	36
Figure 9 Effect of RAP1 Percentage on Mr at (a) Low Cyclic Stress Figure (b) High Cyclic Stress Figure; Effect of RAP2 Percentage on Mr at (c) Low Cyclic Stress (d) High Cyclic Stress.....	38
Figure 10 Relationship between predicted and Measured Mr for 20% RAP1 based on (a) Kw Model (b) Sigmoid Model.....	42
Figure 11 Effect of Moisture Content on Resilient Modulus of (a) RAP1 mixtures (b) RAP2 mixtures ...	43
Figure 12 (a) Effect of RAP1 percentages on Mr at -20 °C (b) Effect of RAP2 percentages on Mr at -20 °C	45
Figure 13 Effect of temperature on Mr for different samples.....	46
Figure 14 Relation between predicted and measured Mr for 40% RAP2 based on (a) K_T Model (b) Sigmoidal Model	49
Figure 15 (a) Effect of Temperature on Mr for RAP1 mixtures based on K_T Model (b) Effect of Temperature on Mr for RAP2 mixtures based on K_T Model.....	50
Figure 16 Effect of confining pressure on Mr for (a) 0% RAP2 (b) 20% RAP2 (c) 40% RAP2 (d) 60% RAP2 (e) 80% RAP2.....	53

Figure 17 Effect of deviator stress on Mr for samples containing (a) 0% RAP2 (b) 40% RAP2 (c) 80% RAP2.....	55
Figure 18 (a) Relationship between Permanent Strain and RAP1 Percentage for specimens tested at 20 °C and 60 °C (b) Relationship between Permanent Strain and RAP2 Percentage for specimens tested at 20 °C and 60 °C.....	57
Figure 19 Relationship between Permanent Strain and RAP percentage for (a) RAP1 and (b) RAP2.....	58
Figure 20 Relationship between Permanent Strain and RAP Percentage for (a) RAP 1 and (b) RAP 2....	59
Figure 21 Relationship between Permanent Strain and Moisture Content for (a) RAP 1 and (b) RAP 2 ..	60
Figure 22 Relationship between permanent strain and time for RAP2 mixtures	63
Figure 23 Relationship between measured and predicted values of (a) $\text{Log}(\epsilon_o/\epsilon_r)$, (b) $\text{Log}\beta$ and (c) $\text{Log } p$	67
Figure 24 Trend of hydraulic conductivity with the increase of RAP2 percentage	68
Figure 25 Effect of Freeze-thaw conditioning on Mr of specimens containing different percentages of RAP2.....	69
Figure 26 Effect of Freeze-thaw conditioning on permeability of specimens containing different percentages of RAP2	70
Figure 27 3-Dimensional images for (a) 80% RAP2 specimen (b) 0% RAP2 specimen	72
Figure 28 Porosity distribution over the depth of (a) 0% RAP2 (b) 80% RAP2	74
Figure 29 Original and segmented images at the depth of 0.39inch for (a) 80% RAP2 (b) 0% RAP2.....	75

CHAPTER1: INTRODUCTION

1.1 PROBLEM STATEMENT

Large amount of construction waste is produced each year and it becomes more difficult to find appropriate locations for landfill. Recycled materials offer viable solutions to the concern, which is beneficial to both environment and economy. The Federal Highway Administration (FHWA) estimates that 100.1 million tons of Hot Mixed Asphalt (HMA) is scraped each year [Cosentino 2001]. Recycled Asphalt Pavement (RAP) is one of the most commonly used recycled materials. RAP is the term given to removed and/or reprocessed pavement materials containing asphalt and aggregates. RAP is generated when asphalt pavements are removed for reconstruction, resurfacing, or to obtain access to buried utilities. RAP consists of high-quality, well-graded aggregates coated by asphalt cement [RMRC 2008]. Many state departments of transportation allow the use of recycled asphalt pavement (RAP) to be blended with aggregate materials to produce a composite base course material. McGarrah conducted a survey among the State Department of Transportation regarding the use of RAP as base course material. The results indicated that the percentage of RAP allowed by highway agencies to use as base course material varied from 2 percent to 60 percent [McGarrah 2007]. Currently, the Washington State Department of Transportation (WSDOT) allows up to 1.2 percent bitumen (about 20 percent RAP) in base materials [WSDOT 2008]. An increased percentage of RAP in base course could offer economical and environmental benefits. However, as more RAP material is incorporated into the base course material, concerns are raised by the agencies, such as the impact of high percentage RAP on pavement design, the appropriate compaction requirements, and drainage characteristics, all of which may affect the overall long-term performance of both flexible and rigid pavement structures [Uhlmeier 2008]. A study is needed to evaluate the potential use of

high percentage (greater than 20%) recycled asphalt pavement as base course material, without compromising the pavement performance. A successful application of high percentage RAP could contribute to the sustainability, in terms of costs, energy, and greenhouse gas emission.

1.2 BACKGROUND

Some studies have been conducted on recycled materials in other states, primarily focusing on laboratory evaluation of physical properties. Kim et al. found that recycled asphalt as base materials had higher resilient modulus, but higher rutting potential than virgin aggregates in Minnesota [Kim et al. 2007]. Wen et al. studied the recycled asphalt pavement with and without fly ash as base course materials in Wisconsin and compared to crushed aggregate [Wen et al. 2008]. Experiment roads were also built at MnROAD in Minnesota. It was found in the study that RAP has high modulus, but high permanent deformation, when compared to crushed aggregate. Adding cementitious materials improved the resistance to permanent deformation. Jeon et al. reported that both the static shear strength and the resilient modulus of the pulverized materials were generally higher than virgin aggregate materials. However, resistance of RAP to permanent deformation at low stress levels was lower than that of the typical aggregate base material in California. In addition, at high stress levels, RAP had higher resistance to permanent deformation than aggregate material [Jeon et al. 2009]. The sources of RAP could bring much variation to the engineering properties of RAP. In addition, due to the existence of asphalt, unlike crushed aggregates, properties of RAP are affected by temperature fluctuation [Consentino 2001]. The permeability of RAP is another concern. The moisture trapped in RAP base could cause further moisture damage to RAP. The stripping, due to moisture damage, can generate fines which affect the permeability [Saeed 2008].

The above studies have shown that RAP has potential to be good base course materials, but also have some issues. The issues related to RAP have to be addressed before high percentage RAP can be used for routine highway construction.

1.3 OBJECTIVES

The primary objectives of this research consisted of the following:

- (1) Engineering performance of RAP, in terms of stiffness (modulus), rutting potential and permeability due to moisture damage, change of moisture content and effect of temperature.
- (2) Evaluation of the resilient modulus model introduced in NCHRP 1-28A specification for samples containing different percentages of RAP.
- (3) Modeling the effect of moisture content on resilient modulus for samples containing different percentages of RAP.
- (4) Development of models evaluating the effect of temperature on resilient modulus for samples containing RAP.
- (5) Modification of the permanent deformation prediction model introduced by Tseng and Lytton (1989), in order to evaluate the effect of RAP percentage on permanent strain of base course material.

1.4 ORGANIZATION OF THESIS

This thesis consists of five chapters. The first chapter presents the introduction of the research topic, background and objectives. Chapter 2 introduces findings based on literature review on past studies of related topics as well as current practice. Chapter 3 describes material and laboratory testing. In this chapter, detailed experiment design and protocol followed by each test are introduced. Chapter 4 presents testing results and analysis. Based

on the testing data, models are developed and evaluated in this chapter. Chapter 5 introduces the conclusions and recommendations of this study.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

According to the National Asphalt Pavement Association (NAPA), more than 90 percent of U.S. roads and highways are paved with HMA. About 500 million tons (454 million metric tons) are produced each year. During rehabilitation or reconstruction, the existing HMA layers are removed partial-depth or full-depth. In response to the shrinking supply of raw materials and the rising costs of virgin aggregates and binders, RAP is considered to be an alternative to virgin materials and a valuable component in HMA. According to a survey by the Federal Highway Administration (FHWA), in 2007 the average amount of RAP incorporated into HMA mixtures by State DOTs was 12 percent by the weight of total mixture. Although the state DOTs are using more RAP in HMA, high percentages of RAP (greater than 25 percent) allowed in HMA productions are still not common. In addition, RAP can be used in-situ as a base course material which eliminates the transportation of RAP to HMA plant and reduces the need for virgin aggregates

2.2 CURRENT USE OF RAP AS BASE COURSE

The use of RAP as a base course material offers economical and environmental benefits. The WSDOT currently allows up to 20 percent RAP to be blended with virgin crushed aggregates to form the base course materials. McGarrah conducted a survey of current practices of State DOTs regarding the use of RAP as base course material and contacted 7 states including Colorado, Florida, Illinois, Minnesota, Montana, New Jersey and Utah [McGarrah 2007]. The result for the survey is listed in Table 1.

Table 1 State DOTs Survey Result [McGarrah 2007]

State	Rap Allowed¹	Max %²	Processed³	Testing⁴
Florida	No	---	---	---
Illinois	No	---	---	---
Montana	Yes	50-60%	No	Corrected Nuclear Gauge
New Jersey	Yes	50% ⁵	Yes – Gradation	Corrected Nuclear Gauge + Sample
Minnesota	Yes	3% ⁶	Yes – Gradation	Dynamic Cone Penetrometer
Colorado	Yes	50% ⁵	Yes – Max Agg. Size	Roller Compaction Strip
Utah	Yes	2% ⁶	Yes – Gradation	Nuclear Gauge or Breakdown Curve
Texas ⁷	Yes	20%	Unknown	Various (including Nuclear Gauge)
California ⁷	Yes	50%	Unknown	No special testing procedure listed
New Mexico ⁷	Yes	Unknown	Unknown	Corrected Nuclear Gauge
Rhode Island ⁷	Yes	Unknown	Yes – Gradation	Unknown
South Dakota ⁷	No	---	---	---

1 Describes whether state allows RAP as a base course material.

2 The maximum percentage of RAP (by weight) allowed.

3 Describes whether the listed state requires the RAP blend to be processed prior to placement and what requirements must be met

4 Describes the type of QA testing required.

5 These are modified values. The current values are 100%, but the materials department is in the process of modifying current values.

6 These values are the maximum AC content allowed in the RAP blend.

7 These states were not contacted and the information listed in the table is from the state's current standard specification.

As shown in the table, the maximum percentage of RAP as base course material allowed by state DOTs vary from 0 percent to 60 percent based on the data collected from the survey. For the state of Montana, whether RAP may be used as base course material is decided on a project-by-project basis instead of being stated in the standard specifications, and the maximum percentage of RAP used as base course material may reach 60%. The maximum percentage of

RAP used as base course was selected on the basis of the research conducted by Mokwa, which proved that the blending of RAP with virgin aggregate only caused minor changes to the engineering properties of the mixed base course material [Mokwa 2005].

For the State of Florida, RAP was allowed to be used as backfill in roadways or as construction material for embankments around pipes and culverts. RAP was also allowed to be used in roadway subbase and base if it could meet specifications, such as the Limerock Bearing Ratio, for subbase/base materials. A study conducted by Cosentino et al. indicated that the deformation potential of RAP significantly increased with the increase of temperature [Cosentino et al. 2001].

2.3 PAST STUDIES ON RESILIENT MODULUS OF RAP

The stiffness of base layer greatly affects the fatigue life of hot mix asphalt surface layer. High stiffness is desired to prolong the pavement life. Resilient modulus (M_r) is a basic property that represents the stiffness of base course material. Resilient modulus test is commonly conducted in the laboratory to determine M_r . M_r test is commonly conducted in accordance with NCHRP 1-28A or AASHTO T307 test protocol for base course material. In the laboratory, M_r is determined by applying repeated compressive loading (Figure 1) on test specimens of the unbound material under confining condition. Resilient modulus is defined as the ratio of the peak repeated axial deviator stress to the peak recoverable axial strain of the specimen, which is shown in Equation 1 [Witczak 2004].

$$M_r = S_{\text{cyclic}} / \epsilon_r \quad (1)$$

where, M_r is the resilient modulus,

$S_{\text{cyclic}} = (P_{\text{max}} - P_{\text{contact}}) / A$, and A is the initial cross-sectional area of the sample,

$r = \frac{e_r}{L}$, and e_r is the recoverable axial deformation due to S_{cyclic} , L is the distant between measurement points for resilient axial deformation, e_r .

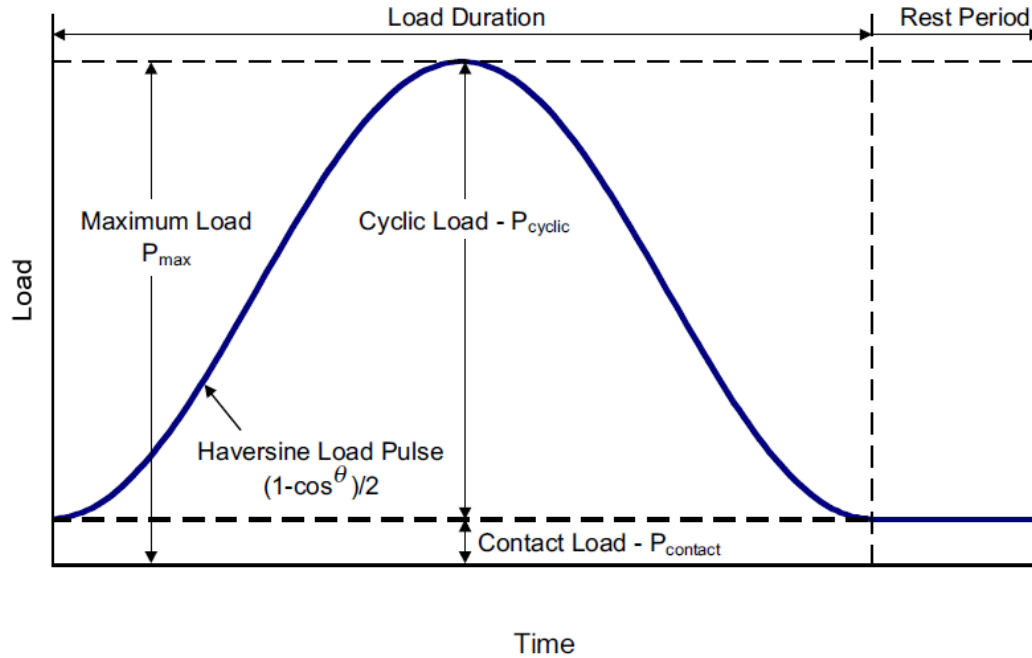


Figure 1 Witczak (2004) Definition of Resilient Modulus Terms

Temperature and moisture content are main factors affecting the in situ modulus of unbound pavement materials on a seasonal basis [Richter 2006]. In a pavement design, such as the American Association of State Highway and Transportation Officials (AASHTO) 1993 design method [AASHTO 1993] or the mechanistic-empirical pavement design guide (MEPDG) [ARA 2004], resilient modulus is the primary design property for unbound materials. In the MEPDG, the effects of moisture content fluctuation on resilient modulus are modeled with the soil-water characteristic curve (SWCC). Moisture content also affects the permanent deformation of unbound materials. MEPDG only considers traditional unbound materials, such as virgin aggregates. The recycle materials, such as RAP, may present unique properties which are not accounted for in MEPDG. For instance, the asphalt in RAP is sensitive to temperature which is

not considered for traditional unbound materials. The resilient modulus of base materials with RAP has to include the effects of climatic effects, such as temperature and moisture contents, in the MEPDG.

Wen et al. studied the resilient modulus of base materials with RAP. It was found that base materials containing RAP had higher resilient modulus [Wen et al. 2010], which agreed with findings by others [Maher 1997]. Kim et al. conducted resilient modulus tests on specimens containing different ratios of RAP at 65 percent and 100 percent of optimum moisture content (OMC), respectively. It was reported that specimens at 100 percent OMC had lower M_r values than those of specimens at 65 percent OMC [Kim et al. 2007]. Attia et al. also found that samples containing RAP had higher M_r values than those of crushed aggregates [Attia et al. 2009]. However, the sensitivity of the resilient modulus of RAP to moisture content was higher than that of granular material [Attia et al. 2010]. Sargious et al. studied the effects of low temperature on the behaviors of RAP. It was concluded that M_r increased with the decrease of temperature from 20°C to -40 °C [Sargious et al. 1991]. However, only low temperatures were considered for the effects on material properties. The effects of high temperature on resilient modulus and permanent deformation were not considered.

2.4 PAST STUDIES ON OTHER ENGINEERING PROPERTIES OF RAP

2.4.1 Moisture-density relationship

Cooley determined OMC and MDUW for samples containing different percentages of RAP using modified proctor compaction method. The results indicated that the increasing percentage of RAP caused a decrease of OMC and MDUW [Cooley 2005]. Attia et al. found that RAP had a lower MDUW comparing to aggregate samples, based on results from both proctor compaction tests and tests using gyratory compactor at 50 gyrations [Attia et al. 2009]. For the

gyratory compaction, increasing RAP decreased OMC whereas for standard proctor compaction, OMC increased with the increase of RAP percentage. Gupta et al. conducted tests to determine the OMC and MDUW for samples containing different percentages of RAP using gyratory compactor at a compaction angle of 1.25 degrees, the compaction pressure of 600 kPa (87.02 psi), and 50 gyrations [Gupta et al. 2009]. It was concluded that increasing RAP increased MDUW but decreased OMC. MacGregor et al. evaluated the relationship between OMC, MDUW and RAP content. The results indicated that no correlation was found between the RAP content and OMC or MDUW [MacGregor et al. 1999].

2.4.2 Permanent deformation

Permanent deformation in base course greatly affects the pavement performance, such as rutting. A series of repeated triaxial compression tests were conducted by Mohammad et al. to determine the permanent deformation of base course materials [Mohammad et al. 2006]. Two vertical linear variable differential transducers (LVDT) were used to detect the displacements. A haversine load pulse of 0.1-second loading and 0.9-second rest period was applied to samples for 10,000 cycles. The samples were conditioned before the tests were conducted by applying a number cycles of vertical stress and confining stress. The permanent deformation of RAP exhibited an initial acceleration and then reached a steady state. It was reported that the M_r was not sufficient in characterizing base course material of pavement structure and permanent deformation should be incorporated in the pavement design procedure [Mohammad et al. 2006].

Kim et al. conducted 20 M_r tests for samples with different percentages of RAP to investigate the effects of RAP percentage on resilient modulus. Specimens were prepared using the gyratory compactor and NCHRP 1-28A test protocol was followed [Kim et al. 2007]. The test results showed that the RAP specimens were stiffer at high confining pressure when

compared with virgin aggregate samples. However, the permanent deformation of specimens containing RAP was greater than that of virgin aggregates.

2.4.3 Permeability

Hydraulic conductivity is recognized as an important parameter for base course material. If the subgrade material is saturated, the pavement may deteriorate rapidly [Attia 2009, ARA 2004]. The moisture trapped between the particles in base layer may lead to the destruction of the pavement structure due to the loss of support. For asphalt pavement, moisture can infiltrate into the base layer through surface cracking or shoulder over time.

Compaction efforts during sample preparation reduce the volume of large pores and increase the volume of small pores [Gupta 2009]. Trzebiatowski et al. conducted a study to determine the hydraulic conductivity of RAP as base course material [Trzebiatowski et al. 2005]. It was concluded that the saturated hydraulic conductivity of RAP ranged from 4.5×10^{-8} to 1.7×10^{-6} m/s when compacted with modified proctor efforts and from 2.4×10^{-5} to 9.0×10^{-5} m/s when compacted with standard proctor efforts. For the hydraulic conductivity testing conducted in the study by Trzebiatowski et al., a rigid-wall, compaction-mold permeameter was selected to conduct for sample preparation and ASTM D5856 test protocol was followed. By comparing the testing result on RAP and crushed stone, it was reported that the permeability of RAP is comparable to that of traditional base course material [Trzebiatowski 2005]. Another study by Gupta found that samples containing RAP had higher hydraulic conductivity when compared to aggregates. However, no correlation was detected between RAP percentage and the hydraulic conductivity [Gupta 2009]. Bouchédid et al. tested base course materials for coefficient of permeability in the triaxial permeameter as well as in the rigid wall permeameter, respectively [Bouchédid et al. 2001]. It was founded that the difference between the two methods was caused

by different boundary conditions and sample preparation methods. Based on the results of field permeability measurements, triaxial permeameter was recommended to be used for lab testing since the average field permeability was close to that from the triaxial permeability. Macgregor et al. conducted 12 hydraulic conductivity tests with samples containing RAP, crushed-stone base materials and gravel-borrow subbase materials [Macgregor et al. 1999]. It was found that hydraulic conductivity was not significantly affected by the change of RAP percentage in the RAP/crushed stone mixtures while the hydraulic conductivity of RAP/gravel-borrow mixtures increased by nearly an order of magnitude with the increase of RAP percentage from 0% to 50%. The uniform gradation of RAP was believed to be the reason for the increased hydraulic conductivity. Since factors such as compaction efforts, type of soil and gradation affect hydraulic conductivity, it is difficult, based on the literature, to determine whether the RAP percentage affects the hydraulic conductivity of mixtures.

2.4.4 Moisture damage

The base materials are subjected to moisture damage and freeze-thaw cycles. When RAP is used in base course, asphalt may strip off the aggregates and affect the permeability. In the laboratory, pavement materials are subjected to freeze-thaw conditioning for determining stripping. For hot mix asphalt, WSDOT Test Method T718 is commonly followed, which specifies a minimum of 16 hours' freezing at -18 ± 3 °C (0 ± 5 °F) followed by 60 ± 1 °C (140 ± 2 °F) for 24 hours. For aggregates, AASHTO T102 introduces procedures for freezing and thawing in which samples should be cooled until the center of the samples reaches -23 ± 3 °C (-9 ± 5 °F) and the temperature shall be held for a minimum of 2 hours prior to the thaw cycle which lasts a minimum of 30 minutes at 21 ± 3 °C (70 ± 5 °F). According to AASHTO T102, the procedure of alternate freezing and thawing should be repeated for 25 cycles.

2.4.4.1 Effect of Freeze-thaw on resilient modulus

The modulus of base course exhibits seasonal variations due to variation of moisture content and/or temperature. The stresses and strains induced in the pavement by traffic loads also vary with the modulus of the pavement layers [Mohammad et al. 2006]. Attia et al. subjected a set of samples to two freeze-thaw cycles to evaluate the effect of freeze-thaw on the resilient modulus of RAP as compared to virgin aggregate [Attia et al. 2009]. One cycle of freeze-thaw conditioning consisted of 24 hours of freeze conditioning at -12 °F followed by 24 hours thawing conditioning at room temperature. Based on test results, samples containing RAP compacted at OMC did not show loss of strength due to freeze-thaw cycles. It was reported that the moisture content was decreased, which indicated loss of moisture during conditioning and/or testing. The decreased moisture content could be a reason for higher modulus after freeze-thaw conditioning for samples.

Chapter 3: MATERIAL AND EXPERIMENTS

In order to study the effects of high percentage of RAP on the performance of base course, lab tests were conducted, in terms of resilient modulus, rutting potential and hydraulic conductivity.

3.1 CHARACTERIZATION OF BASE COURSE MATERIAL CONTAINING RAP

3.1.1 Sampling

Material used in this study includes crushed aggregates and RAP. Crushed aggregates were sampled from POE Asphalt Paving Inc. in Pullman, WA site. RAP was collected from two sources: POE Asphalt Paving Inc in Pullman, WA and Fairmount Road construction site in Pullman, WA. The RAP sample from Fairmount Road was collected after the milling of the existing pavement section. The RAP collected from POE Asphalt Paving Inc was referred to as RAP1 and the RAP from Fairmount Road Project was referred to as RAP2.

3.1.2 Gradation

As some fine particles might adhere to large RAP particles, more accurate result would be obtained by performing wet sieving instead of dry sieving method. According to AASHTO T 11-05, the amount of material finer than No.200 sieve can be determined by washing. Particle gradation for RAP was conducted according to AASHTO T 11-05, in which procedure A was chosen.

Since the objective of this study was to evaluate the effects of RAP, in order to eliminate the effect of gradation on the material properties, one single gradation was selected to meet the WSDOT specifications 9-03.9(3) for crushed surfacing base course material. Crushed aggregate particles of different sizes were added to obtain the target gradation of the mixture. Table 2 and Figure 2 show the typical gradations for mixtures containing RAP1 and RAP2, the original

gradations of RAP1 and RAP2, and the gradation required in WSDOT specification for base course material. RAP 1 has a top size of 12.5 mm (0.5 inch) which is process for use in HMA while the RAP has top size of 31.5mm (1.25 inches).

Table 2 Gradation for evaluated samples and required gradation in WSDOT specifications

Sieve size, "(mm)	Passing percentage				
	Typical gradation		RAP1	RAP2	WSDOT specification
	RAP1 mixtures	RAP2 mixtures			
1-1/4"(31.5)	100	100		100.00	100
1"(25.0)	99	94		93.56	80-100
3/4(19.0)	86	84		82.26	
5/8(16.0)	76	75		71.23	50-80
1/2(12.5)	72	66	100.00	61.31	
3/8(9.5)					
1/4(6.3)					
No.4(4.75)	39	31	47.10	22.20	25-45
No.6(3.35)					
No.8(2.36)	22	18	21.79	11.07	
No.10(2.00)					
No.16(1.18)	15	12	10.62	5.70	
No.20(0.850)					
No.30(0.600)					
No.40(0.425)	10	7	5.14	2.52	3-18
No.50(0.300)					
No.80(0.180)					
No.100(0.150)	7	4	3.13	1.44	
No.200(0.075)	3	2	2.47	1.08	7.5max

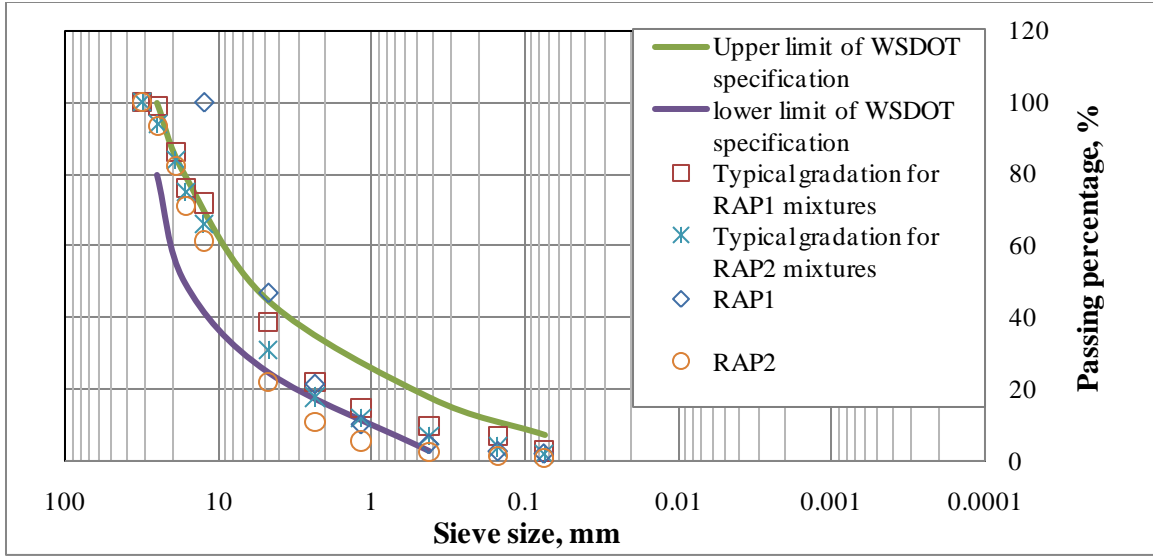


Figure 2 Gradation for evaluated samples and required gradation in WSDOT specifications

3.1.3 Asphalt content determination

The Ignition Method was used to determine the asphalt contents in RAP1 and RAP2 and the typical correction factor was used for the testing [AASHTO T308]. Ignition oven was preheated to 538 °C (1000 °F) and the weight of the assembly with lid was recorded. Mixtures were placed on the tray and spread evenly with a hot spatula. The tray containing the sample was placed into the ignition oven and the ignition started until the weight loss become constant. The calibrated asphalt content was calculated as follows:

$$AC\% = [(WS - WA) / WS] \times 100 - CF \quad (2)$$

where,

AC% = measured (corrected) asphalt content percent by weight of the HMA sample;

WA = total weight of aggregate remaining after ignition;

WS = total weight of the HMA sample prior to ignition; and

CF= calibration factor, percent by weight of HMA sample, which depends on oven setup and efficiency.

3.1.4 Specific gravity

The bulk specific gravity of coarse aggregates was determined in accordance with the AASHTO T 85. Aggregate retained on No. 4 sieve was soaked in water for 15 hours before testing. Based on the testing data, bulk specific gravity can be calculated according to the equation presented as follows:

$$G_{sb} = A / (B - C) \quad (3)$$

where,

G_{sb} = bulk specific gravity

A = mass of oven-dry test sample in air, g;

B = mass of saturated-surface-dry test sample in air, g;

C = mass of test sample in water, g.

3.1.5 Moisture-density relationship

The modified proctor compaction test was conducted to determine the optimum moisture content (OMC) and maximum dry unit weight (MDUW) in accordance with D method of the AASHTO T 180, because less than 30 percent by mass of the material is retained on the 19 mm (3/4 inch) sieve. This procedure uses a 48 N (10 lb) hammer and a 45.72 cm (18 inches) drop height. Particles retained on the 19-mm (0.75 inch) sieve were removed prior to compaction, and samples were compacted in 5 lifts in a 152-mm (6 inches) mold using 56 blows per layer. The wet density was calculated as shown in Equation 4. Based on the wet density and the average moisture content, dry density was calculated according to Equation 5.

$$W1 = (A - B) / V \quad (4)$$

where,

W1 is wet density;

A is the mass of compacted specimen and mold;

B is the mass of mold;

V is the volume of mold.

$$W = \frac{W1}{w+100} \times 100 \quad (5)$$

where,

W is the dry density;

w is the moisture content of the specimen by percentage.

3.1.5.1 Correction for OMC and MDUW

As specified in AASHTO T-224, corrections to OMC and MDUW values were recommended if more than 5% particles are retained on 19-mm sieve. Based on the typical gradations chosen in this study, 14% particles were retained on 19.00 mm (3/4 inch) sieve for testing samples containing different percentages of RAP1 and 16% were retained on 19.00 mm (3/4 inch) sieve for samples containing RAP2. The OMC and MDUW values from the compaction tests were corrected in accordance with the adjustment equations expressed as follows:

$$MC_T = (MC_f \cdot P_f + MC_C P_C) / 100 \quad (6)$$

where,

MC_T is the corrected moisture content of the testing sample, expressed as a decimal;

MC_f is the moisture content of the fine particles, which are passing 19.00mm sieve, expressed as a decimal;

MC_C is the moisture content of the oversized particles, which are retained on 19.00mm sieve, expressed as a decimal; can be assumed to be 0.02 for most construction applications.

P_f is the percentage of fine particles, by weight;

P_C is the percentage of coarse particles, by weight.

$$D_d = 100 D_f k / (D_f \cdot P_C + k \cdot P_f) \quad (7)$$

where,

D_d is the corrected total dry density, kg/m^3 ;

D_f is the dry density of the fine particles, kg/m^3 ;

K equals to $1000 \times$ Bulk Specific Gravity of coarse particles, kg/m^3 .

$$P_f = 100 M_{DF} / (M_{DF} + M_{DC}) \quad (8)$$

$$P_C = 100 M_{DC} / (M_{DF} + M_{DC}) \quad (9)$$

where,

M_{DF} = mass of fine particles;

M_{DC} = mass of coarse particles

3.1.6 Stiffness

3.1.6.1 Introduction

The fatigue life of hot mix asphalt surface layer is greatly affected by the stiffness of base course. High stiffness of base course is considered to reduce the tensile strain at the bottom of HMA layer and prolong the fatigue life of pavement. Resilient modulus, adopted in the

mechanistic-empirical pavement design guide, is recognized as an effective measure of engineering performance of granular materials.

3.1.6.2 Resilient modulus test

3.1.6.2.1 Sample preparation and conditioning

The resilient modulus tests were conducted on mixtures containing different percentages of RAP and crushed aggregate in accordance with the NCHRP 1-28A test protocol. Samples for resilient modulus testing were prepared in accordance with the manual compaction procedure in the NCHRP 1-28A. Sample particles retained on 25.0 mm (1 inch) sieve were removed before sample preparation. After the materials were well-mixed, the mixture was compacted in a split mold with a diameter of 152 mm (6 inches) for 6 layers with each layer of 2-inch height to make a target height of 304.8 mm (12-inch). The mass of each layer was determined in accordance with corrected OMC and 95% MDUW in accordance with the protocol. For testing samples containing moisture contents other than the OMC, the dry density of samples was kept constant. Latex membrane was placed between the sample and the split mold, and vacuum was applied during the compaction.

Table 3 shows the testing schedule. For testing samples containing RAP1 or RAP2 with OMC, temperatures were varied from -20 to 60 °C (-4 to 140F) in order to determine the effects of temperature on Mr. For tests on specimens with varied moisture contents, the moisture contents varied from OMC-4% to OMC+2% to evaluate the effects on stiffness of base course material, while controlling other factors the same, such as the temperature and the percentage of RAP. Tests designed to evaluate the effects of moisture content were conducted right after sample preparation to avoid moisture loss. Samples used to determine the effect of temperature

on M_r were put in the environmental chamber of the Geotechnical Consulting and Testing Systems (GCTS) overnight set at the target temperature.

Table 3 Test variables of RAP percentage, temperature and moisture content

RAP	Percentage, %	Temperature, °C						
		-20	20				40	60
RAP1	0	OMC	OMC-4%	OMC-2%	OMC	OMC+2%		OMC
	20	OMC	OMC-4%	OMC-2%	OMC	OMC+2%		OMC
	40	OMC	OMC-4%	OMC-2%	OMC	OMC+2%		OMC
	60	OMC	OMC-4%	OMC-2%	OMC	OMC+2%		OMC
RAP2	0	OMC	OMC-4%	OMC-2%	OMC	OMC+2%	OMC	OMC
	20	OMC	OMC-4%	OMC-2%	OMC	OMC+2%	OMC	OMC
	40	OMC	OMC-4%	OMC-2%	OMC	OMC+2%	OMC	OMC
	60	OMC	OMC-4%	OMC-2%	OMC	OMC+2%	OMC	OMC
	80	OMC	OMC-4%	OMC-2%	OMC	OMC+2%	OMC	OMC

3.1.6.2.2 Resilient modulus test procedures

Samples were placed in a triaxial cell of the GCTS, as presented in Figure 3, for testing, following the NCHRP 1-28A protocol for base and subbase materials. Two linear variable differential transducers (LVDTs) were used to measure the axial deformation. The resilient modulus was calculated based on the average value of the two LVDTs' readings. A triaxial chamber was used to provide an air-tight environment so that the target confining pressure could be reached during the test. The water valves for drainage were kept open [Witczak 2004].

According to the NCHRP1-28A protocol, the test sequence for base and subbase material consisted of 1 pre-conditioning sequence and 30 load sequences. Confining pressure was varied from 3 to 20psi. For each confining pressure, cyclic stress increased from 0.5 to 7 times of confining pressure. For each sequence, the axial loading was applied using a haversine-shaped loading, 0.1-second load pulse followed by a 0.9-second rest period. The test sequences for base and subbase materials are listed in Table 4.



Figure 3 Resilient Modulus Sample during Testing in GCTS

Table 4 Test Sequence for Base/Subbase Materials [Witczak 2004]

Sequence	Confining pressure		Contact stress		Cyclic stress		Maximum stress		Number of load
	kPa	Psi	kPa	Psi	kPa	Psi	kPa	Psi	
0	103.5	15	20.7	3	207	30	227.7	33	1000
1	20.7	3	4.1	0.6	10.4	1.5	14.5	2.1	100
2	41.4	6	8.3	1.2	20.7	3	29	4.2	100
3	69	10	13.8	2	34.5	5	48.3	7	100
4	103.5	15	20.7	3	51.8	7.5	72.5	10.5	100
5	138	20	27.6	4	69	10	96.6	14	100
6	20.7	3	4.1	0.6	20.7	3	24.8	3.6	100
7	41.4	6	8.3	1.2	41.4	6	49.7	7.2	100
8	69	10	13.8	2	69	10	82.8	12	100
9	103.5	15	20.7	3	103.5	15	124.2	18	100
10	138	20	27.6	4	138	20	165.6	24	100
11	20.7	3	4.1	0.6	41.4	6	45.5	6.6	100
12	41.4	6	8.3	1.2	82.8	12	91.1	13.2	100
13	69	10	13.8	2	138	20	151.8	22	100
14	103.5	15	20.7	3	207	30	227.7	33	100
15	138	20	27.6	4	276	40	303.6	44	100
16	20.7	3	4.1	0.6	62.1	9	66.2	9.6	100
17	41.4	6	8.3	1.2	124.2	18	132.5	19.2	100
18	69	10	13.8	2	207	30	220.8	32	100
19	103.5	15	20.7	3	310.5	45	331.2	48	100
20	138	20	27.6	4	414	60	441.6	64	100
21	20.7	3	4.1	0.6	103.5	15	107.6	15.6	100
22	41.4	6	8.3	1.2	207	30	215.3	31.2	100
23	69	10	13.8	2	345	50	358.8	52	100
24	103.5	15	20.7	3	517.5	75	538.2	78	100
25	138	20	27.6	4	690	100	717.6	104	100
26	20.7	3	4.1	0.6	144.9	21	149	21.6	100
27	41.4	6	8.3	1.2	289.8	42	298.1	43.2	100
28	69	10	13.8	2	483	70	496.8	72	100
29	103.5	15	20.7	3	724.5	105	745.2	108	100
30	138	20	27.6	4	966	140	993.6	144	100

3.1.7 Permanent deformation

Base materials are subjected to stresses such as the weight of surface layer and repeated traffic loading. Compressive and extensional deformation of pavement layers occurs due to

repeated dynamical traffic loading. In the field, the permanent deformation of base layer contributes to the rutting of asphalt pavement. With the adding of RAP to base course material, permanent deformation should be evaluated to determine the rutting potential. In this study, permanent deformation was evaluated based on two testing methods, which were resilient modulus testing method and repeated load triaxial compression testing method.

3.1.7.1 Resilient modulus testing method

Permanent deformation was evaluated following NCHRP 1-28A protocol for base course material containing different percentage of RAP. For each test, a total of 30 sequences were conducted on each testing sample and different confining pressures as well as deviator stresses were applied for each sequence, which lasts 100 seconds. Direct on-sample measuring techniques were recognized as the most accurate method of measuring strains in a sample [Wijeratne 1987]. Two vertical LVDTs were mounted on the testing samples to measure the axial deformation. As shown in Figure 4, two clamps were used to fix the LVDTs so that the accurate deformation could be read.



Figure 4 LVDTs used for measuring the permanent deformation

3.1.7.2 Repeated load triaxial compression testing method

Since no test procedures for repeated load permanent deformation has been introduced for base course material, test procedures similar to NCHRP 1-28A protocol was followed. For each cycle, a 0.1 second haversine load pulse was followed by a 0.9-second rest period. Repeated loading was applied to samples until no obvious permanent deformation could be observed. In this study, five samples containing different percentages of RAP2 were selected for testing since RAP2 was collected from the construction site which could better simulate the field condition. Samples were compacted and prepared in accordance with the procedures introduced in NCHRP 1-28A protocol. Cylindrical samples after preparation were placed in GCTS, and vertical LVDTs were mounted on the samples to measure the permanent deformation as shown in Figure 4. The samples were conditioned before the test by applying 15psi cyclic stress combined with 15psi confining pressure for 1000 cycles. The pre-conditioning process was supposed to minimize the effect of different compaction efforts during sample preparation and stable the sample for more consistent results. For samples containing different percentages of RAP2, combinations of different cyclic stress and confining pressure were applied.

3.1.8 Permeability

Based on the typical gradations for both RAP1 and RAP2, less than 10% particles passed 75- μm sieve, constant head method was chosen for determining the permeability, in accordance with the AASHTO T-215 specification. As shown in Figure 5, a constant-head permeameter was used to conduct the hydraulic conductivity test. Only RAP2 mixtures were tested due to time limitation. Particles larger than 19mm were removed and the percentage of oversize particles was recorded. A permeameter with a diameter of 152 mm (6 inches) was selected for conducting the testing. Water was added to the dry samples containing different percentages of RAP such that

OMC could be reached. According to the specification, samples were compacted in the permeability cylinder in thin layers to a height about 2.03 cm (0.8 inch) above the upper manometer outlet. As shown in Figure 5, the distance between the bottom of permeameter and upper manometer outlet is about 20.32 cm (8 inches), thus the total sample height of 22.35 cm (8.8 inches) would make the top surface of the sample reach 2.03 cm (0.8 inch) above the upper manometer outlet. Since the compaction was conducted inside the permeameter mold which was made of acrylic to be transparent, only 90% MDUW could be achieved by using the hammer of 22.2 N (5 pounds) with standard proctor compaction efforts, which simulates the worst compaction scenario possible in the field. Samples were compacted into the permeameter for four layers with each layer of 5.5 cm (2.2 inches) to make the total height of 22.35 cm (8.8 inch). The weight of samples added to each layer was calculated on the basis of 90% MDUW. Hydraulic conductivity tests were conducted in accordance to AASHTO T125 test protocol to evaluate the permeability of base course material containing different percentages of RAP. After the sample was saturated, test runs were repeated at an increment of 0.5 cm (0.2 inch) head so that the range for laminar flow can be established. When the relationship between velocity and hydraulic gradient started to deviate from the linear relationship, it indicates the start of turbulent flow. The test was run within the range of laminar flow. Coefficient of permeability was calculated as follows:

$$K = QL/Ath \quad (10)$$

where,

K is coefficient of permeability;

Q is quantity of water discharged;

L is the distance between manometers, which is 15.24cm (6 inches) in this study;

A is the cross-sectional area of specimen, which equals 182.3cm^2 (28.26in^2) in this study;
t is total time of discharge and h is difference in head on manometers.



Figure 5 Constant-head Permeability Test Equipment

3.1.9 Moisture damage

In order to evaluate the engineering performance of RAP in terms of stiffness (modulus), rutting potential and permeability due to moisture damage, testing samples after freezing-thawing were tested for resilient modulus, rutting potential and permeability.

3.1.9.1 Freeze-thaw conditioning of Mr test samples

Samples containing different percentages of RAP1 and RAP2 were prepared based on the selected gradation and water was added to achieve OMC. Well-mixed samples were compacted into the split mold by 2 inches height per layer, totaling 304.8 mm (12 inches). The membrane used for compaction was cut off and replaced with a new membrane using a membrane stretcher so that minimum amount of moisture would be lost during conditioning and testing. Samples

with the new membrane were placed in the triaxial cell for freezing and thawing to eliminate external disturbance due to handling. The freezing-thawing consisted of the following steps:

- Freezing for 24 hours at -20 °C after sample preparation
- Thawing for 24 hours at 60 °C after freezing

Samples after the thawing were moved out of the triaxial cell and kept inside the membrane for 12 hours at room temperature. Resilient modulus tests were not conducted on the samples until the temperature of the samples decreased to room temperature.

3.1.9.2 Freeze-thaw conditioning of permeability test samples

Samples containing different percentages of RAP2 were prepared and mixed thoroughly at OMC and were kept inside of sealed plastic bags to prevent moisture from evaporation during freezing-thawing. The steps were listed as follows:

- Put the well-mixed samples containing OMC in the freezer for 24 hours at a temperature below -18 °C.
- Leave the sample in the oven for 24 hours with the temperature set as 60 °C

Samples after the thawing conditioning were moved out of the oven and kept inside the plastic bags for 12 hours at room temperature. Samples were compacted in the permeameter. Permeability tests were conducted in accordance with the AASHTO T-215 specification. Permeability tests were not conducted on the samples until the temperature of the samples decreased to room temperature.

3.2 X-RAY COMPUTED TOMOGRAPHY SCANNING FOR SPECIMENS CONTAINING RAP

3.2.1 Introduction

Tomographic techniques combine information from radiographic projections taken at different angles to produce a detailed map of internal properties of the object. In recent years, systems for acquiring and processing this data have been developed and are in regular use in medical and industrial applications. The term "computed tomography," or CT, refers to the use of a computer to combine the projection data into a complete map.

High resolution X-Ray Computed Tomography (X-ray CT) is becoming a widely used technique to study solids including geological materials in 3D at a pore-scale level [Cnudde et al. 2009]. Defects such as voids in geological materials can be constructed via computed tomography based on the three dimensional topology. The internal structure of specimens can be studied without disturbing the samples and their macroscopic behavior can be estimated by the advanced characterization simulation.

Based on the literature review, higher resilient modulus and higher permanent deformation were reported by researchers for base course materials containing RAP. X-Ray CT scanning was conducted to investigate the microstructure of specimens containing RAP.

3.2.2 X-Ray CT scanning methods for specimens containing RAP

The X-ray CT scanning set up at Washington State University involves two X-ray sources that are capable of generating 420 keV and 225 keV voltages. The 420 keV source was used for scanning RAP mixtures since it is preferably used for relatively bigger samples where sufficient detail of sample constituent structures can be visualized with a relatively lower resolution. The X-ray sources are networked to a central work station, a processing platform that consists of four parallel computing processors with each consisting of a double core Central Processing Units (CPUs) and a set of software that control the scanning process and subsequent image analyses.

Scanning of the samples was initiated with FlashCT Data-Acquisition (DAQ), which is a specifically devised acquisition that controls hardware operation, calibration and scanning. After the scan parameters are entered, the object would be rotated such that radiographic images at the desired angles can be collected. The datasets are saved as Unified Directory Structure file (UDS) for later processing and reconstruction by Data Processing System software (DPS). The UDS header files, which are text files containing data fields separated by linefeeds, are processed with FlashCT DPS, which is a program providing reconstructed images of the scanned slices. In addition, calibration files are used to correct pixel to pixel differences in the detector such as bad pixel correction since radiographs taken for the object range from completely dark where an image was taken with no exposing radiation, to light where an image was taken with full exposure.

In this study, 0% RAP and 80% RAP samples after resilient modulus testing were applied with X-ray CT scanning. For each sample, over 700 slices of transversal surfaces were scanned, which could finally form the image of the cylinder with the total height of 304.8-mm.

Chapter 4: ANALYSIS AND RESULTS

After the completion of laboratory tests, the test results were analyzed to determine resilient modulus, rutting potential and hydraulic conductivity. The effects of temperature and moisture on resilient modulus and rutting were also evaluated.

4.1 ASPHALT CONTENT DETERMINATION

Asphalt contents in RAP1 and RAP2 were 4.86% and 6.11%, respectively. The asphalt contents for samples containing different percentages of RAP are listed in Table 5.

Table 5 Asphalt content corresponding to RAP percentage

	RAP1 percentage, %			
	20	40	60	
Asphalt Content, %	0.97	1.94	2.92	
	RAP2 percentage, %			
	20	40	60	80
Asphalt Content, %	1.22	2.44	3.67	4.89

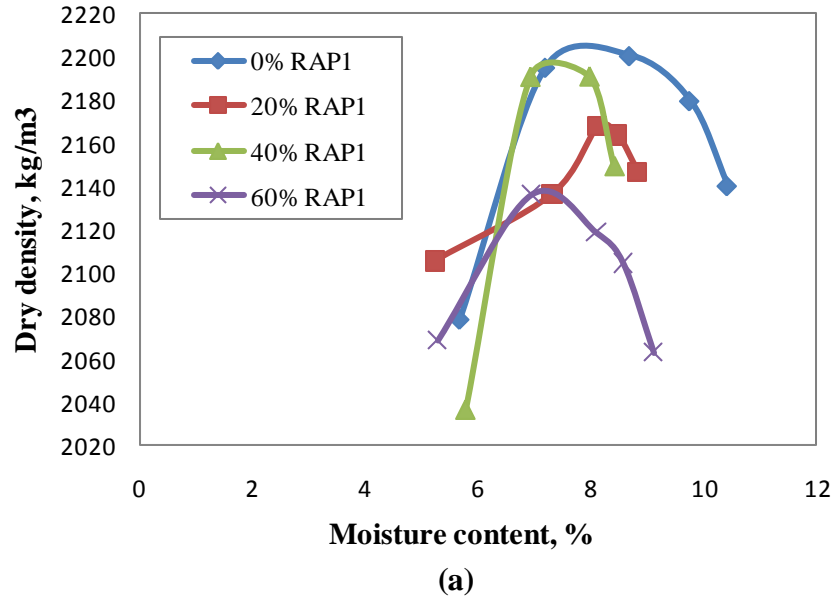
4.2 BULK SPECIFIC GRAVITY AND MOISTURE-DENSITY RELATIONSHIP

The relationships between moisture content and dry density for samples containing different percentages of RAP1 and RAP2 were established based on the modified proctor tests. As recommended by the AASHTO T-224, corrections to OMC and MDUW were made since more than 5% oversize particles were retained on 19.00 mm (3/4 inch) sieve for both RAP1 and RAP2 mixtures. Bulk specific gravity tests were conducted because bulk specific gravity is needed for corrections to OMC and MDUW. Table 6 shows the OMC and MDUW values from modified proctor tests. The corrected values (See Section 3.1.5.1) of OMC and MDUW for samples containing different percentages of RAP were calculated based on bulk specific gravity values as listed in Table 6. The moisture-density relationship curves are shown in Figure 6. As

shown in Figure 7, OMC value and bulk specific gravities of mixtures, decreased with the increase of RAP percentage.

Table 6 Compaction Characteristics before and after Correction

Material	Proctor compaction result		Bulk specific gravity	After correction	
	Optimum moisture content, %	Maximum dry density, kg/m ³		OMC, %	MDUW, kg/m ³
0% RAP1	8.9	2199	2.603	7.9	2247
20% RAP1	8.2	2169	2.581	7.3	2218
40% RAP1	7.5	2207	2.559	6.7	2250
60% RAP1	7.2	2138	2.537	6.5	2186
0% RAP2	9.0	2200	2.590	7.9	2254
20% RAP2	8.8	2142	2.510	7.7	2193
40% RAP2	7.9	2113	2.510	7.0	2167
60% RAP2	7.5	2143	2.460	6.6	2189
80% RAP2	7.1	2127	2.440	6.3	2172



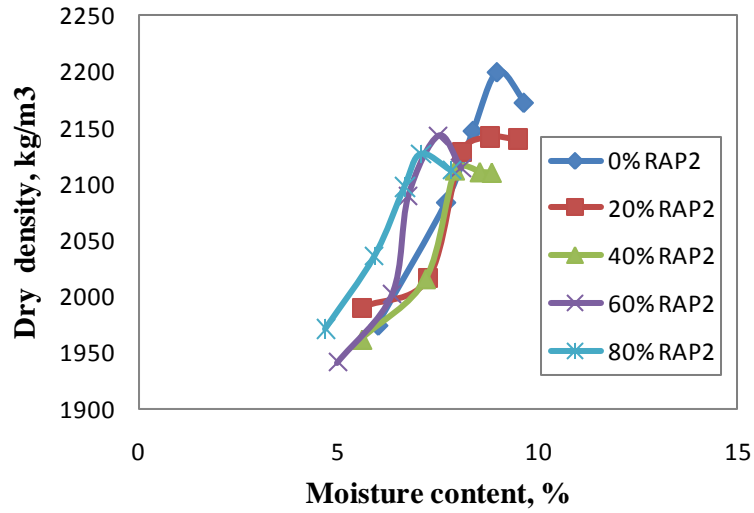
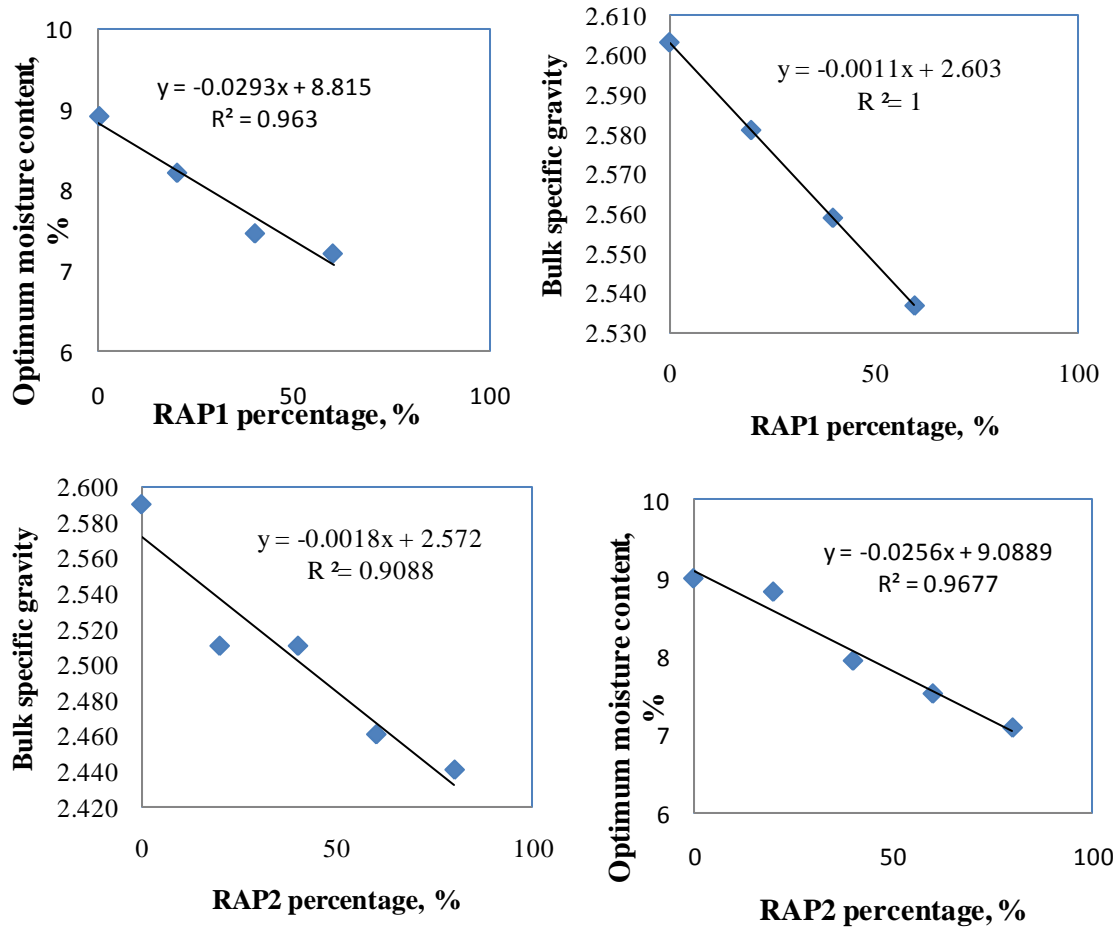


Figure 6 Moisture-density relationship for (a) RAP1 mixtures (b) RAP2 mixtures



4.3 STIFFNESS

4.3.1 Modeling of resilient modulus

Resilient modulus is dependent on the stress states, such as deviator and confining stresses. Similar to the MEPDG, the resilient modulus can be modeled as shown in Equation 11 [Witczak 2004].

$$M_r = k_1 p_a \left(\frac{\sigma_b - 3k_6}{p_a} \right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + k_7 \right)^{k_3} \quad (11)$$

where, M_r is resilient modulus, k_1, k_2, k_3, k_6, k_7 are empirical constants, P_a is the atmospheric pressure, τ_{oct} is the octahedral shear stress, and σ_b is the bulk stress. Bulk stress is calculated by

$$\sigma_b = \sigma_1 + \sigma_2 + \sigma_3 \quad (12)$$

where σ_b is the bulk stress and $\sigma_1, \sigma_2, \sigma_3$ are the principal stresses acting on the specimen.

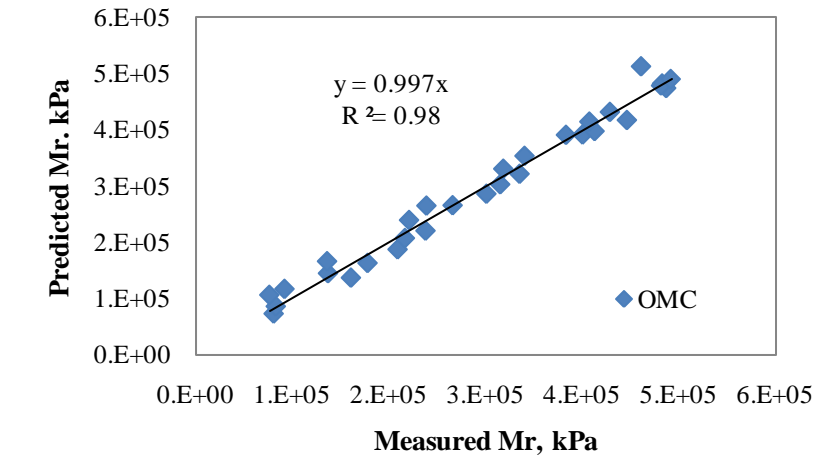
Octahedral shear stress is calculated as:

$$\tau_{oct} = \frac{1}{3} \cdot \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2} \quad (13)$$

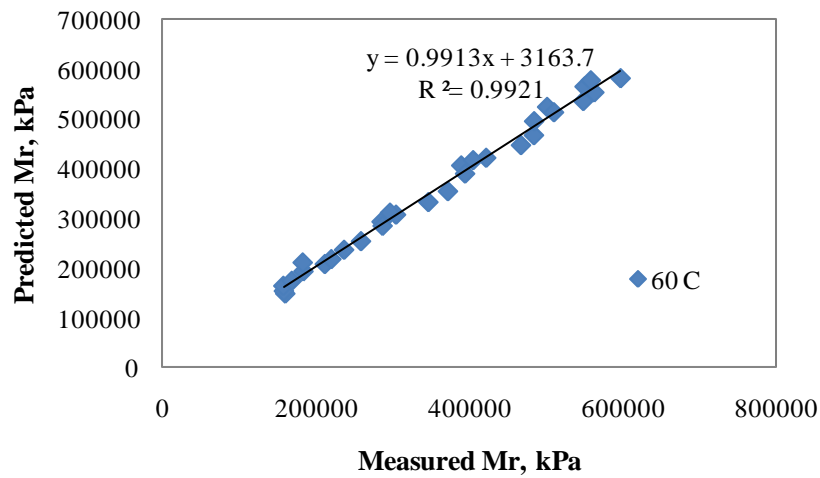
Based on M_r test data, model coefficients were determined using the Excel Solver (Table 7). As an illustration, Figure 8 shows the relationship between measured and predicted M_r for 0% RAP1 sample based on the NCHRP 1-28A model. It can be seen the model is effective in characterizing the resilient modulus.

Table 7 Coefficients and R2 for Different Samples Based on NCHRP 1-28A Model

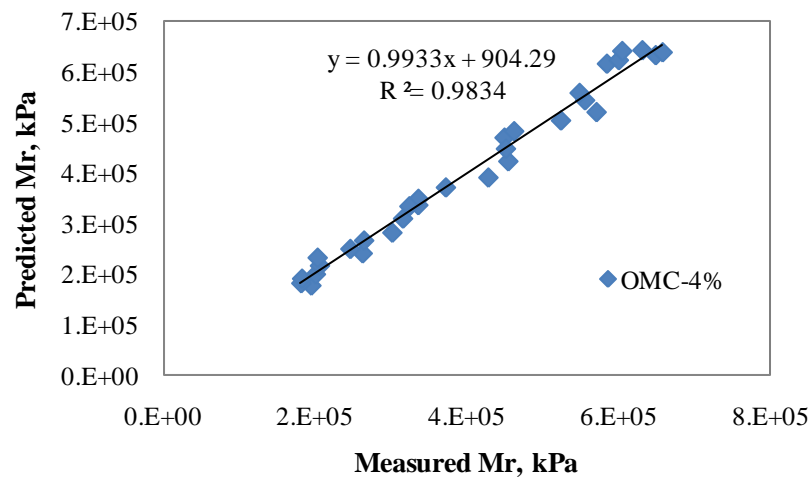
RAP1 percentage	Condition	Model coefficients					Coefficient of determination
		k1	k2	k3	k6	k7	R ²
0	OMC-4%	3045.17	1.95	-2.19	-107.40	4.29	0.98
	OMC-2%	4878.25	2.12	-2.66	-107.29	4.57	0.99
	OMC	1913.71	1.19	-1.17	-8.01	2.10	0.99
	OMC+2%	315556.61	1.49	-3.23	-46.24	7.91	0.99
	20C	1913.71	1.19	-1.17	-8.01	2.10	0.99
	60C	4136.65	1.51	-1.77	-67.82	4.23	0.99
20	OMC-4%	8.64E+09	1.20	-5.77	-40.86	17.08	0.95
	OMC-2%	2013.37	1.40	-1.41	-38.77	2.72	0.98
	OMC	614.02	1.49	-1.05	-35.75	1.29	0.99
	OMC+2%	765.04	1.27	-0.80	-25.13	1.20	0.99
	20C	614.02	1.49	-1.05	-35.75	1.29	0.99
	60C	332.97	1.38	-0.58	-52.25	1.00	0.91
40	OMC-4%	1348.81	1.25	-0.83	-44.01	1.00	0.97
	OMC-2%	1274.34	1.35	-1.14	-35.24	1.80	0.99
	OMC	74.96	2.40	-1.43	-114.53	1.00	0.94
	OMC+2%	1306.94	1.27	-1.08	-22.86	1.66	0.99
	20C	74.96	2.40	-1.43	-114.53	1.00	0.94
	60C	733.63	1.25	-0.70	-44.00	1.00	0.91
60	OMC-4%	28.60	3.02	-1.90	-168.03	1.00	0.77
	OMC-2%	1080.94	1.32	-1.02	-30.32	1.34	0.99
	OMC	2006.57	1.02	-0.82	-13.56	1.00	0.98
	OMC+2%	1083.87	1.26	-0.86	-42.14	1.40	0.99
	20C	218.77	1.82	-0.90	-84.85	1.00	0.97
	60C	1310.75	1.33	-1.24	-43.66	2.15	0.99



(a)



(b)

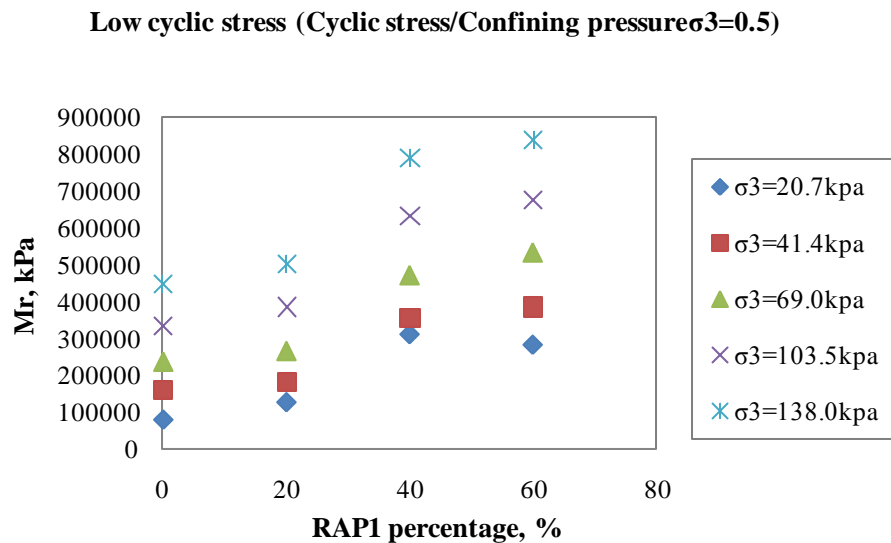


(c)

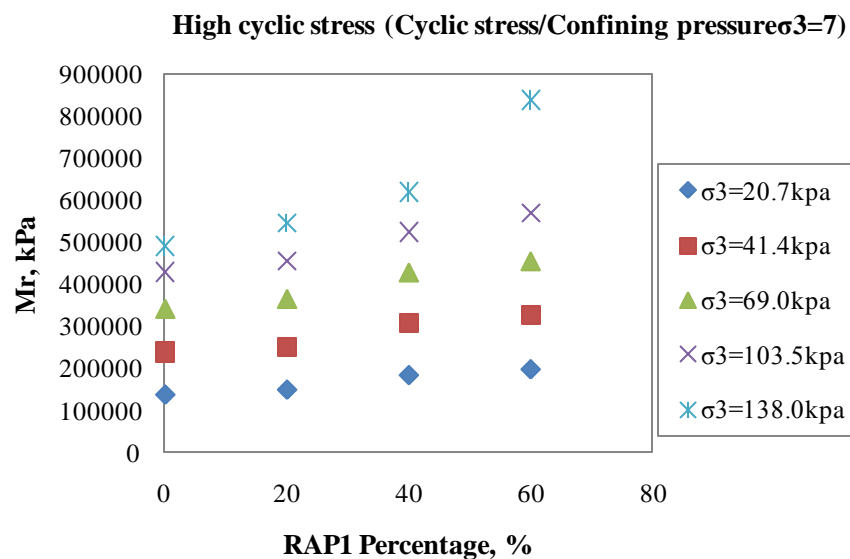
Figure 8 Relation between Predicted Mr and Measured Mr for (a) 0% RAP1 with OMC tested at 20 °C (b) 0% RAP1 with OMC tested at 60 °C (c) 0% RAP1 with OMC-4% tested at 20 °C

4.3.2 Effect of RAP percentage on resilient modulus

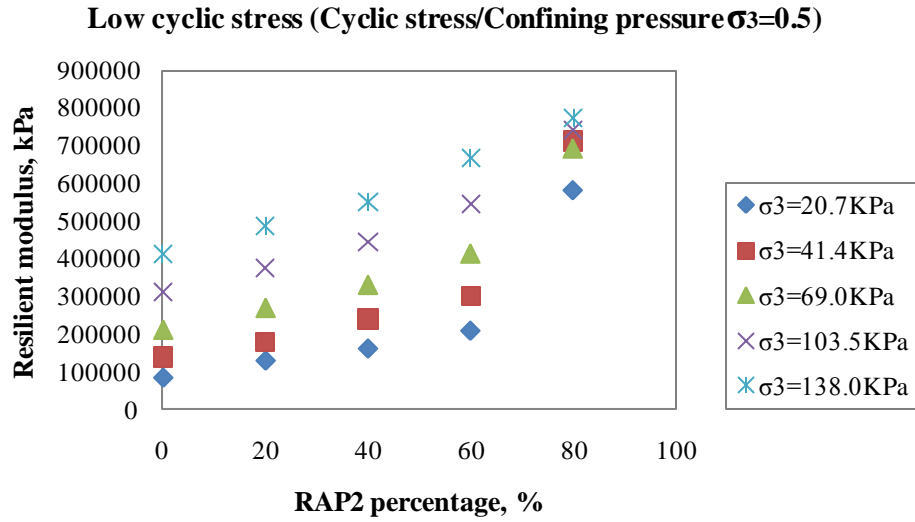
Figure 9 shows the relationship between M_r and RAP percentage at OMC and room temperature. The results indicated that increasing RAP percentage increased M_r for both RAP1 and RAP2 at low cyclic stress and high cyclic stress. Confining pressure (σ_3) was found to be a significant parameter that affects M_r of RAP [Richter 2006]. Detailed resilient modulus testing results for all samples are presented in the Appendix.



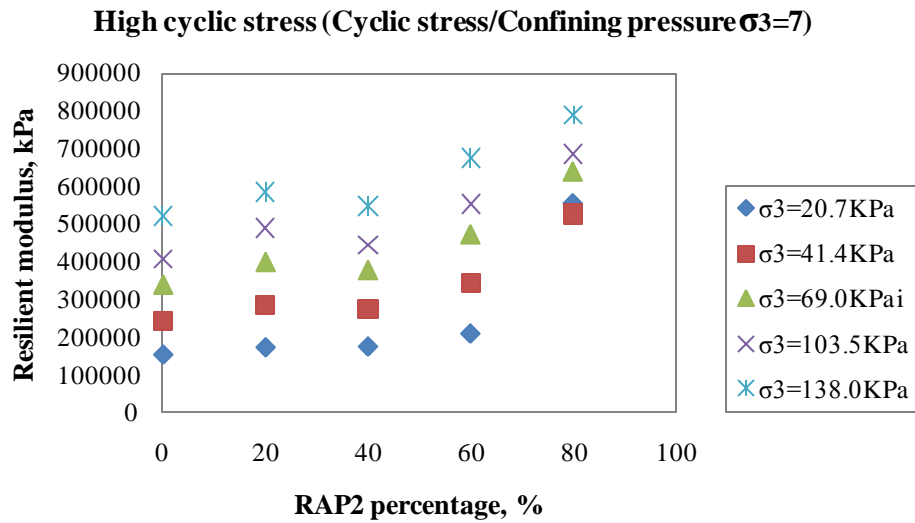
(a)



(b)



(c)



(d)

Figure 9 Effect of RAP1 Percentage on Mr at (a) Low Cyclic Stress Figure (b) High Cyclic Stress Figure; Effect of RAP2 Percentage on Mr at (c) Low Cyclic Stress (d) High Cyclic Stress

4.3.3 Modeling the effect of moisture content on M_r

In the pavement structure, the moisture content in the unbound base layers may change with time due to environmental conditions, which would affect the resilient modulus [ARA 2004]. In MEPDG, for the purpose of designing a new pavement or evaluation of an existing one, it is necessary to estimate the change of modulus in response to the change of moisture content.

Both the dry density and moisture content affect the resilient modulus. In this study, modulus was determined at different moisture contents while keeping the density constant which simulates the field condition.

For the models used in this study, dry density was assumed to be constant, which was 95% of the maximum dry density. The moisture contents in this study were varied from OMC-4% to OMC+2%. In the MEPDG, models are proposed to account for the effects of moisture content on resilient modulus of unbound materials [ARA 2004], as shown in Equation 14. The model is referred to as K_w model for the rest of the paper.

$$\text{Log} \frac{M_r}{M_{r_{\text{opt}}}} = K_w (W - W_{\text{opt}}) \quad (14)$$

where,

M_r = resilient modulus at moisture content w (%);

$M_{r_{\text{opt}}}$ = resilient modulus at optimum moisture content W_{opt} (%) and maximum dry density;

K_w = gradient of log resilient modulus ratio ($\log (M_r/M_{r_{\text{opt}}})$) with respect to variation in percent moisture content ($W - W_{\text{opt}}$); K_w is material constant.

Witczak et al. developed a sigmoid model predicting the changes of resilient modulus due to changes of degree of saturation for MEPDG [Witczak et al. 2000]. The model was developed based on test results with the degree of saturation ranging from 30% to -30% of S_{opt} – the

degree of saturation at maximum dry density and optimum moisture content. The same model was introduced on the basis of the moisture content, presented in Equation 15. This model is referred to as sigmoid model for the rest of the thesis.

$$\text{Log} \frac{M_r}{M_{r_{\text{opt}}}} = a + \frac{b-a}{1+\text{Exp}[\beta+K_s*(W-W_{\text{opt}})]} \quad (15)$$

where, a = minimum of $\log(M_r/M_{r_{\text{opt}}})$

b = maximum of $\log(M_r/M_{r_{\text{opt}}})$; For coarse grained soil, b is assumed to be 0.30

β = location parameter – obtained as a function of a and b by imposing the condition of a zero intercept: $\beta = \text{Ln}(-b/a)$

K_s = regression parameter

M_r = resilient modulus at moisture content W

$M_{r_{\text{opt}}}$ = resilient modulus at OMC and maximum dry density.

Both the K_w model and the Sigmoid model were selected to evaluate the effect of moisture content on M_r of RAP. Table 8 shows the model parameters and R^2 for all the testing samples. The relationship between measured and predicted M_r is shown in Figure 10 for the sample containing 20% RAP1, as an illustration. The main factor to determine the reliability of a model is the goodness of fit statistics and the mathematical stability [Attia et al. 2010]. Models are considered to have good fit with $R^2 > 0.7$. Based on the same set of testing data, random numbers were selected as original value for each parameter. Five trial tests were conducted for each model, and regression results showed that the two models under evaluation were stable as the coefficients kept constant. In addition, statistic analysis for comparing the means of measured data and predicted data was done using the t-method. Measured data and predicted data were assumed as two groups, and the 30 loading sequences were subjects randomly assigned to each group. The hypotheses for the comparison of means for the two groups were:

Ho: measured data = predicted data (means of the two groups are equal)

Ha: measured data \neq predicted data (means are not equal)

By using the data analysis function in Excel, F-test was firstly conducted to determine whether the variances were equal in both groups. Based on the result from F-test, T-test was conducted for either equal or unequal variances case and probability p-value could be obtained. Generally, the null hypotheses Ho of equal means is rejected if p value is less than 0.05, which indicates that significant difference exists between the two groups under comparison. The results for F-test and T-test were included in Table 8. Based on available testing data in this study, both of the two models are effective constitutive models to determine the effects of moisture content on M_r .

Table 8 Model coefficients P-value and R^2 for determining the effect of moisture content on M_r

Material	Model											
	Kw model			Sigmoid model($b=\log(2)$)				Sigmoid model				
	Kw	R^2	P	a	Ks	R^2	P	a	b	Ks	R^2	P
0% RAP1	-0.028	0.929	0.074	-0.001	57.770	0.748	0.0003	-1E-08	0.130	57.770	0.923	0.862
20%RAP1	-0.014	0.937	0.749	-0.010	0.590	0.935	0.968	-5E-05	0.070	3.480	0.941	0.833
40%RAP1	-0.04	0.78	0.698	-1E-05	2.450	0.745	0.409	-1E-06	0.260	3.500	0.884	0.286
60%RAP1	-0.024	0.806	0.204	-0.006	2.000	0.765	0.060	-1E-05	0.500	3.000	0.763	0.060
0% RAP2	-0.045	0.932	0.569	-0.003	1.362	0.978	0.854	-2E-04	0.229	3.104	0.972	0.149
20%RAP2	-0.009	0.975	0.926	-8E-07	2.453	0.957	0.875	-0.046	0.027	11.593	0.987	0.764
40%RAP2	-0.034	0.939	0.34	-2E-05	2.453	0.971	0.494	-1E-05	0.500	2.453	0.970	0.536
60%RAP2	-0.07	0.852	0.494	-0.1526	60.000	0.713	0.688	-3E-05	0.300	2.453	0.851	0.504
80%RAP2	0.0147	0.537	0.347	-0.0001	2.658	0.702	0.433	-1E-04	0.309	2.658	0.56	0.347

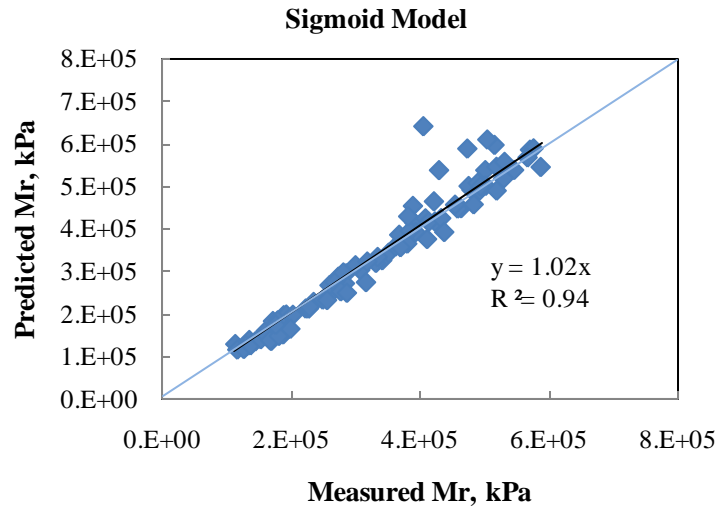
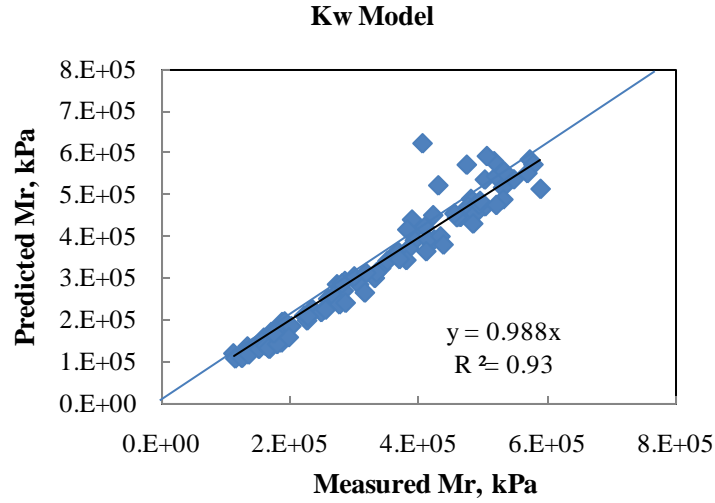
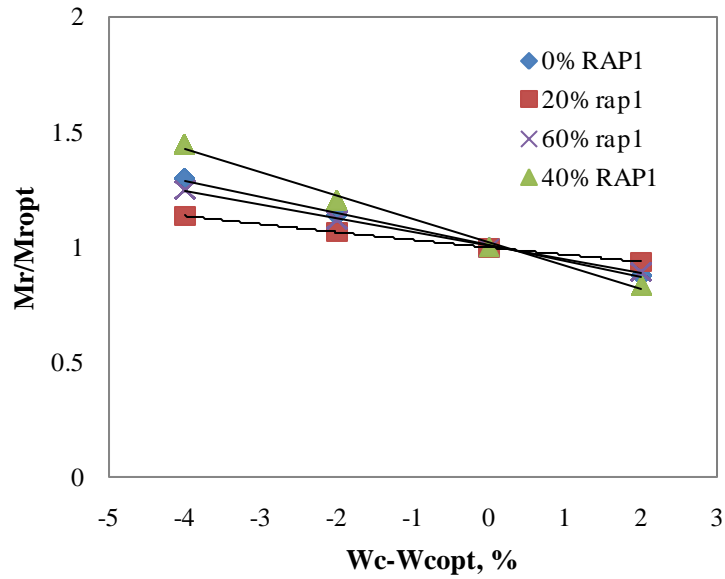
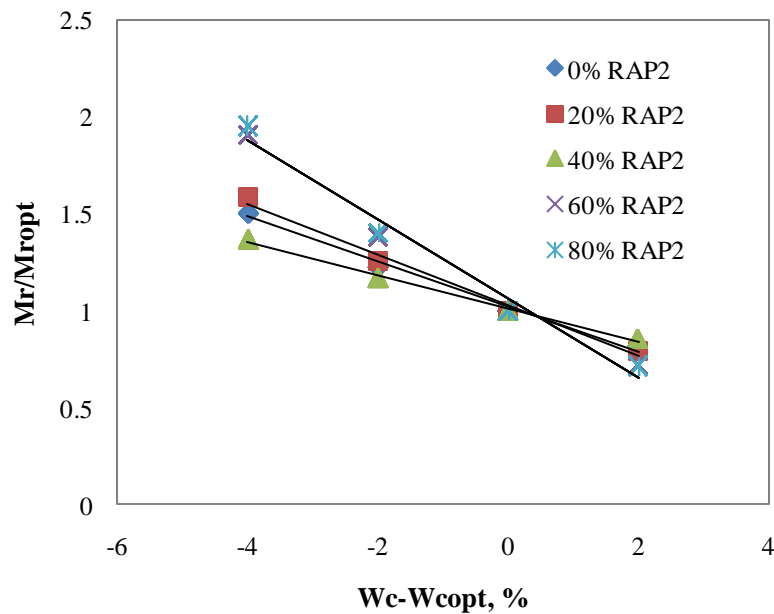


Figure 10 Relationship between predicted and Measured M_r for 20% RAP1 based on (a) Kw Model (b) Sigmoid Model

Based on K_w model, the relationship between M_r and the moisture content of samples was plotted in Figure 11. For all the samples, M_r values decreased with the increase of moisture content from OMC-4% to OMC+2%. However, the effect of RAP percentage on the sensitivity of resilient modulus to moisture content is not pronounced.



(a)



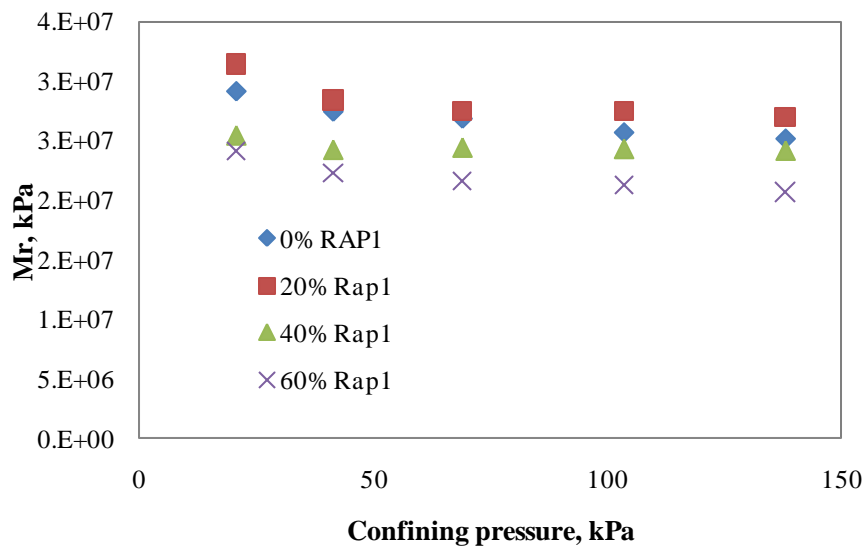
(b)

Figure 11 Effect of Moisture Content on Resilient Modulus of (a) RAP1 mixtures (b) RAP2 mixtures

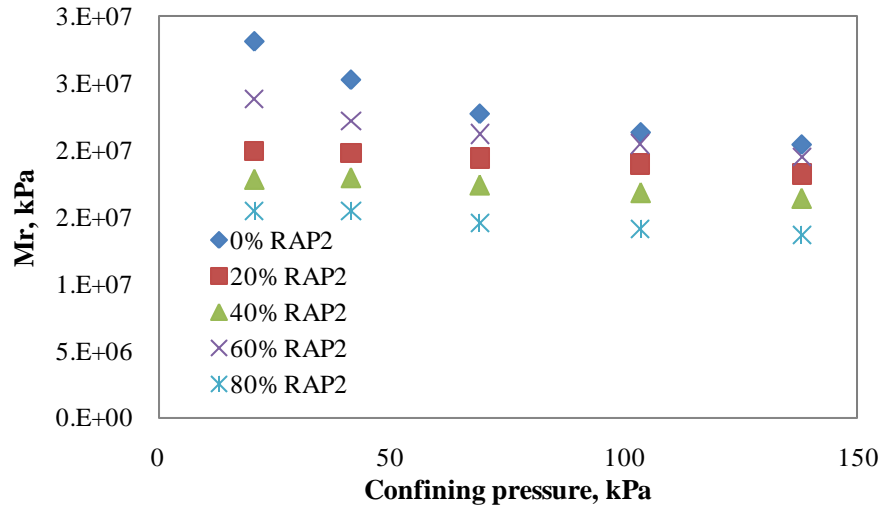
4.3.4 Effect of temperature on resilient modulus

The temperature was varied from -20 °C (-4 °F) to 60 °C (140 °F) to evaluate the effects of temperature on M_r . The M_r value for frozen coarse-grained material recommended by the

MEPDG varies from 10,342 MPa (1500 ksi) to 34,473 MPa (5000 ksi) [ARA 2004]. Figure 12 shows the relationship between M_r at high cyclic stresses (Cyclic stress/Confining pressure=7) and confining pressure for different samples tested at -20 °C. The M_r values range from 12,800 MPa (1856 ksi) to 33,607 MPa (4874 ksi), which is consistent with values recommended by the MEPDG for granular materials. When the RAP1 percentage increased from 0% to 20%, no significant change of M_r was observed and the values remained about 27,000 MPa (3916 ksi). However, M_r of the 60% RAP1 sample decreased by up to 30%. The M_r values of samples decreased with the increase of RAP1 percentage at -20 °C (-4 °F). For the tests at 60 °C (140 °F), Figure 13 shows the effect of high temperature on resilient modulus. Except for the 0% RAP sample, the resilient modulus at 60 °C (140 °F) were lower than those at 20 °C (-4 °F), as expected. This is due to the fact that the asphalt's stiffness reduces as temperature increases.

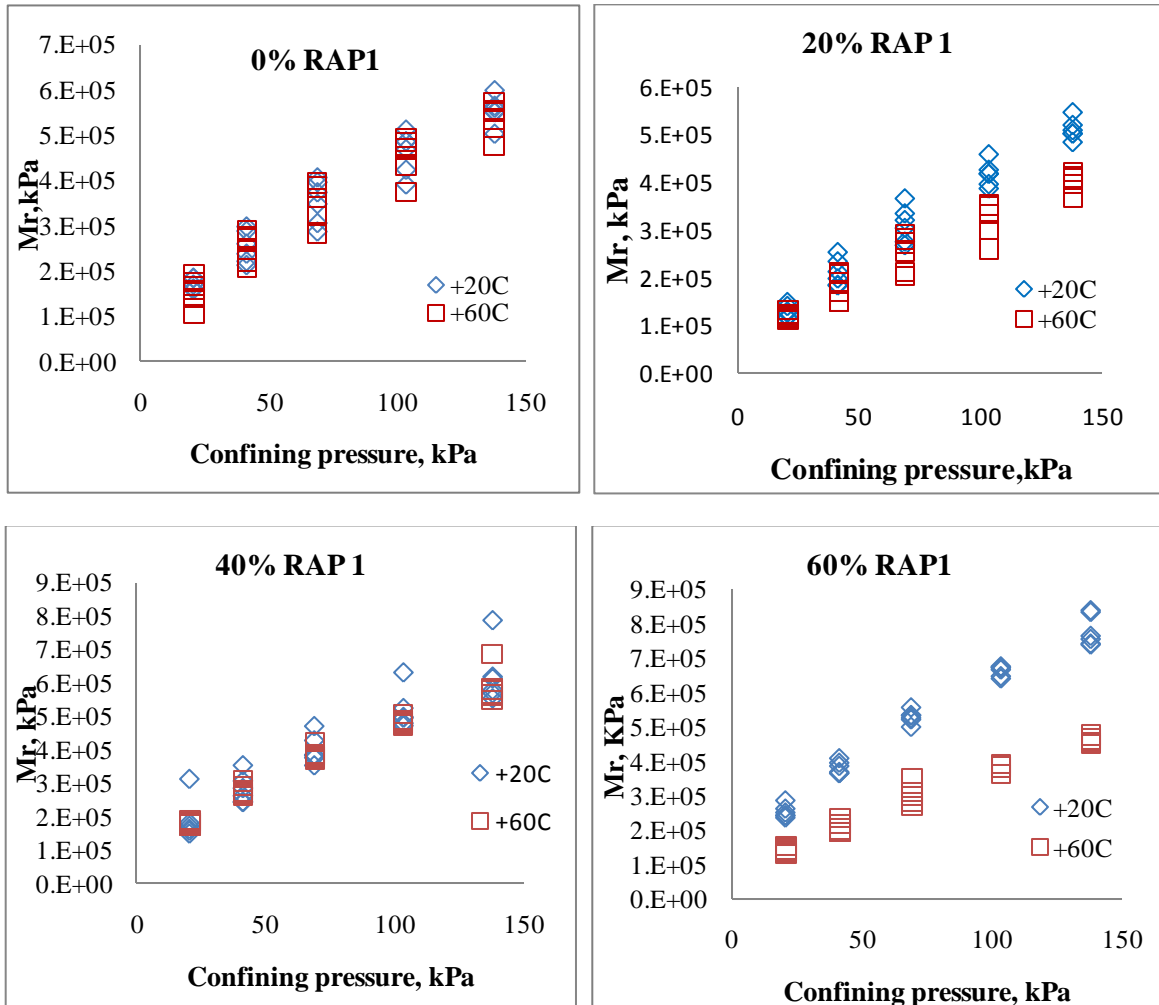


(a)



(b)

Figure 12 (a) Effect of RAP1 percentages on Mr at -20 °C (b) Effect of RAP2 percentages on Mr at -20 °C



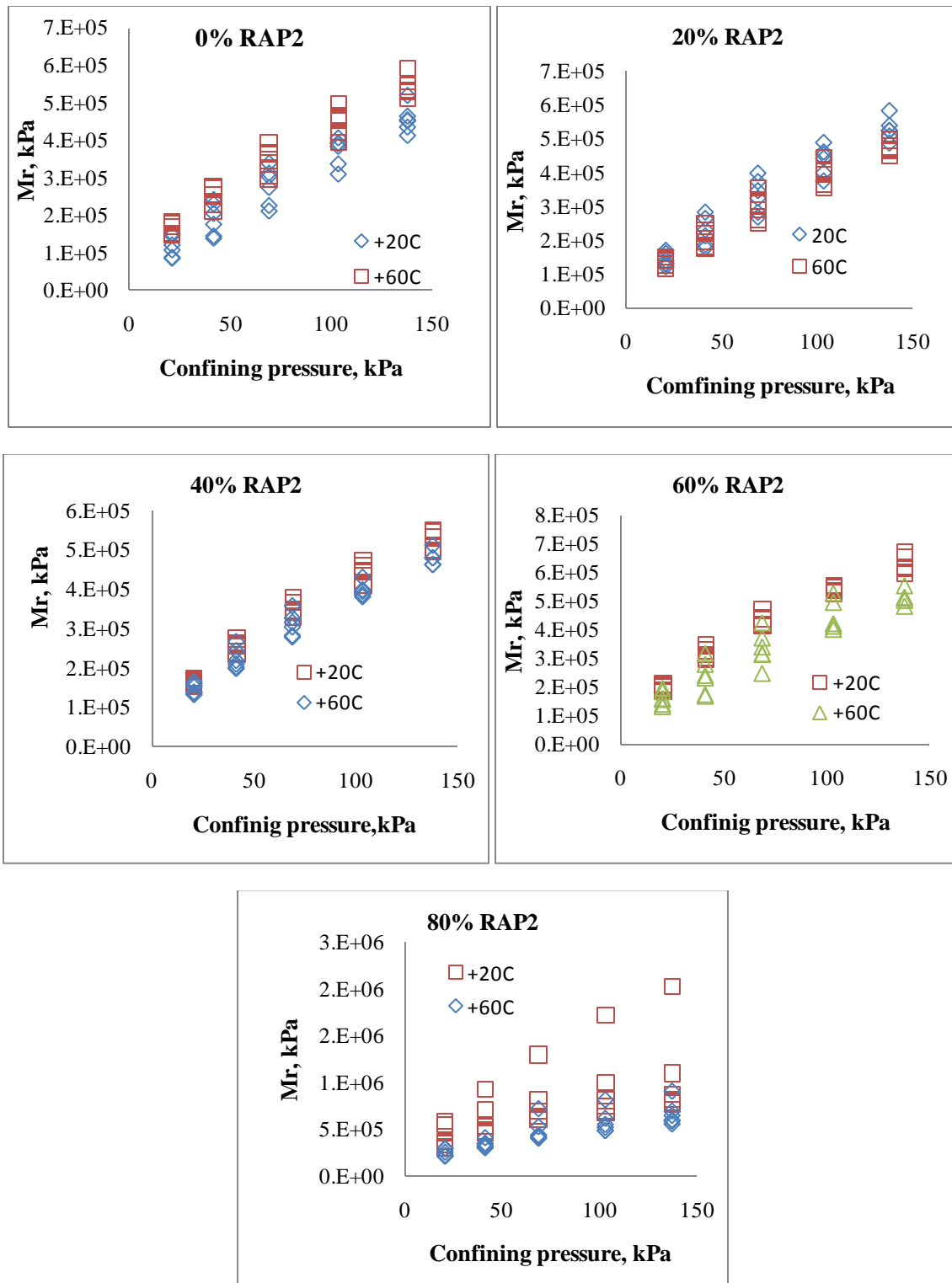


Figure 13 Effect of temperature on Mr for different samples

Models are needed to account for the effects of temperature on resilient modulus. Based on the observation of the test data, similar to the models for evaluating the effects of moisture content, K_T model and Sigmoidal model were proposed. K_T model is expressed as Equation 16.

$$\text{Log} \frac{M_r}{M_{r_{\text{opt}}}} = K_T(T - T_{\text{opt}}) \quad (16)$$

where,

M_r = resilient modulus at temperature $T(^{\circ}\text{C})$;

$M_{r_{\text{opt}}}$ = resilient modulus at 20°C ;

K_T = gradient of log resilient modulus ratio ($\log (M_r/M_{r_{\text{opt}}})$) with respect to variation in temperature; K_T is material constant.

Sigmoid model proposed in Equation 17.

$$\text{Log} \frac{M_r}{M_{r_{\text{opt}}}} = a + \frac{b-a}{1+\text{Exp}[\beta+K_s*(T-T_{\text{opt}})]} \quad (17)$$

where

a = minimum of $\log(M_r/M_{r_{\text{opt}}})$;

b = maximum of $\log(M_r/M_{r_{\text{opt}}})$; Both a and b are obtained by regression.

β = location parameter – obtained as a function of a and b by imposing the condition of a zero intercept: $\beta = \text{Ln}(-b/a)$

K_s = regression parameter;

M_r = resilient modulus at temperature $T(^{\circ}\text{C})$;

$M_{r_{\text{opt}}}$ = resilient modulus at 20°C .

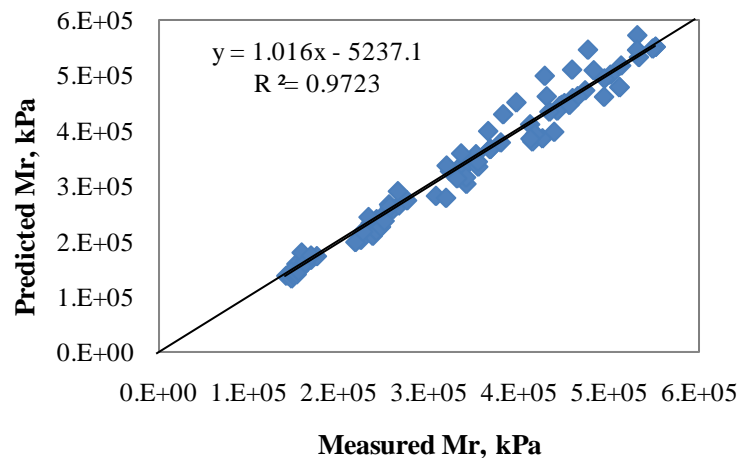
Based on the M_r testing data for RAP1 samples tested at 20°C (68°F) and 60°C (140°F) as well as that for RAP2 samples tested at 20°C (68°F), 40°C (104°F) and 60°C (140°F), models in Equations 16 and 17 were evaluated for the fitness and reliability. Model coefficients were

obtained using the Excel Solver. The same statistic methods as used for models evaluating the effect of moisture content on M_r , including F-test and T-test, were conducted for comparing the measured data and the predicted data. Table 9 lists model coefficients, coefficients of determination. The relationship between tested and predicted M_r was plotted in Figure 14 for 40% RAP2, as an example, based on the two models. For test samples containing different percentages of RAP, M_r decreased with the increase of temperature, as shown in Figure 15.

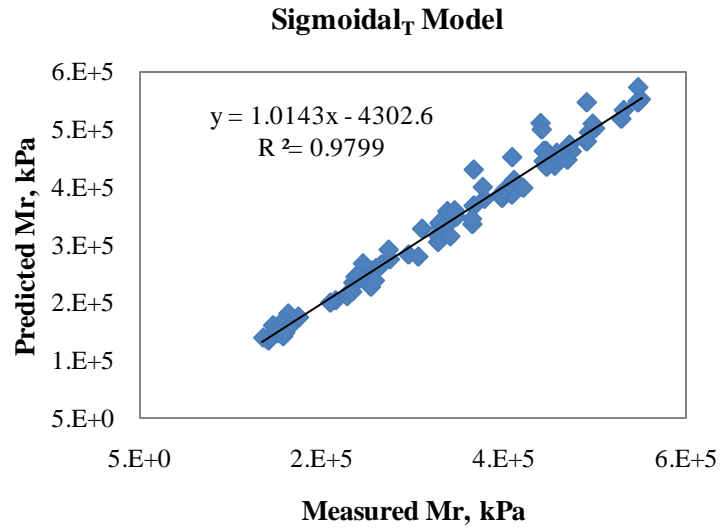
Table 9 Model efficient, R^2 and P-value for evaluating the effects of temperature on M_r

Material	Model							
	Equation (16)			Equation (17)				
	KT	R^2	P	a	b	Ks	R^2	P
0% RAP1	0.00266	0.982	0.733	-5.3E-07	2.006	1.00	0.912	0.224
20%RAP1	-0.00190	0.952	0.972	-0.07585	2.014	1.00	0.952	0.972
40%RAP1	-0.00036	0.943	0.922	-0.01444	3.000	1.00	0.943	0.922
60%RAP1	-0.00609	0.997	0.985	-0.24353	1.793	1.00	0.997	0.985
0% RAP2	0.00305	0.980	0.342	-0.00001	2.006	1.00	0.920	0.002
20%RAP2	-0.00054	0.975	0.882	-1.36330	1.0E-05	0.20	0.980	0.877
40%RAP2	-0.00082	0.972	0.907	-1.12997	1.0E-04	0.16	0.980	0.901
60%RAP2	-0.00166	0.906	0.541	-0.16598	0.175	0.06	0.902	0.140
80%RAP2	-0.00674	0.932	0.996	-0.17388	0.301	1.00	0.854	0.672

K_T Model

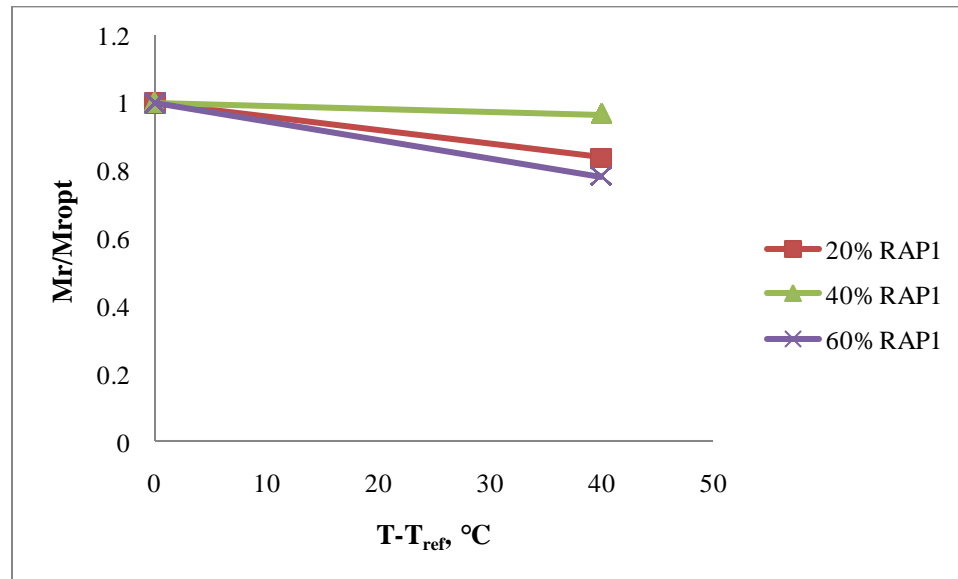


(a)

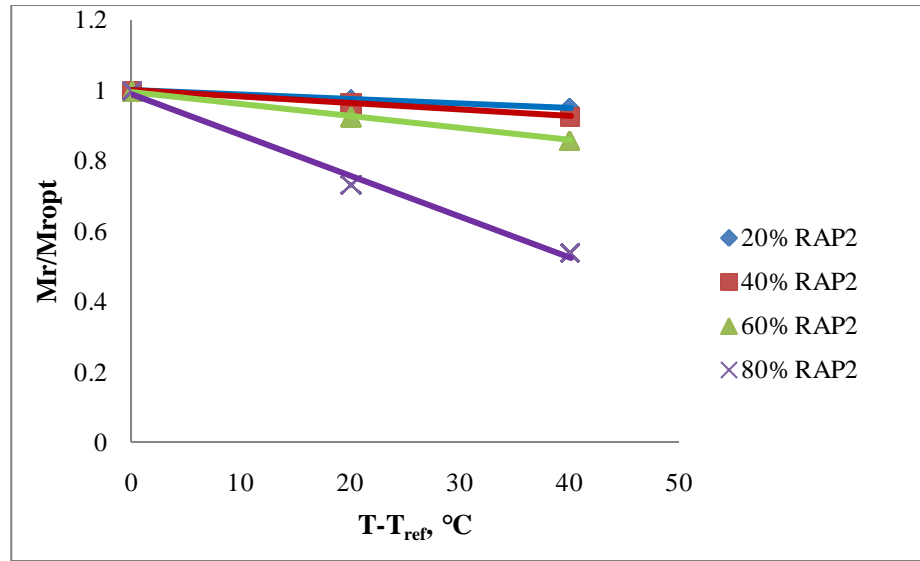


(b)

Figure 14 Relation between predicted and measured Mr for 40% RAP2 based on (a) K_T Model (b) Sigmoidal Model



(a)



(b)

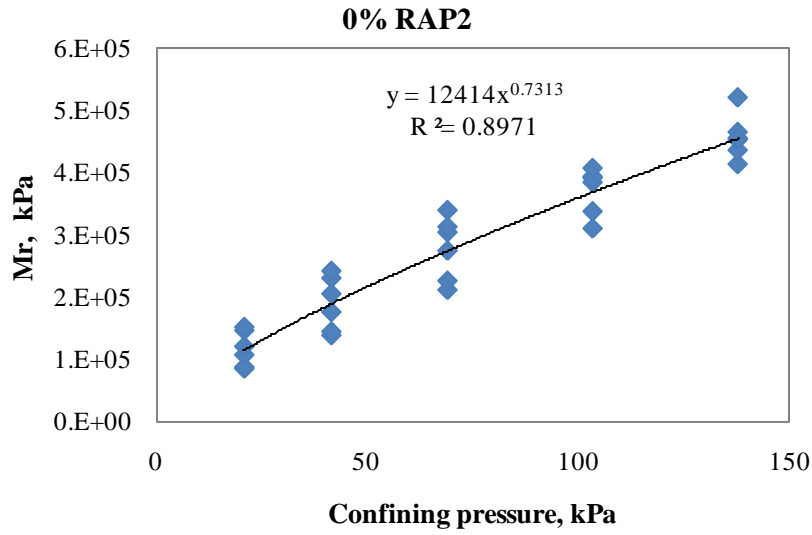
Figure 15 (a) Effect of Temperature on Mr for RAP1 mixtures based on K_T Model (b) Effect of Temperature on Mr for RAP2 mixtures based on K_T Model

Based on K_T model, M_r decreased with the increase of temperature from 20 °C (68 °F) to 60 °C (140 °F) for samples containing different percentages of RAP2 varying from 20% to 80%. The samples with higher RAP percentage were more sensitive to the temperature. As shown in Figure 15, M_r value of samples containing higher RAP percentages decreased more rapidly with the increasing temperature when compared to samples with lower RAP percentages, which indicated that the asphalt in RAP was more sensitive to temperature compared to virgin aggregate.

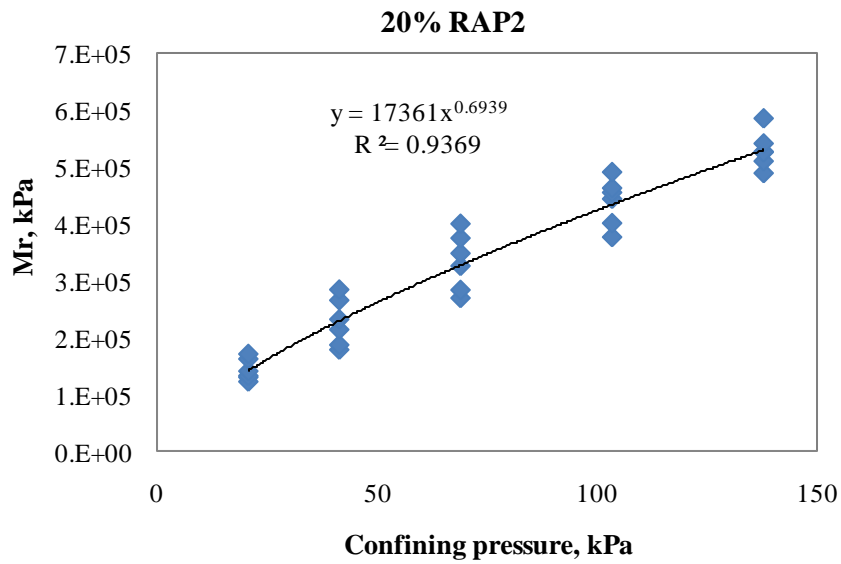
4.3.5 Effect of state of stress on resilient modulus

4.3.5.1 Effect of Confining Pressure on Resilient Modulus

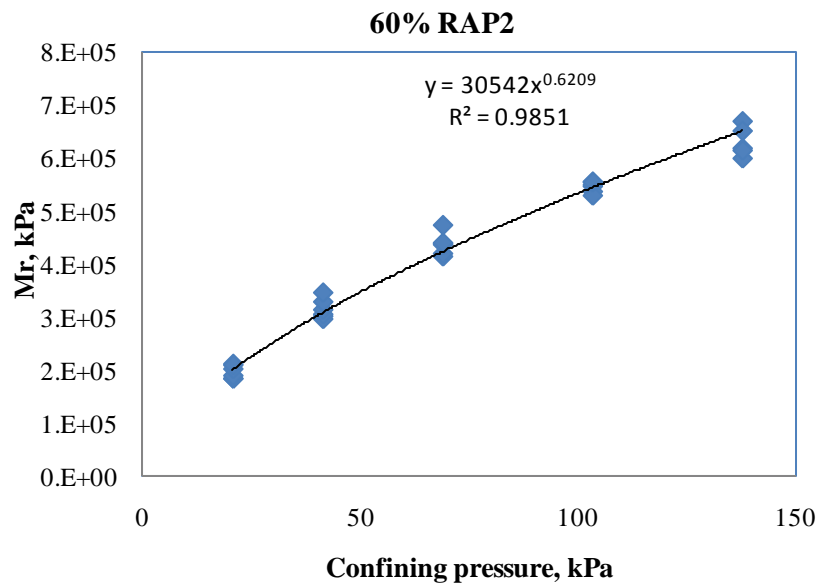
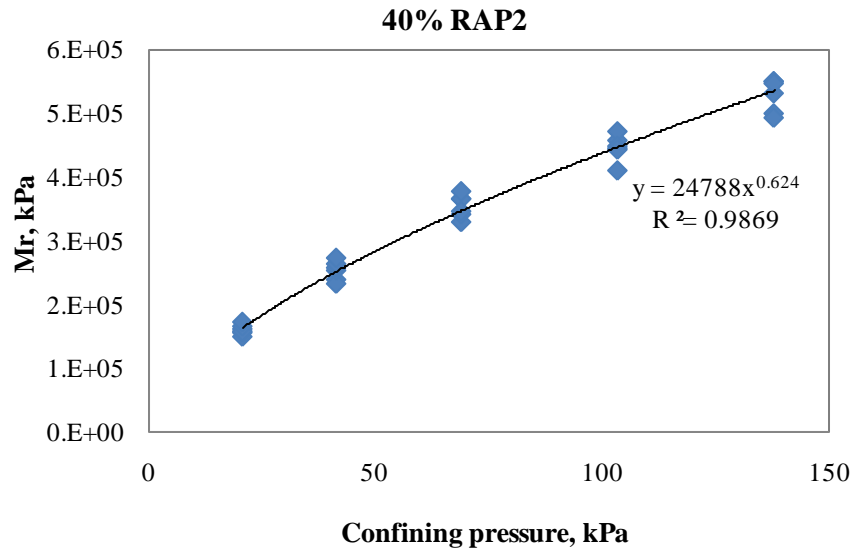
The test results indicated M_r increased with the increase of confining pressure. Figure 16 presents the effects of confining pressure on M_r measured at OMC and room temperature.

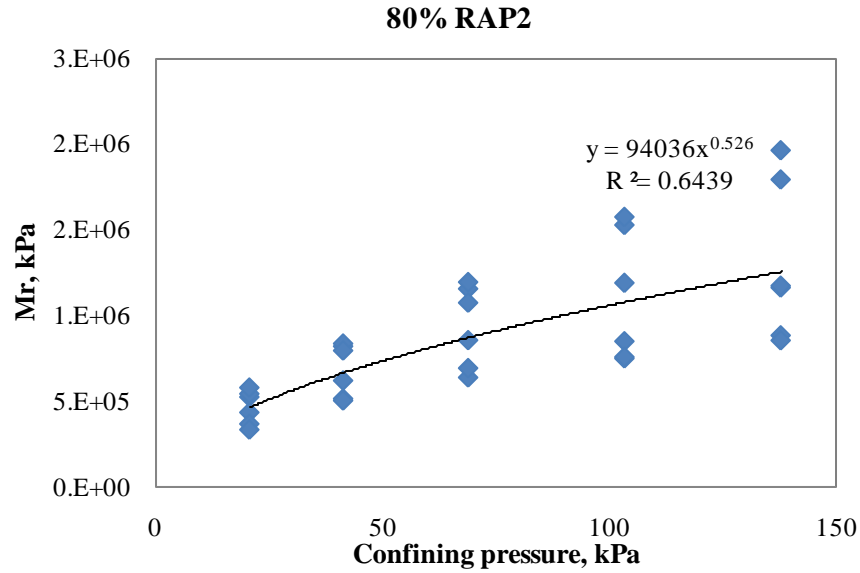


(a)



(b)



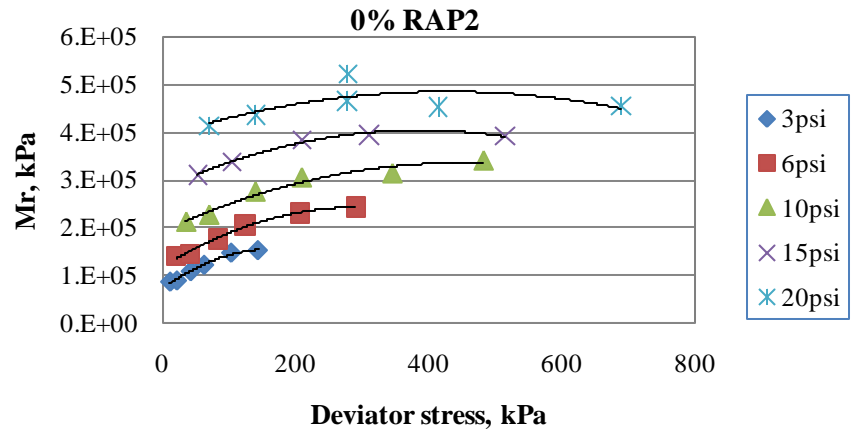


(e)

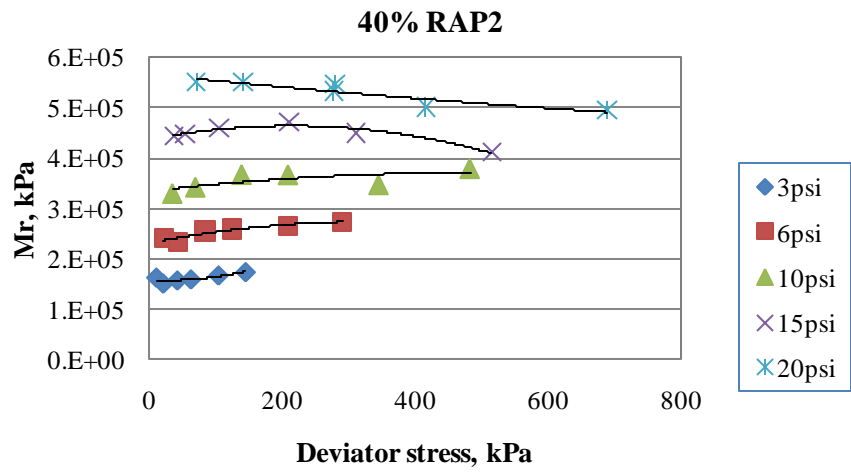
Figure 16 Effect of confining pressure on Mr for (a) 0%RAP2 (b) 20%RAP2 (c) 40%RAP2 (d) 60%RAP2 (e) 80%RAP2

4.3.5.2 Effect of deviator Stress on Resilient Modulus

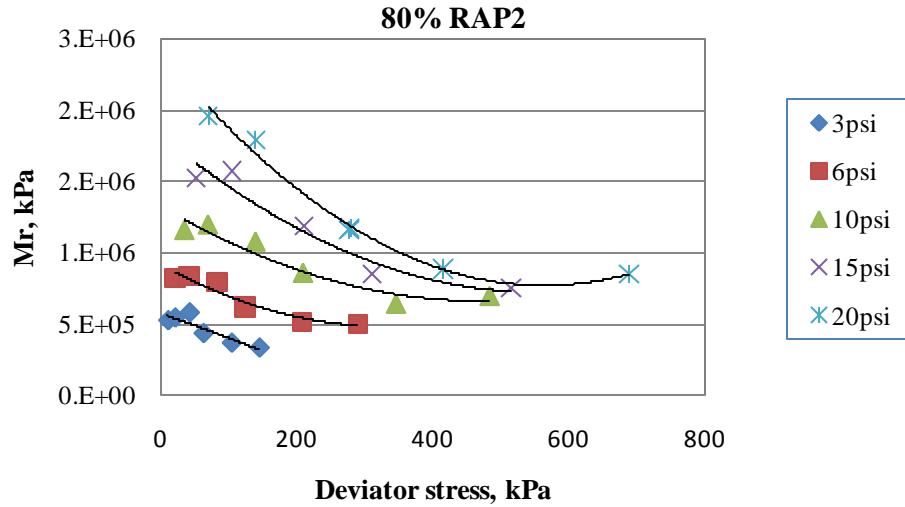
As shown in Table 4, the loading sequence for base course material specified in NCHRP 1-28A consisted of 30 sequences with varied confining pressures and cyclic stresses. Results showed that increasing confining pressure led to an increase of M_r . However, the response of M_r with the gain of deviator stress differed for samples containing different percentages of RAP. Figure 17 presents the effect of deviator stress on M_r of samples containing 0, 40 and 80% RAP2. For 0% RAP2 samples, increase of deviator stress led to an increase of M_r , especially at low confining pressures. However, increasing deviator stress led to the decrease of M_r for the sample containing 80% RAP2 for which the M_r value reduced more rapidly at high confining pressure. For 40% RAP2 sample, the effect of deviator stress on M_r was dependent on the confining pressure. Increasing deviator stress resulted in increased M_r at low confining pressure; however, the opposite was true at high confining pressure. It can be concluded that the effects of deviator stress on M_r containing RAP are dependent on RAP percentage as well as confining pressure.



(a)



(b)



(c)

Figure 17 Effect of deviator stress on Mr for samples containing (a) 0% RAP2 (b) 40% RAP2 (c) 80% RAP2

4.4 PERMANENT DEFORMATION

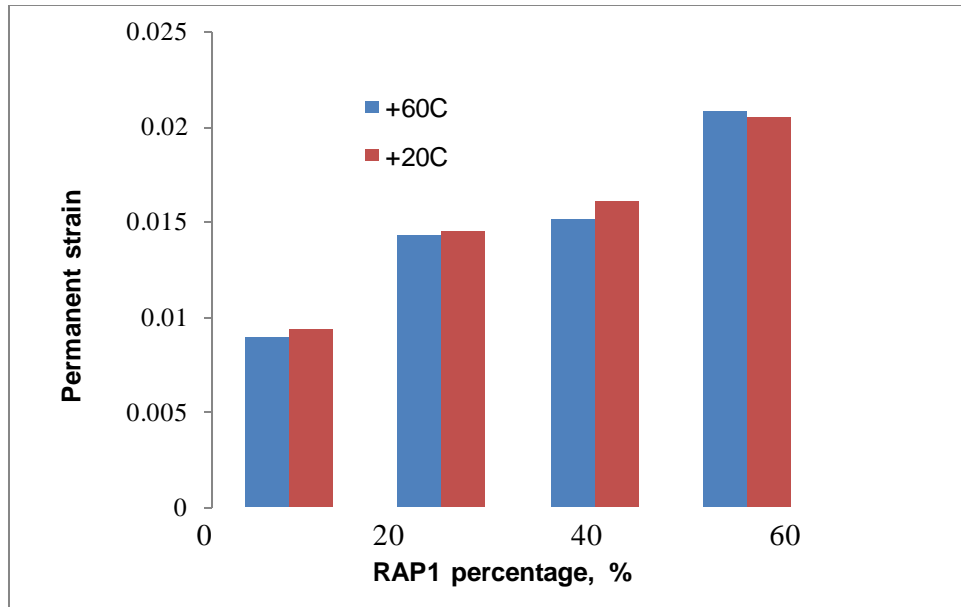
4.4.1 Permanent deformation determined by resilient modulus test method

Permanent deformation was determined based on the average readings of two LVDTs clamped on the specimen after resilient modulus tests. In accordance with the NCHRP 1-28A protocol, 30 loading sequences were applied to the specimen, in addition to the pre-conditioning. In this study, only the permanent deformation generated during the 30 sequences were considered since the deformation generated during pre-conditioning may differ considerably due to compaction during the sample preparation. Figure 18 shows the permanent strain of RAP1 mixtures tested at room temperature, around 20 °C (68 °F) and 60 °C (140 °F). For RAP 1, the difference in permanent strain between 20 °C (68 °F) and 60 °C (140 °F) was insignificant whereas the opposite was true for RAP2. This might be due to the fact that the top size of RAP1 is only 12.5 mm (0.5 inch) while the top size of RAP2 is 31.5 mm (0.75 inch). The large particles might play a significant role in resisting the permanent deformation. When the RAP percentage

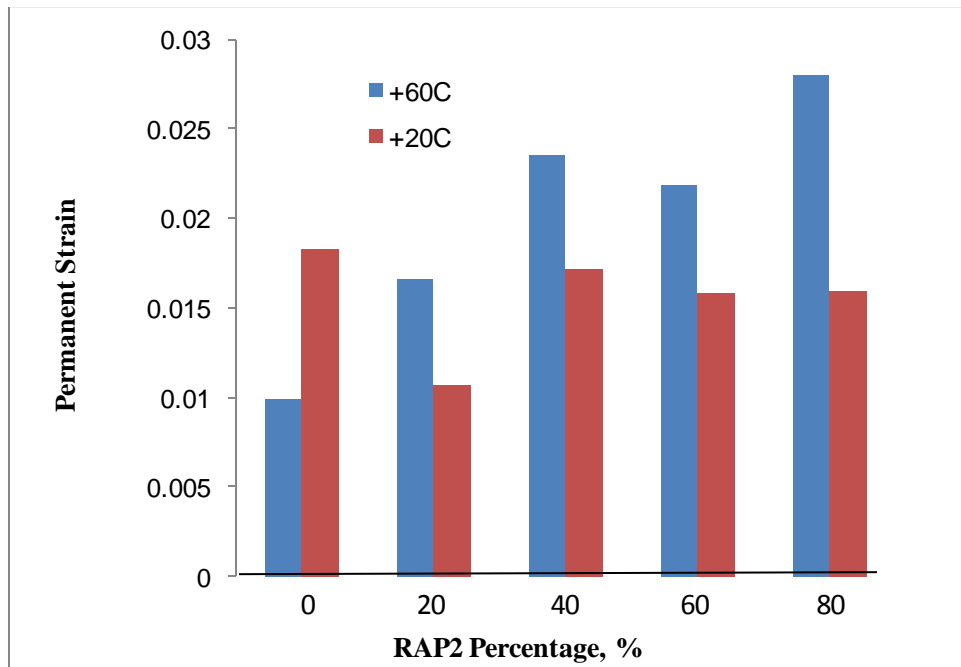
increases, the permanent strain increased under certain conditions, such as 60 °C (140 °F), OMC-4 or OMC-2; and OMC at 20 °C for RAP1, as shown in Figure 19. At high temperature, high asphalt content in mixture led to higher permanent deformation. In addition, at OMC-4 and OMC-2, the high permanent deformation at high RAP percentage could be because it was more difficult to compact RAP than aggregate when materials were dry. However, at OMC+2 or after freeze-thaw conditioning, the permanent deformation was not sensitive to RAP percentage, as shown in Figure 20. With regard to moisture content, as shown in Figure 21, increasing moisture content increased the permanent deformation, as expected.

Table 10 Permanent Strain for RAP1 and RAP2 mixtures

RAP percentage	Temperature, °C		After Freeze-thaw Conditioning	Moisture content, %			
	60	20		OMC-4	OMC-2	OMC	OMC+2
0% RAP1	8.95E-03	9.40E-03	9.29E-03	3.93E-03	7.85E-03	9.40E-03	1.37E-02
20% RAP1	1.43E-02	1.45E-02	9.01E-03	1.22E-02	1.18E-02	1.45E-02	1.54E-02
40% RAP1	1.52E-02	1.61E-02	9.74E-03	2.14E-03	9.62E-03	1.61E-02	1.63E-02
60% RAP1	2.09E-02	1.90E-02	1.02E-02	9.65E-03	1.66E-02	1.90E-02	1.63E-02
0% RAP2	9.91E-03	1.83E-02	6.85E-03	1.43E-03	9.79E-03	1.83E-02	1.27E-02
20% RAP2	1.66E-02	1.07E-02	4.93E-03	4.28E-03	8.89E-03	1.07E-02	1.36E-02
40% RAP2	2.35E-02	1.72E-02	1.18E-02	4.28E-03	1.01E-02	1.72E-02	1.33E-02
60% RAP2	2.19E-02	1.58E-02	9.56E-03	7.24E-03	1.06E-02	1.58E-02	1.21E-02
80% RAP2	2.80E-02	1.59E-02	7.20E-03	9.35E-03	1.44E-02	1.59E-02	1.36E-02

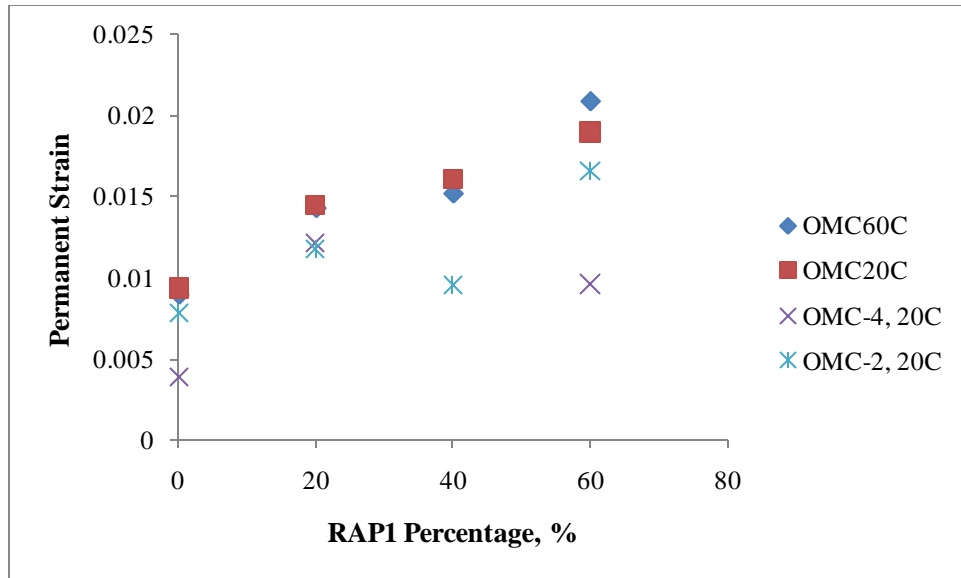


(a)

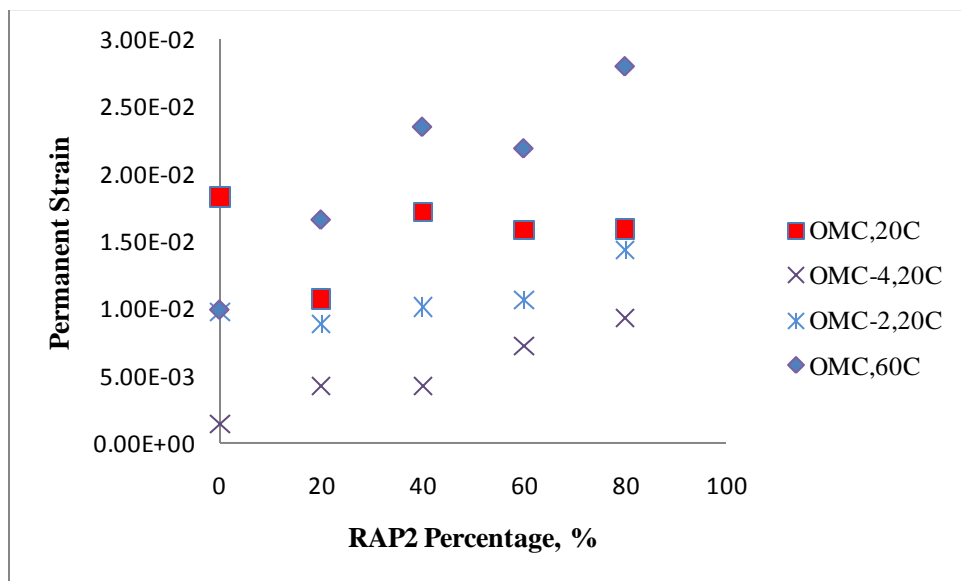


(b)

Figure 18 (a) Relationship between Permanent Strain and RAP1 Percentage for specimens tested at 20 °C and 60 °C (b) Relationship between Permanent Strain and RAP2 Percentage for specimens tested at 20 °C and 60 °C

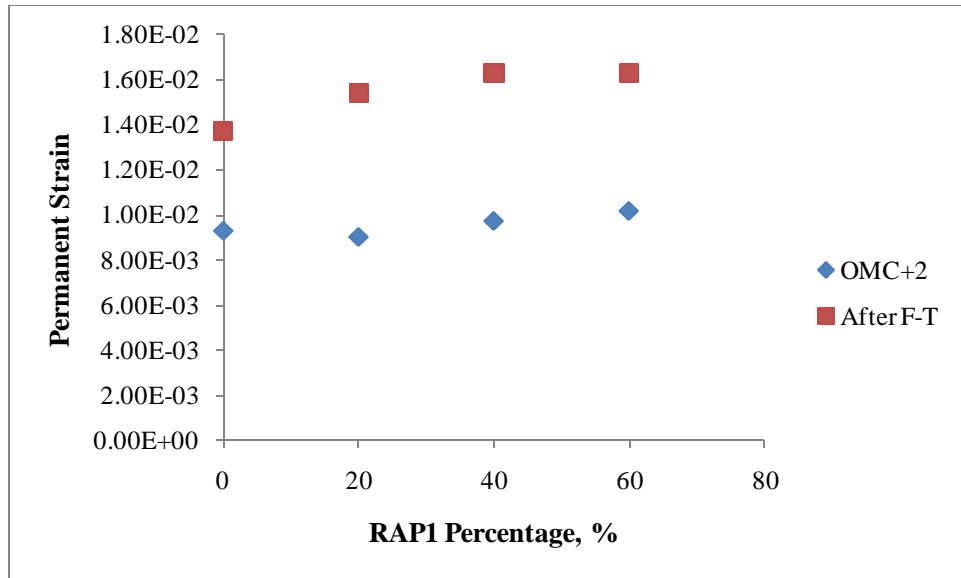


(a)

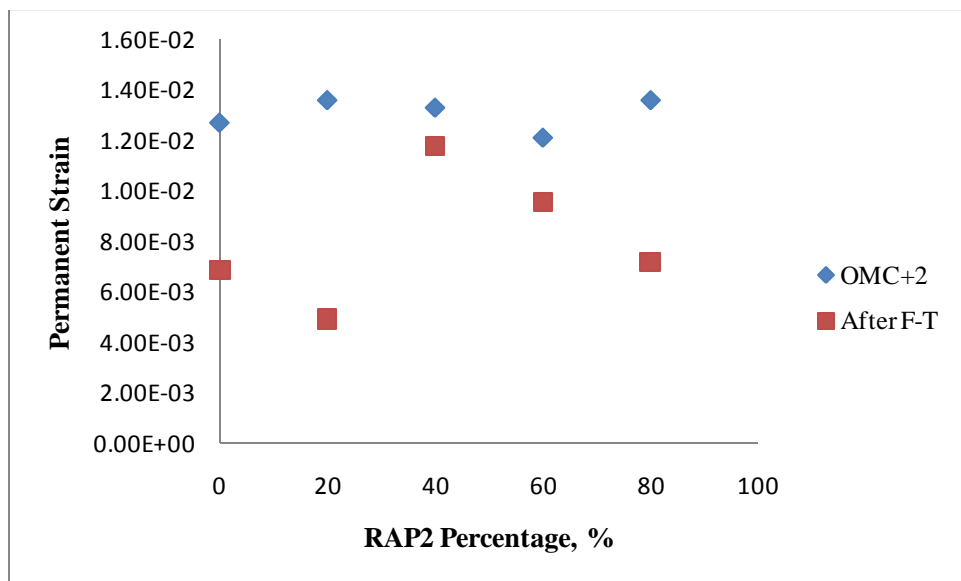


(b)

Figure 19 Relationship between Permanent Strain and RAP percentage for (a) RAP1 and (b) RAP2

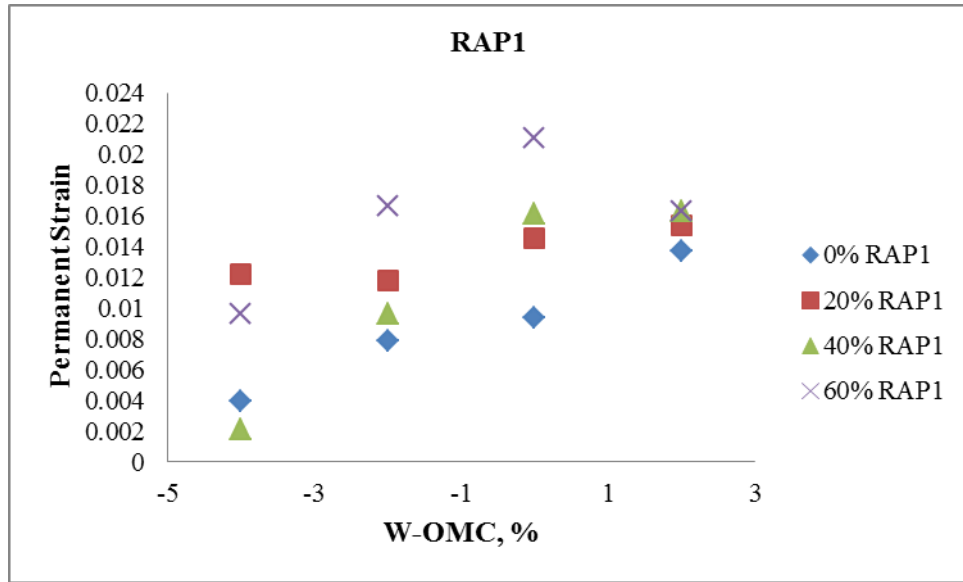


(a)

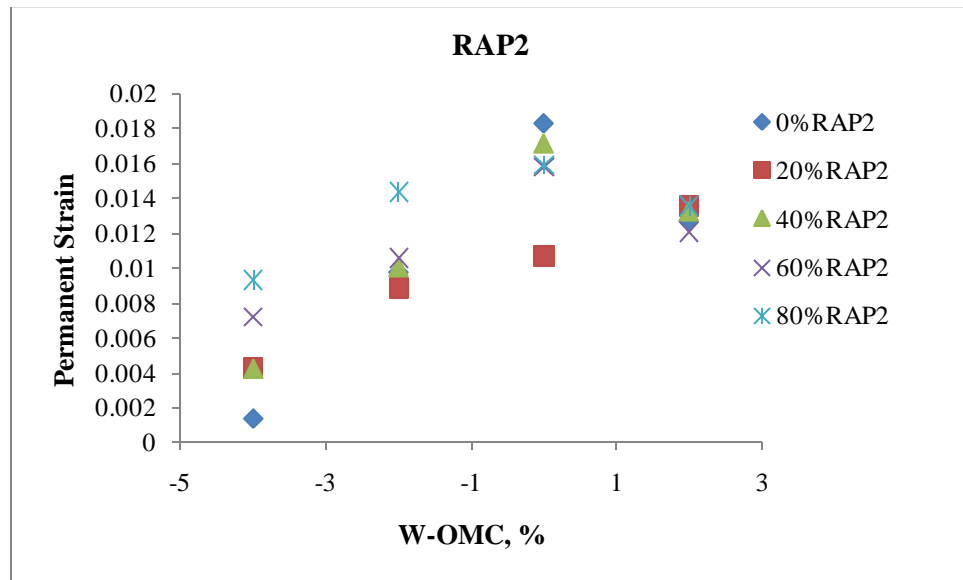


(b)

Figure 20 Relationship between Permanent Strain and RAP Percentage for (a) RAP 1 and (b) RAP 2



(a)



(b)

Figure 21 Relationship between Permanent Strain and Moisture Content for (a) RAP 1 and (b) RAP 2

4.4.2 Permanent deformation determined by repeated load triaxial compression test method

Since the pre-conditioning process was designed to remove the irregularities in the top surface of the cylindrical sample caused by compaction and moving, the permanent deformation that took place in the pre-conditioning process was not considered in this study. The stress levels of cyclic stress and confining pressure applied to samples containing different percentages of RAP2 were listed in Table 11.

Table 11 Cyclic stress and confining pressure applied to RAP2 samples

RAP2 Percentage, %	0	20	40	60	80
Cyclic stress, kPa	690.0	414.0	310.5	207.0	138.0
Confining pressure, kPa	138.0	138.0	103.5	69.0	69.0

4.4.2.1 Permanent deformation characterization

Tseng and Lytton introduced the method that characterized permanent deformation of the pavement materials in terms of three parameters including ϵ_o , β and ρ [Tseng et al. 1989]. The relationship between cumulated permanent strain and loading cycles from repeated load triaxial tests can be plotted and the three parameter can be resolved by fitting a curve. The equation for the curve can be expressed in the form of Equation 18.

$$\epsilon_a = \epsilon_o e^{-\left(\frac{\rho}{N}\right)^\beta} \quad (18)$$

where,

ϵ_a = cumulated permanent strain;

N = number of load cycles, and

ϵ_o , β , ρ = material parameters.

In this model, values of ϵ_0 , β , ρ vary for different samples, which may depend on the type of materials as well as the testing conditionings such as temperature and stress levels. Based on the test data, model coefficients were obtained by using Excel Solver, which produced least-square estimates of the parameters by regression. The values of the three parameters were listed in Table 12. Figure 22 shows the trend of cumulated permanent strain with the increasing number of cycles for samples containing different percentages of RAP2. In order to evaluate the fitness of the model, the relationship between measured permanent strain and predicted permanent strain based on the model was plotted and values of R^2 were included in Table 12. Good fitness of the model can be proved with $R^2 > 0.95$. In order to evaluate the reliability of the selected model, the same statistic methods as used for models evaluating the effect of moisture content on M_r including F-test and T-test were conducted for comparing the measured data and the predicted data based on the model (See Section 4.3.3). As shown in Table 12, no significant difference could be observed with P-value greater than 0.05. Based on the testing data in this study, the model expressed in the form of Equation 18 is effective in characterizing permanent deformation of base course material containing RAP.

Table 12 Model coefficients, P-value and R2 for Permanent Deformation Characterization

RAP percentage	0	20	40	60	80
ϵ_0	0.018	0.006	0.008	0.005	0.004
β	0.214	0.254	0.209	0.219	0.450
σ	884.335	450.356	564.213	472.242	3537.663
R^2	0.990	0.990	0.990	0.980	0.980
P	0.990	0.840	0.880	0.960	0.850

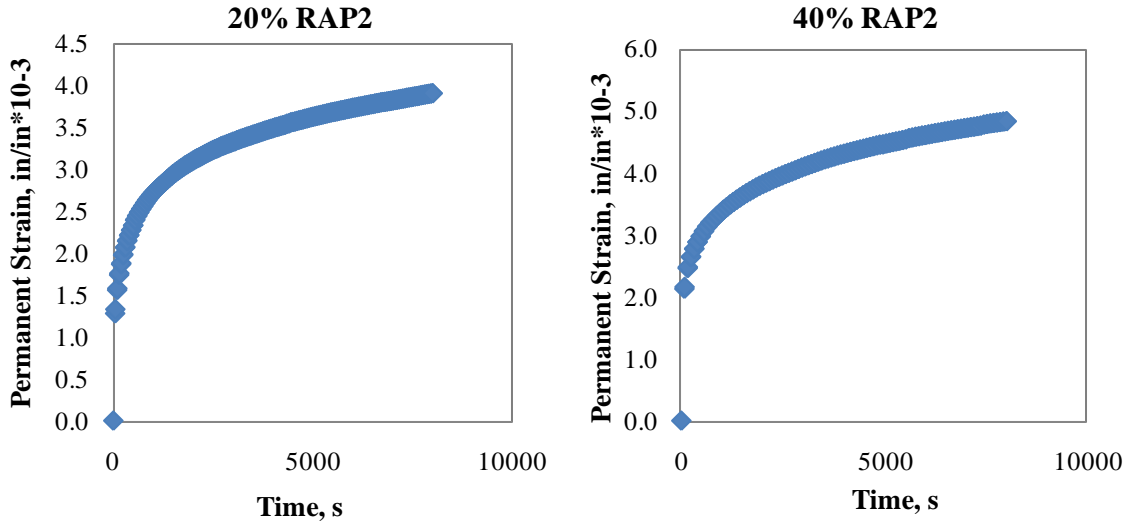


Figure 22 Relationship between permanent strain and time for RAP2 mixtures

4.4.2.2 Predictive equations for permanent deformation model coefficients

Rutting depth in the wheel path of a flexible pavement is produced by repetitive traffic loads. The model of permanent deformation is based on the vertical resilient strain in each layer as well as the fractional increase of total strains for each layer. This approach can be applied to either a single-axle load or multiple axle loads on the pavement surface. For a single axle load, the permanent deformation can be expressed in the form of Equation 19 [Tseng et al. 1989].

$$\delta_a(N) = \sum_{i=1}^n \left\{ \left(\frac{\epsilon_{oi}}{\epsilon_{ri}} \right) e^{-\left(\frac{\rho_i}{N} \right)^{\beta_i}} \int_{d_{i-1}}^{d_i} \epsilon_c(z) dz \right\} \quad (19)$$

where, n is number of pavement layers; ϵ_{ri} is resilient strain determined in the laboratory test; N is expected number of load cycles; d_i is the depth of i^{th} layer; and ϵ_c is the vertical resilient strain from the finite element solution.

In this equation, $\left(\frac{\epsilon_{oi}}{\epsilon_{ri}} \right) e^{-\left(\frac{\rho_i}{N} \right)^{\beta_i}}$ is defined as the fractional increase of total strains. In order to determine appropriate values of ϵ_o/ϵ_r , β and ρ , the relationship between each of these parameters and material characteristics including density, moisture content needs to be

investigated. Tseng and Lytton conducted a comprehensive literature review of permanent deformation test data reported by other researchers. Based on the available data collected, the most reliable equation defining ϵ_o/ϵ_r , β and ρ were developed for granular base material [Tseng et al. 1989]

$$\text{Log} \left(\frac{\epsilon_o}{\epsilon_r} \right) = 0.80978 - 0.06626w_c + 0.003077 \sigma_\theta + 0.000003E_r \quad (20)$$

$$\text{Log} \beta = -0.9190 + 0.03105 w_c + 0.001806 \sigma_\theta - 0.0000015E_r \quad (21)$$

$$\text{Log} \rho = -1.78667 + 1.45062w_c - 0.0003784\sigma_\theta^2 - 0.002074w_c^2\sigma_\theta - 0.0000105E_r \quad (22)$$

where,

w_c = water content, %;

σ_θ = bulk stress, psi;

E_r = resilient modulus, psi.

The analysis conducted by Tseng and Lytton showed that deviator stress, bulk stress, moisture content, and resilient modulus were most significant in affecting ϵ_o/ϵ_r and β for granular base material [Tseng et al. 1989]. Based on the results of resilient modulus testing conducted in this study, RAP percentage had effects on permanent deformation for base course materials containing RAP. Since the values of ϵ_o/ϵ_r , β and ρ are material constants which are derived from a permanent deformation test, RAP percentage should also be considered as one of the factors affecting the three parameters. In accordance with the testing data determined by repeated load test method conducted in this study, combined with permanent deformation test data collected by Tseng and Lytton (1989), the models expressed in the form of Equation 20, 21

and 22 were modified by adding RAP percentage as a parameter. Table 13 reflects the permanent deformation data reported by different researchers as well as that determined by repeated load testing conducted in this study. The regression analysis of ϵ_o/ϵ_r , β and ρ in terms of RAP percentage was performed for samples containing different percentages of RAP. Several forms of equations were established and evaluated in the analysis. Based on the available testing data, the most reliable equations were determined and shown as Equation 23, 24 and 25 following the rule of highest R^2 and lowest standard error.

Table 13 Permanent deformation data for base material [Tseng et al. 1989]

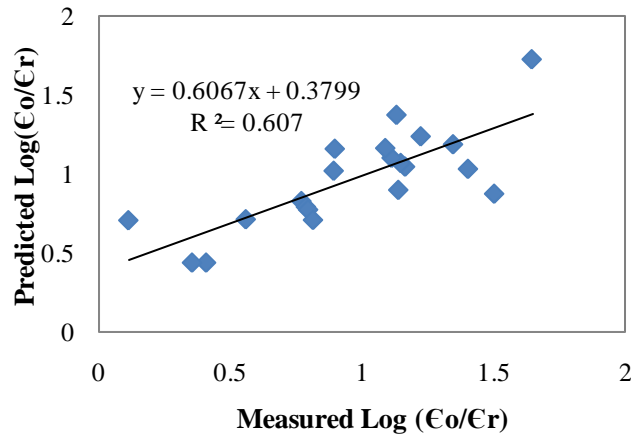
Data source	RAP,%	W _c ,%	σ_o ,psi	E _r ,psi	ϵ_o	ϵ_r	β	σ
Lab testing	0	7.87	164.0	76071	0.01845	0.001267	0.2136	884.3
	20	7.73	124.0	71754	0.00625	0.000801	0.2544	450.4
	40	6.99	93.0	70676	0.00845	0.000603	0.2088	564.2
	60	6.63	62.0	73455	0.00510	0.000394	0.2194	472.2
	80	6.27	52.0	90672	0.00367	0.000220	0.4499	3537.7
Barksdale 1972	0	4.20	76.0	37500	0.01688	0.001230	0.1756	3375.0
	0	4.20	58.3	32600	0.00510	0.000868	0.2319	224.2
	0	4.20	49.4	29800	0.00398	0.000651	0.1661	1779.0
	0	4.20	45.0	28400	0.00329	0.000528	0.1592	8870.0
Chisolm and Townsend 1976	0	2.40	191.0	189000	0.02710	0.000614	0.1200	6093.0
	0	2.40	75.9	120000	0.00849	0.000383	0.1370	31.0
	0	2.40	101.4	167000	0.00335	0.000248	0.1400	199.6
	0	4.50	76.4	109000	0.01076	0.000426	0.1300	1638.0
	0	5.60	62.6	90000	0.01150	0.000362	0.1250	349.3
Kalcheff and Hicks 1973	0	5.00	30.0	46000	0.00212	0.000326	0.1904	2853.0
	0	5.00	30.0	45000	0.00043	0.000333	0.1628	6596.0
	0	5.00	30.0	48000	0.00113	0.000313	0.1835	3856.0
	0	5.00	120.0	116000	0.00633	0.000517	0.1992	2255.0
	0	5.00	120.0	114000	0.00414	0.000526	0.1977	2382.0
	0	10.00	50.0	37000	0.00138	0.000541	0.2858	1052.0
	0	10.00	50.0	37000	0.00122	0.000541	0.2759	730.3

$$\text{Log} \left(\frac{\epsilon_o}{\epsilon_r} \right) = 0.82808 - 0.06388w_c + 0.003411 \sigma_o + 0.0000021E_r + 0.005512\text{RAP} \quad (23)$$

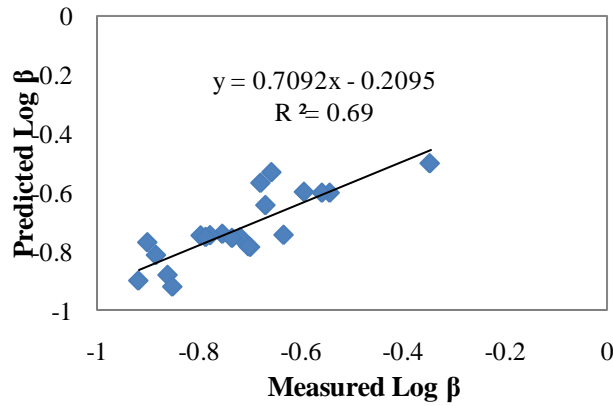
$$\text{Log } \beta = -0.84638 + 0.026273 w_c + 0.000506 \sigma_\theta - 0.0000011E_r + 0.003216\text{RAP} \quad (24)$$

$$\text{Log } \rho = 3.364796 - 0.00334w_c + 0.0000911\sigma_\theta^2 - 0.00016w_c^2\sigma_\theta - 0.000015E_r - 0.16851\sqrt{\text{RAP}} + 0.035955\text{RAP} \quad (25)$$

where, RAP = RAP percentage contained in the base course material, %. The relationship between measured and predicted values of ϵ_o/ϵ_r , β and ρ were plotted in Figure 23. In order to draw a general conclusion, more laboratory testing for specimens containing RAP is needed to evaluate the reliability of the modified models.



(a)



(b)

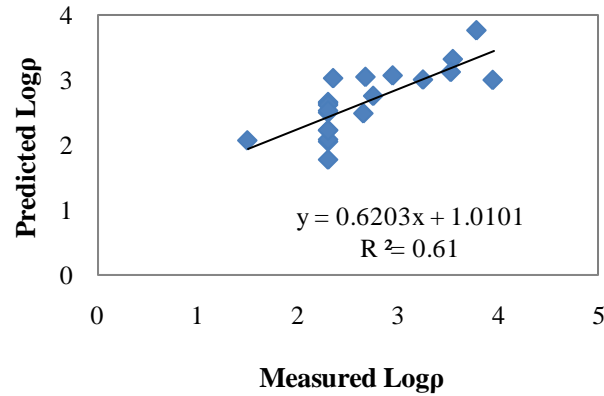


Figure 23 Relationship between measured and predicted values of (a) $\text{Log}(C_o/C_r)$, (b) $\text{Log}\beta$ and (c) $\text{Log } \rho$

4.5 PERMEABILITY

Hydraulic conductivity tests were conducted following AASHTO T 215 for samples containing different percentages of RAP2 only at room temperature. Coefficient of permeability was calculated based on Equation 10. The results are presented in Table 14 and Figure 24. The capacity of compacted samples to drain decreased with the increase of RAP percentage.

Considering the same gradation used for all the mixtures, the reduction of permeability might be due to the aggregation of RAP particles as a result of compaction. The asphalt in RAP could form bond between particles.

Table 14 Coefficient of permeability for RAP2 mixtures

RAP2 Percentage, %	k, cm/s
0	0.16170
20	0.085742
40	0.075111
60	0.038278
80	0.010585

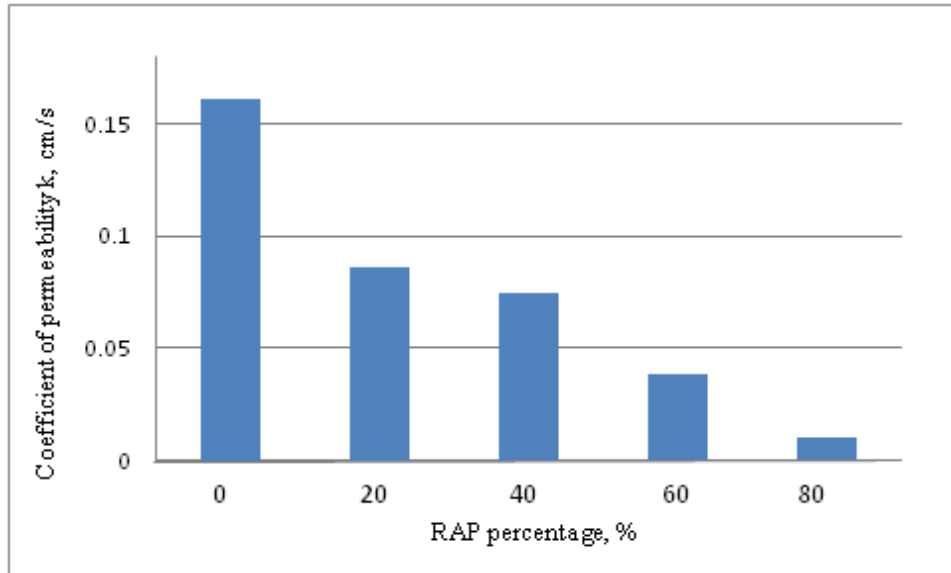


Figure 24 Trend of hydraulic conductivity with the increase of RAP2 percentage

4.6 MOISTURE DAMAGE

4.6.1 Effect of freeze-thaw on resilient modulus

Two set of samples containing different percentages of RAP1 and RAP2 were tested to study the effects of freezing-thawing on resilient modulus. One set was tested for M_r right after compaction while the other set was placed in the triaxial cell for freezing and thawing condition prior to the testing. For RAP mixtures and virgin aggregates, M_r values increased after freezing-thawing as shown in Figure 25. However, , the moisture contents in the conditioned samples were reduced, indicating loss of moisture, as indicated in Table 15. During 24-hour thawing, some water was drained to the bottom of the sample and was lost through the water drain line at the bottom of the triaxial chamber. The lower moisture content is believed to be the reason for higher M_r after freeze-thaw conditioning.

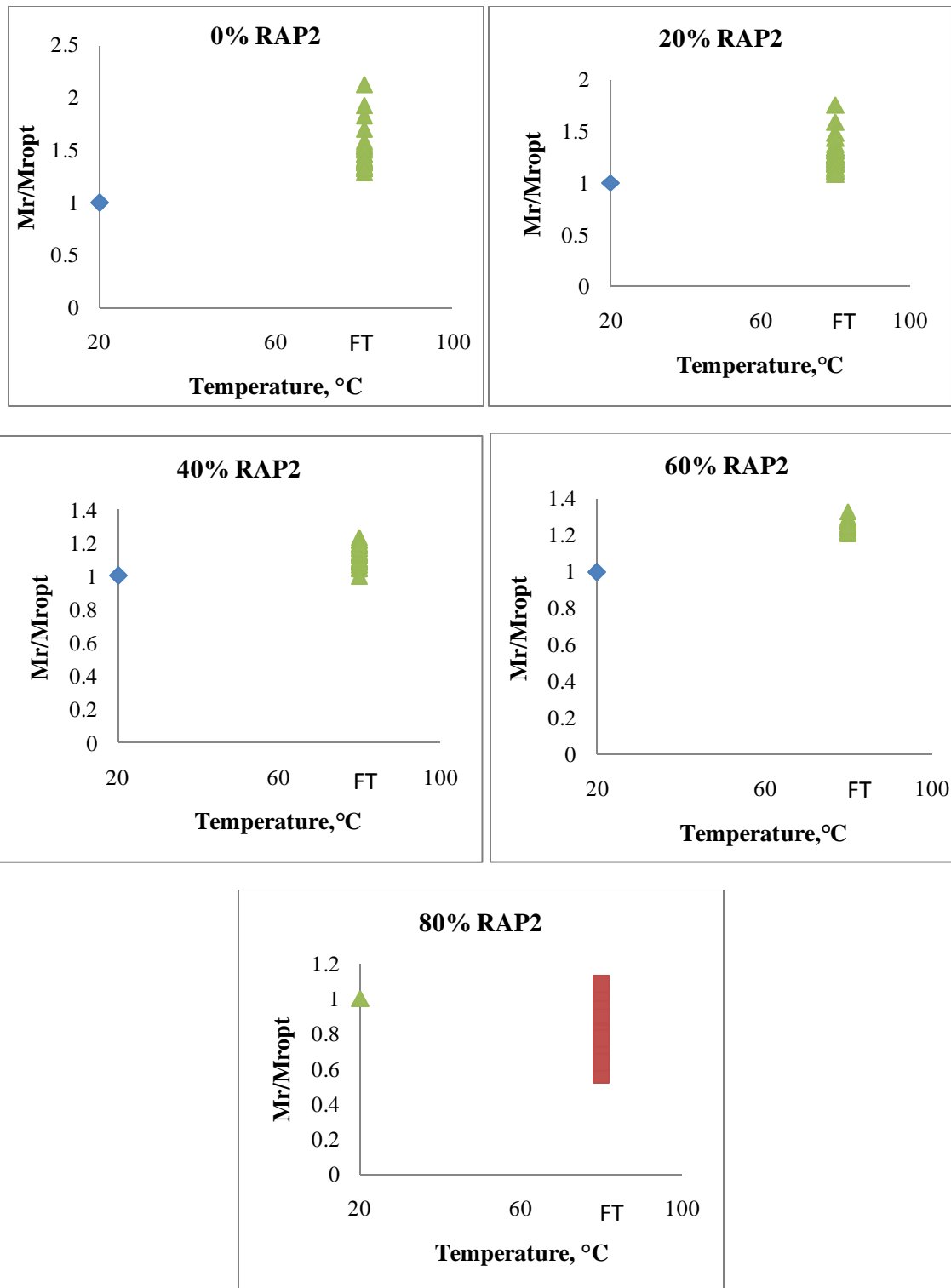


Figure 25 Effect of Freeze-thaw conditioning on M_r of specimens containing different percentages of RAP2

Table 15 Moisture Content of Specimens before and after Mr Test

Sample	Condition	MC before test, %	MC after test, %
0% RAP2	no freeze-thaw cycle	7.87	7.24
20% RAP2	no freeze-thaw cycle	7.73	7.53
40% RAP2	no freeze-thaw cycle	6.99	6.67
60% RAP2	no freeze-thaw cycle	6.63	6.33
80% RAP2	no freeze-thaw cycle	6.27	6.17
0% RAP2	with freeze-thaw cycle	7.87	5.85
20% RAP2	with freeze-thaw cycle	7.73	5.37
40% RAP2	with freeze-thaw cycle	6.99	4.60
60% RAP2	with freeze-thaw cycle	6.63	4.46
80% RAP2	with freeze-thaw cycle	6.27	4.20

4.6.2 Effect of freeze-thaw on permeability

As introduced in Chapter 3, the well-mixed loose samples containing OMC were conditioned with freezing-thawing, followed by the permeability tests. Figure 26 shows the relationship between the coefficient of permeability and RAP percentage. The results indicated that the permeability increased after freezing-thawing. The change of gradation of RAP particles during conditioning could be a reason. During the freezing and thawing, RAP particles could disintegrate which could change the gradation of RAP and lead to an increase in permeability and this need to be verified by more lab testing.

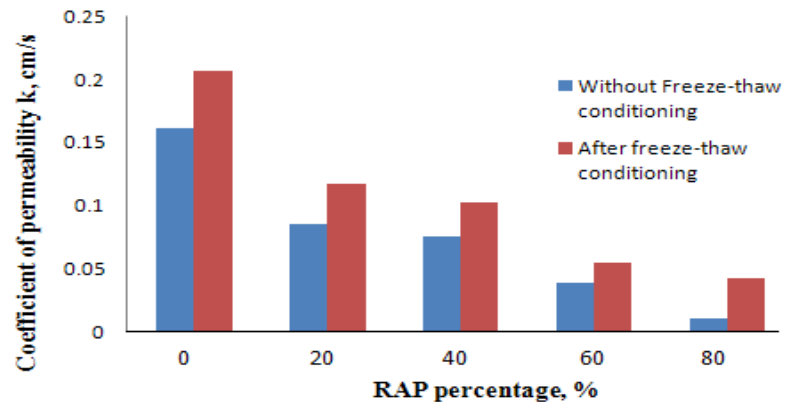
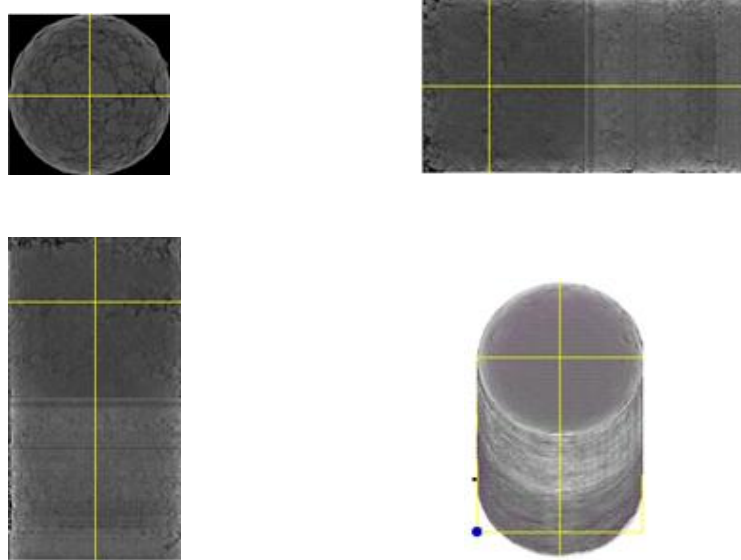


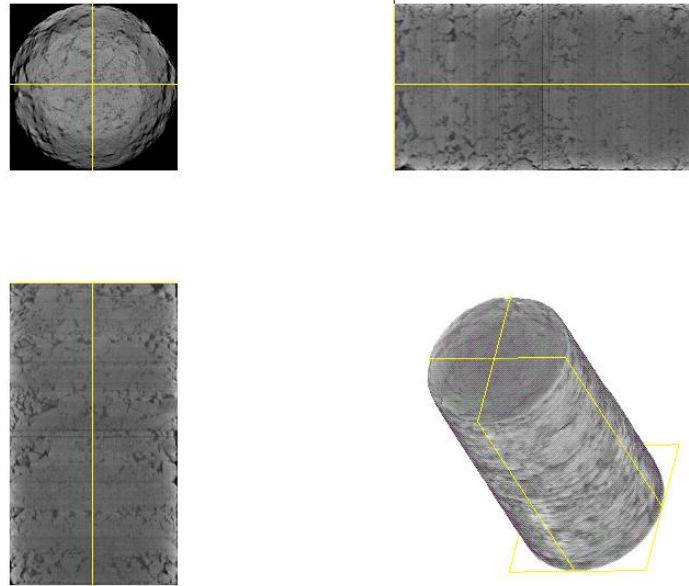
Figure 26 Effect of Freeze-thaw conditioning on permeability of specimens containing different percentages of RAP2

4.7 X-RAY CT SCANNING FOR SPECIMENS CONTAINING RAP

The reconstructed images of the slices were converted into a 3-Dimensional image with FlashCT Visualization (VIZ). The processed image was analyzed with Matlab File Converter (MFC) to get XY, XZ and YZ-sliced image formats so that other image processing software could handle. In this study, Image Pro Plus was used as the image processing software. Figure 27 shows the 3-Dimensional images formed by more than 700 slices scanned for 0% RAP and 80% RAP specimens. It is obvious that larger pores could be detected for 0% RAP when compared to 80% RAP specimen.



(a)



(b)

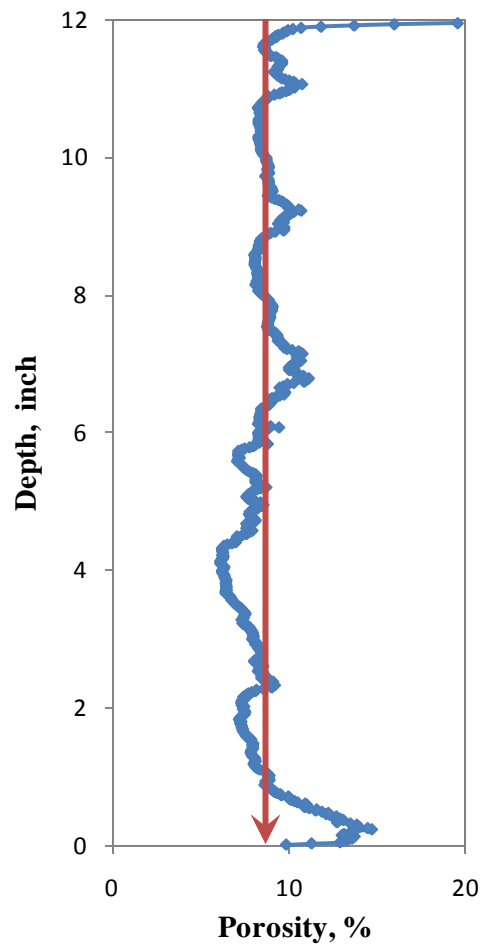
Figure 27 3-Dimensional images for (a) 80% RAP2 specimen (b) 0% RAP2 specimen

In the Image Pro Plus platform, visual basic macros can be integrated and run to quantify desired physical properties of specimens. In this study, macro was developed to count the black pixels which indicate void spaces and the average value of porosity for each slice can be calculated with porosity computing algorithm. The values of porosity for slices were integrated and averaged over the depth of the specimen and the distribution of porosity could be determined over the entire depth. As shown in Figure 28, the average porosity for 0% RAP is 8.67%, which is higher than that of 80% RAP as 5.73%. Figure 29 shows the original and segmented images for the slice at the depth of 9.9mm for both 0% RAP and 80% RAP. More black area can be observed for 0% RAP image when compared to 80% RAP, which reflects that more void spaces could be detected for 0% RAP.

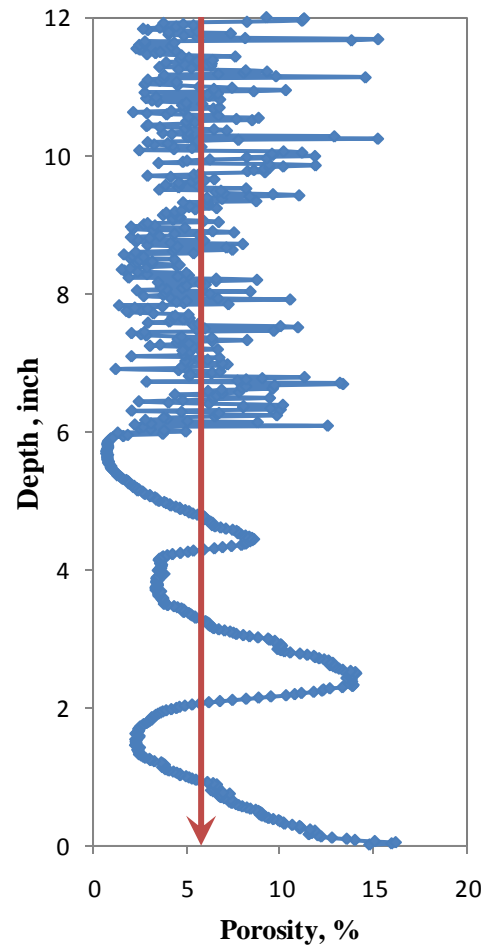
Although the gradation of all the tested samples containing different percentages of RAP was controlled constant, the porosity of 80% RAP was proved to be lower than that of virgin

aggregate. Porosity is a measure of the void spaces in the compacted sample, and is a fraction of the volume of voids over the total volume. Higher porosity reflects more void spaces in the compacted sample, which may cause higher resilient deformation under cyclic stresses during triaxial testing. In addition, higher resilient deformation is supposed to result in lower resilient modulus under the same level of stress. In this study, a conclusion was drawn in evaluating the effect of RAP percentage on resilient modulus that increasing RAP percentage leads to the gain of M_r . Based on the analysis on porosity, it can be suggested that the lower air void for specimens containing higher RAP percentage might be one of the reasons leading to the increased M_r .

Particle size and porosity were reported to have effects on hydraulic conductivity of crushed granite. It was demonstrated that for a given d_{10} value, which indicates the diameter for which 10% of all particle are smaller, hydraulic conductivity decreased with decreasing porosity [Cote et al. 2011]. More void spaces in the compacted sample is suggested to increase the ability of the sample to drain, which leads to the increase of permeability. In this study, it was concluded that permeability of compacted samples containing RAP decreased with the increase of RAP percentage. Based on the analysis on porosity, it can be concluded that the lower air void for specimens containing higher RAP percentage should be one of the reasons leading to the decreased permeability.

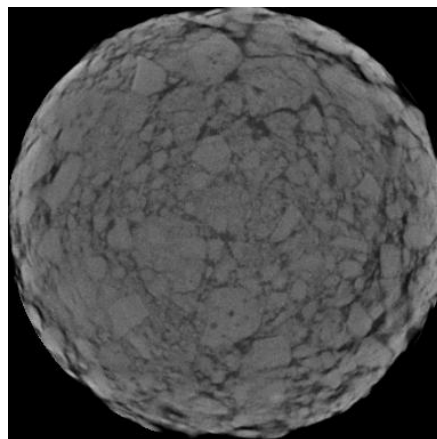


(a)

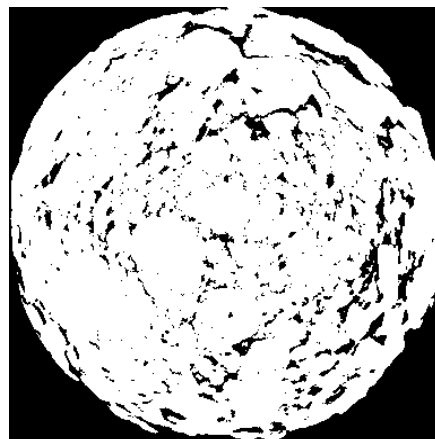


(b)

Figure 28 Porosity distribution over the depth of (a) 0% RAP2 (b) 80% RAP2



Original



Segmented

(a)

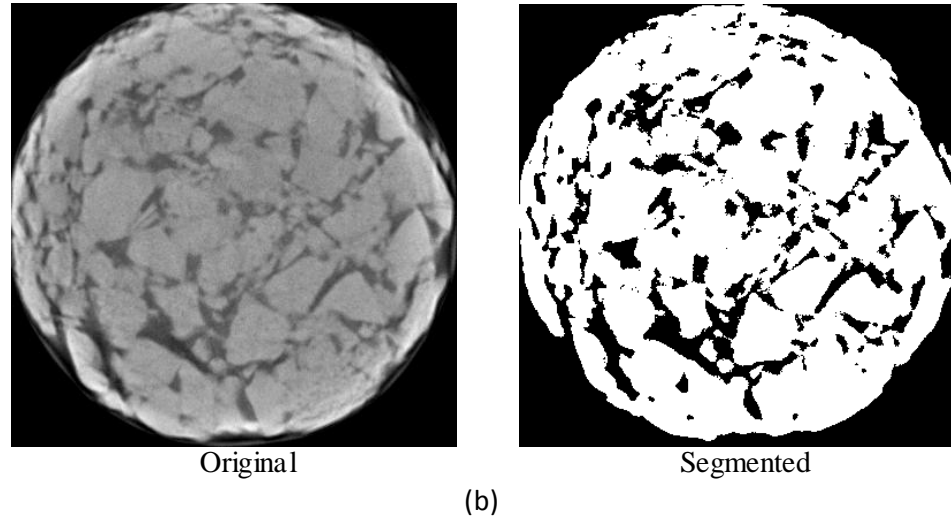


Figure 29 Original and segmented images at the depth of 0.39inch for (a) 80% RAP2 (b) 0% RAP2

4.8 SUMMARY

Based on the laboratory experiments, the resilient moduli of mixtures containing RAP were higher than that without RAP and increased with the increase of RAP percentage. Based on the NCHRP 1-28A report, the resilient modulus shall be reported at confining pressure of 35kPa (5.07psi) and deviator stress of 103kPa (14.94psi). The stress states which are close to these criteria were used to interpolate the resilient modulus values at confining pressure of 41kPa (5.95psi) and deviator stress of 103kPa (14.94psi), as shown in Table 16.

Table 16 Resilient Modulus at Confining Pressure of 41kPa (5.95psi) and Deviator Stress of 103kPa (14.94psi)

RAP, %	RAP 1			RAP2		
	Deviator Stress					
	82kpa (11.89psi)	122kPa (17.69psi)	Average	82kpa (11.89psi)	122kPa (17.69psi)	Average
0	209.53 MPa (30.39 ksi)	217 MPa (31.48 ksi)	213.2 MPa (30.94 ksi)	176.99 MPa (25.67 ksi)	206.22 MPa (29.91 ksi)	191.61 MPa (27.79 ksi)
20	197 MPa (28.65 ksi)	212 MPa (30.75 ksi)	204.77 MPa (29.70 ksi)	214.91 MPa (31.17 ksi)	232.84 MPa (33.77 ksi)	223.87 MPa (32.47 ksi)

40	246.21 MPa (35.71 ksi)	263 MPa (38.25 ksi)	254.97 MPa (36.98 ksi)	255.66 MPa (37.08 ksi)	259.31 MPa (37.61 ksi)	257.45 MPa (37.34 ksi)
60	368.46 MPa (53.44 ksi)	364.8 MPa (52.91 ksi)	366.67 MPa (53.18 ksi)	304.54 MPa (44.17 ksi)	313.02 MPa (45.40 ksi)	308.82 MPa (44.79 ksi)
80				527.86 MPa (76.56 ksi)	482.15 MPa (69.93 ksi)	505.4 MPa (73.25 ksi)

The higher Mr values of mixtures containing RAP are beneficial to the pavement performance, because it strengthens the support to the surface layer from the base and reduces the tensile strain at the bottom of HMA. However, the rutting potential in base is also increased, especially at high temperature and excessive moisture content.

Therefore, RAP as a base course material has its advantage and disadvantages when compared to virgin aggregates. Current pavement design method, such as the AASHTO 1993, is not capable of capturing the performance of base material containing RAP. For instance, only resilient modulus is used in a pavement design. The MEPDG includes prediction model for both fatigue, rutting, and other performance distresses and can be used to predict the performance of a pavement containing RAP base material. Thus a life cycle cost analysis is possible to evaluate the cost-effectiveness of using RAP. However, it is noted that the characteristics of RAP is different from those of traditional materials. For instance, the rutting potential of virgin aggregates is negatively correlated with stiffness of virgin aggregates. That is, high stiffness materials are more resistant to rutting. This is, apparently, not the case for RAP. Therefore, the rutting prediction model for granular materials in MEPDG is not applicable to base materials containing RAP. A rutting prediction model specific to RAP, such as the model developed in this study, after validation, can be included in the MEPDG before the cost-effectiveness of using RAP as a base material can be assessed.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

Currently WSDOT allows up to 1.2 bitumen content (about 20% RAP to be blended with crushed aggregates) in the base materials [WSDOT 2008]. A successful application of high percentage RAP could contribute to the sustainability, in terms of costs, energy, and greenhouse gas emission. This study investigated the potential of using high percentage of RAP as base course material and the following conclusions and recommendations can be made.

5.1 CONCLUSIONS

(1) RAP collected from different sources have various asphalt contents and gradations, for example, RAP1 used in this study contains 4.86% asphalt content while RAP2 contains 6.11%.

(2) Modified proctor compaction method was used in this study to evaluate the relationship between moisture content and dry density. For RAP from two sources, OMC decreased with the increase of RAP percentage. However, no obvious trend was detected for MDUW with the increased RAP percentage. In addition, increase of RAP percentage led to the reduction of bulk specific gravity.

(3) Mr test was conducted following NCHRP 1-28A protocol. Overall, Mr increased with the increase of RAP percentage for samples containing different moisture contents when tested at room temperature.

(4) Moisture content was varied to investigate the effect on M_r of base course materials containing RAP, Mr decreased with the gain of moisture content. Models were evaluated for good-fit and mathematical stability based on available testing data in this study. It was concluded

that both Kw model and Sigmoid model can be used as constitutive models to determine the effects of moisture content on M_r .

(5) Based on testing data varying temperature, K_T model and Sigmoidal model were used to account for the effects of temperature on M_r . Both the fitness and mathematical stability were evaluated and models were proved of reliability. For RAP collected from two sources, M_r reduced with the elevated temperature. In addition, specimens containing higher percentage of RAP were more sensitive to the increase of temperature. For samples tested at -20 °C, the range for M_r values was consistent with values recommended by the MEPDG.

(6) M_r increased with the increase of confining pressure. However, the effect of deviator stress on M_r of samples containing RAP is dependent on RAP percentage as well as confining pressure.

(7) Based on resilient modulus test results, for specimens containing different percentages of RAP1 and RAP2, permanent strain increased with the increase of RAP percentage. However, the increased permanent strain occurred only at high temperature and/or dry side of OMC.

(8) Permanent deformation prediction models for granular base course materials introduced by Tseng and Lytton in 1989 were modified by adding the RAP percentage as a parameter for base course materials containing RAP. Based on available testing data in this study, permanent strain increased with the increase of RAP percentage. However, more lab testing is needed to draw a general conclusion.

(9) Constant-head permeameter was selected for conducting permeability test for specimens containing RAP as base course material. The result indicated that permeability was

reduced by the addition of RAP. Comparing the coefficient of permeability of 20% RAP2 mixture to that of virgin aggregate indicates a decrease by up to 50%.

(10) Freeze-thaw cycles were applied to specimens to investigate moisture damage. Comparing M_r values for samples applied with FT cycles with those without conditioning presented that no bad effect of FT conditioning was noticed on specimens containing RAP. However, comparing the result of samples after conditioning to that without conditioning indicates the increase in permeability. The effect of freeze-thaw conditioning on hydraulic conductivity of base course materials was much greater for 80% RAP specimen than 0% RAP specimen.

(11) X-Ray Scanning was conducted for 0%RAP2 and 80% RAP2 specimens. Image Pro Plus software was used for porosity analysis. It was reflected that 0% RAP2 specimen had higher air void when compared to 80% RAP2, which suggested that the lower air void might be one of the reasons leading to higher M_r for samples containing higher RAP percentage.

5.2 RECOMMENDATIONS

(1) More sources of RAP should be studied to draw a general conclusion on the use of RAP in base course.

(2) Current pavement design method, such as AASHTO 1993, could not capture the rutting potential of RAP in a base course. The cost-effectiveness of the use of RAP as a base material should be determined by the MEPDG.

(3) The rutting model for granular materials in the MEPDG is not applicable to RAP as a base material. A rutting model for RAP is needed in MEPDG.

REFERENCES

- American Association of State Highway and Transportation Officials (AASHTO). (1993) Guide for Design of Pavement Structures, Washington, D.C.
- Applied Research Associates, Inc. (ARA). (2004) Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures, Washington, DC.
- Attia, M., Abdelrahman, M. and Alam, T. (2009) "Investigation of Stripping in Minnesota Class 7 (RAP) and Full-Depth Reclamation Base Materials." Report No. MN/RC 2009-05, Minnesota Department of Transportation, St. Paul, MN
- Attia, M., Abdelrahman, M. (2010) Modeling the effect of moisture on resilient modulus of untreated reclaimed asphalt pavement. *Transportation Research Record: Journal of the Transportation Research Board*, No 2167, pp. 30-40.
- Bouchedid, M.B. and Humphrey, D.N. (2005) Permeability of Base Material for Maine Roads. *Transportation Research Record: Journal of the Transportation Research Board*, No1936, pp. 142-149.
- Cooley, D.A. (2005) Effects of Reclaimed Asphalt Pavement on Mechanical Properties of Base Materials, submitted for degree, Brigham Young University.
- Cosentino, P. J. and Kalajian, E. H. (2001) Developing Specifications for Using Recycled Asphalt Pavement as Base, Subbase or General Fill., www.dot.state.fl.us/research-center/Completed_Proj/Summary_SMO/FDOT_BB892_rpt.pdf. Accessed July 2007.
- Gupta, S., Kang, D.H. and Ranaivoson, A. (2009) "Hydraulic and Mechanical Properties of Recycled Materials." Report No. MN/RC 2009-32, Minnesota department of Transportation, St. Paul, MN
- Guthrie, W. S., Cooley, D.A. and Eggett, D. L. (2007) Effects of Reclaimed Asphalt Pavement on Mechanical Properties of Base Materials. *Transportation Research Record: Journal of the Transportation Research Board*, No 2005, pp. 44-52.
- Jeon, E., Steven, B. and Harvey, J. (2009) Comprehensive Laboratory Testing and Performance Evaluation of Recycled Pulverized Hot-Mix Asphalt Material. *Transportation Research Record: Journal of the Transportation Research Board*, No 2104, pp. 42-52.
- Kim, W., Labuz, J.F. and Dai, S. (2007) Resilient Modulus of Base Course Containing Recycled Asphalt Pavement. *Transportation Research Record: Journal of the Transportation Research Board*, No 2005, pp. 27-35.

- MacGregor, J. A. C., Highter, W. H. and DeGroot, D. J. (1999) Structural Numbers for Reclaimed Asphalt Pavement Base and Subbase Course Mixes. *Transportation Research Record: Journal of the Transportation Research Board*, No 1687, pp. 22-28.
- McGarrah, E.J. (2007) "Evaluation of Current Practices of Reclaimed Asphalt Pavement/Virgin Aggregate as Base Course Material." Report No. WA-RD 713.1, Washington State Department of Transportation, Olympia, WA
- Maher, M. H., Gucunski, N. and Papp, W. J., Jr. (1997) Recycled Asphalt Pavement as a base and subbase material. *Testing soil mixed with waste or recycled materials*, pp. 42-53.
- Mohammad, L. N., Herath, A., Rasoulia, M. and Zhang, Z. (2006) Laboratory Evaluation of Untreated and Treated Pavement Base Materials From a Repeated Load Permanent Deformation Test. *Transportation Research Record: Journal of the Transportation Research Board*, No 1967, pp. 78-88.
- Mokwa, R. L. and Peebles, C. S. (2005) "Evaluation of the Engineering characteristics of RAP/Aggregate Blends." Montana Department of Transportation, Helena, MT
- Recycled Materials Resource Center (RMRC). (2008) User Guidelines for Byproducts and Secondary Use Materials in Pavement Construction. www.rmrc.unh.edu/tools/uguidelines/rap131.asp. Accessed Nov 2010.
- Richter, C.A. (2006) "Seasonal Variations in the Moduli of Unbound Pavement Layers." Publication FHWA-HRT-04-079, U.S. Department of transportation, Washington, DC.
- Saeed, A. (2008) "Performance-Related Tests of Recycled Aggregates for Use in Unbound Pavement Layers." Final report to National Cooperative Highway Research Program, Report No. 598, Washington, DC.
- Sargious, M. and Mushule, N. (1991) "Mushule Behavior of recycled asphalt pavement at low temperature." *Canadian Journal of Civil Engineering*, Volume 18, Issue 3, pp. 428-435.
- Trzebiatowski, B.D and Benson, C.H. (2005) "Saturated hydraulic conductivity of compacted recycled asphalt pavement." *Geotechnical Testing Journal*, Vol. 28, No. 5.
- Tseng, K.H. and Lytton, R.L. (1989) "Prediction of permanent deformation in flexible pavement materials." *American Society for Testing and Materials*, pp. 154-172.
- Uhlmeier, J. "Construction and Performance of Reclaimed Asphalt Pavement (RAP) in Untreated Aggregate Base." Research Need Statement, Washington Department of Transportation, Olympia, WA.

Washington Department of Transportation (WSDOT). (2008) Standard specifications for Road, Bridge, and Municipal Construction. Olympia, WA.

Wen. H., Warner, J., Edil, T. and Wang, G. (2010) Laboratory comparison of crushed aggregate and recycled pavement material with and without high carbon fly ash. *Geotechnical and Geological Engineering*. Volume 28, No 4, pp.405-411.

Wijeratne, A and Sargious, M(1987) "Prediction of Rutting in Virgin and Recycled Asphalt Mixtures for Pavements Using Triaxial Tests." *Journal of Asphalt Paving Technology*. Vol. 56, pp. 111-129.

Witczak, M. W. (2004) "Laboratory determination of resilient modulus for flexible pavement design." Final report to National Cooperative Highway Research Program, Report No. 285, Washington, DC

Witczak, M.W., Andrei, D. and Houston, W.N. (2000) "Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. Appendix DD-1: Resilient modulus as Function of Soil Moisture-Summary of Predictive Models." Final report to National Cooperative Highway Research Program, Report No. 1-37A, Washington, DC

Appendix Detailed Testing Results

Table 1 Resilient modulus test result for 0% RAP1 sample containing OMC tested at 20 °C

0% RAP1 Sample containing OMC tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.27	80958.24
2	41.37	21.14	161102.89
3	68.95	35.44	238468.96
4	103.42	53.22	336029.77
5	137.90	70.43	447345.62
6	20.68	20.94	83171.45
7	41.37	41.76	178319.10
8	68.95	70.53	266585.78
9	103.42	105.92	384168.97
10	137.90	140.47	462024.56
11	20.68	45.76	76469.75
12	41.37	83.50	209510.98
13	68.95	140.09	301618.04
14	103.42	208.07	401392.07
15	137.90	276.14	483915.41
16	20.68	60.14	92176.01
17	41.37	124.84	217074.53
18	68.95	208.30	315945.34
19	103.42	310.79	413844.00
20	137.90	415.48	488100.53
21	20.68	103.04	137302.19
22	41.37	207.08	221404.44
23	68.95	344.43	319144.51
24	103.42	519.40	408431.62
25	137.90	699.83	482812.25
26	20.68	142.06	136350.71
27	41.37	289.55	239406.65
28	68.95	482.75	341166.37
29	103.42	726.28	429729.52
30	137.90	966.03	492788.97

Table 2 Resilient modulus test result for 20% RAP1 sample containing OMC tested at 20 °C

20% RAP1 Sample containing OMC tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.54	128628.59
2	41.37	21.19	182931.69
3	68.95	35.03	267323.52
4	103.42	52.72	386202.92
5	137.90	70.02	501069.57
6	20.68	20.99	115590.60
7	41.37	41.71	184345.12
8	68.95	69.45	274721.59
9	103.42	104.65	395386.73
10	137.90	139.85	508384.91
11	20.68	44.37	117093.66
12	41.37	83.23	197541.68
13	68.95	139.68	303383.10
14	103.42	208.54	417491.33
15	137.90	275.76	501483.26
16	20.68	63.56	125663.84
17	41.37	124.82	212020.67
18	68.95	208.84	319847.78
19	103.42	309.40	416822.53
20	137.90	414.44	483384.52
21	20.68	106.56	139929.09
22	41.37	206.53	233359.95
23	68.95	343.77	333864.82
24	103.42	518.89	425344.45
25	137.90	693.61	519195.89
26	20.68	147.23	148154.54
27	41.37	288.98	252803.16
28	68.95	484.01	365291.12
29	103.42	732.71	457853.23
30	137.90	970.51	545871.70

Table 3 Resilient modulus test result for 40% RAP1 sample containing OMC tested at 20 °C

40% RAP1 Sample containing OMC tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.32	313994.13
2	41.37	21.05	354817.98
3	68.95	34.71	471980.59
4	103.42	52.50	632538.80
5	137.90	70.08	788560.25
6	20.68	20.62	164570.95
7	41.37	41.75	244384.66
8	68.95	69.64	354549.09
9	103.42	104.92	499228.67
10	137.90	139.28	614529.69
11	20.68	41.62	150353.97
12	41.37	83.47	246204.88
13	68.95	138.94	377791.32
14	103.42	207.91	496587.98
15	137.90	274.88	570610.09
16	20.68	62.19	158606.99
17	41.37	125.00	263738.24
18	68.95	208.18	384699.86
19	103.42	308.49	473421.59
20	137.90	412.95	555000.36
21	20.68	103.62	173596.19
22	41.37	207.68	286511.63
23	68.95	342.63	386037.44
24	103.42	516.71	480833.46
25	137.90	692.70	580373.07
26	20.68	144.47	182814.48
27	41.37	288.15	308119.80
28	68.95	484.24	429329.62
29	103.42	731.06	525911.38
30	137.90	972.23	619900.71

Table 4 Resilient modulus test result for 60% RAP1 sample containing OMC tested at 20 °C

60% RAP1 Sample containing OMC tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.33	175306.09
2	41.37	21.20	268805.89
3	68.95	34.60	371723.93
4	103.42	51.99	494657.45
5	137.90	70.04	605214.87
6	20.68	19.96	156393.77
7	41.37	41.43	256264.33
8	68.95	69.20	375516.05
9	103.42	104.67	502524.36
10	137.90	140.13	602429.39
11	20.68	40.23	157007.41
12	41.37	82.98	265461.93
13	68.95	138.31	393566.52
14	103.42	205.51	514838.40
15	137.90	275.14	592287.21
16	20.68	60.40	165818.91
17	41.37	124.76	276865.86
18	68.95	208.37	405046.29
19	103.42	308.33	505916.58
20	137.90	413.04	583979.02
21	20.68	101.32	180346.16
22	41.37	207.60	304844.79
23	68.95	340.68	407211.24
24	103.42	521.36	513383.61
25	137.90	702.13	625382.04
26	20.68	145.42	196686.73
27	41.37	288.89	329072.96
28	68.95	484.77	456453.60
29	103.42	731.95	570458.40
30	137.90	971.37	839216.03

Table 5 Resilient modulus test result for 0% RAP1 sample containing OMC+2% tested at 20 °C

0% RAP1 Sample containing OMC+2% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	9.97	123423.05
2	41.37	21.17	178484.57
3	68.95	35.11	272632.48
4	103.42	52.86	389271.09
5	137.90	70.12	512963.03
6	20.68	20.20	121526.99
7	41.37	41.91	191453.61
8	68.95	69.57	295454.13
9	103.42	104.88	424558.45
10	137.90	139.43	544203.17
11	20.68	41.29	136585.14
12	41.37	83.45	225658.50
13	68.95	139.94	339408.20
14	103.42	208.26	473545.70
15	137.90	277.26	576994.63
16	20.68	62.16	152153.50
17	41.37	125.25	250617.52
18	68.95	208.06	370255.35
19	103.42	311.95	486866.37
20	137.90	412.88	561819.27
21	20.68	103.41	188764.66
22	41.37	206.57	274383.75
23	68.95	344.76	379266.79
24	103.42	519.66	471249.75
25	137.90	698.93	547974.60
26	20.68	149.33	164626.11
27	41.37	290.65	280478.71
28	68.95	485.72	399661.48
29	103.42	734.60	488941.69
30	137.90	977.06	530696.34

Table 6 Resilient modulus test result for 20% RAP1 sample containing OMC+2% tested at 20 °C

20% RAP1 Sample containing OMC+2% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	9.54	111963.96
2	41.37	21.20	170679.71
3	68.95	34.85	258884.34
4	103.42	52.57	367580.18
5	137.90	70.32	475793.39
6	20.68	19.86	115032.13
7	41.37	41.68	178050.20
8	68.95	69.45	267199.41
9	103.42	104.92	384286.18
10	137.90	140.18	489900.06
11	20.68	40.73	125312.21
12	41.37	83.12	201809.54
13	68.95	139.50	306837.37
14	103.42	208.17	423289.82
15	137.90	277.02	502317.52
16	20.68	61.63	135681.92
17	41.37	124.87	226320.40
18	68.95	208.20	331244.81
19	103.42	311.50	413568.21
20	137.90	412.80	486997.37
21	20.68	102.90	151670.86
22	41.37	208.12	248273.30
23	68.95	343.63	333906.19
24	103.42	519.46	433032.11
25	137.90	697.20	530441.24
26	20.68	143.99	161944.05
27	41.37	290.42	276472.86
28	68.95	483.47	380114.85
29	103.42	732.89	483667.20
30	137.90	974.90	588191.72

Table 7 Resilient modulus test result for 40% RAP1 sample containing OMC+2% tested at 20 °C

40% RAP1 Sample containing OMC+2% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	9.51	124671.00
2	41.37	20.82	198196.68
3	68.95	34.76	294157.91
4	103.42	52.37	410762.04
5	137.90	70.11	529427.71
6	20.68	19.37	120065.30
7	41.37	41.58	203347.07
8	68.95	69.56	313228.81
9	103.42	104.70	429295.15
10	137.90	139.39	540748.90
11	20.68	40.58	131214.12
12	41.37	83.43	227016.77
13	68.95	138.99	343110.69
14	103.42	208.30	460066.45
15	137.90	277.02	544051.49
16	20.68	61.40	143417.84
17	41.37	124.06	243309.08
18	68.95	208.17	359113.42
19	103.42	311.33	454867.80
20	137.90	412.12	528386.60
21	20.68	102.84	160799.52
22	41.37	207.10	269495.37
23	68.95	345.08	367256.13
24	103.42	518.38	453868.06
25	137.90	695.49	544113.54
26	20.68	143.89	172644.72
27	41.37	290.40	289690.11
28	68.95	483.45	393876.78
29	103.42	732.72	479626.88
30	137.90	971.77	561688.27

Table 8 Resilient modulus test result for 60% RAP1 sample containing OMC+2% tested at 20 °C

60% RAP1 Sample containing OMC+2% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	7.69	235842.06
2	41.37	19.96	298529.19
3	68.95	33.80	392808.10
4	103.42	52.96	510074.12
5	137.90	70.96	644342.62
6	20.68	16.46	197286.58
7	41.37	40.78	278113.81
8	68.95	70.00	392670.20
9	103.42	105.28	527814.33
10	137.90	139.66	649851.53
11	20.68	37.98	189991.92
12	41.37	85.12	302300.62
13	68.95	139.66	428488.46
14	103.42	208.37	556027.68
15	137.90	277.58	651292.54
16	20.68	61.36	197914.00
17	41.37	125.86	317944.82
18	68.95	208.31	453047.59
19	103.42	309.71	564673.70
20	137.90	416.60	646348.99
21	20.68	102.21	216150.63
22	41.37	207.70	348192.12
23	68.95	341.44	471677.22
24	103.42	519.25	581820.96
25	137.90	695.47	692881.71
26	20.68	143.33	231656.94
27	41.37	290.99	382141.91
28	68.95	481.24	519568.20
29	103.42	728.33	623092.98
30	137.90	966.29	711628.55

Table 9 Resilient modulus test result for 0% RAP1 sample containing OMC-4% tested at 20 °C

0% RAP1 Sample containing OMC-4% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	9.47	194101.20
2	41.37	21.19	261835.29
3	68.95	35.35	335140.35
4	103.42	53.45	448945.21
5	137.90	70.96	584041.08
6	20.68	19.45	180801.21
7	41.37	41.91	245542.98
8	68.95	70.60	335367.88
9	103.42	105.94	461638.45
10	137.90	139.92	599733.54
11	20.68	40.54	181869.90
12	41.37	84.12	263696.88
13	68.95	139.57	371579.14
14	103.42	207.98	523443.06
15	137.90	276.53	648438.11
16	20.68	62.03	200058.27
17	41.37	125.32	300956.14
18	68.95	207.03	427647.30
19	103.42	311.81	570368.77
20	137.90	412.98	657539.19
21	20.68	103.95	205408.60
22	41.37	207.02	315049.03
23	68.95	346.06	453930.12
24	103.42	522.19	555165.83
25	137.90	687.72	630842.69
26	20.68	144.99	202388.70
27	41.37	290.93	323405.47
28	68.95	485.98	450751.63
29	103.42	728.98	547995.29
30	137.90	957.79	604270.29

Table 10 Resilient modulus test result for 20% RAP1 sample containing OMC-4% tested at 20 °C

20% RAP1 Sample containing OMC-4% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	8.80	186496.28
2	41.37	20.62	227692.46
3	68.95	34.75	299384.14
4	103.42	52.33	388947.03
5	137.90	69.89	473780.12
6	20.68	18.86	167983.86
7	41.37	41.55	227520.09
8	68.95	69.27	317731.09
9	103.42	105.41	421724.71
10	137.90	139.61	516182.88
11	20.68	39.86	166439.43
12	41.37	83.05	255064.64
13	68.95	140.09	369531.40
14	103.42	207.49	493133.70
15	137.90	276.67	577070.48
16	20.68	60.95	179953.16
17	41.37	125.42	286022.10
18	68.95	207.89	410996.46
19	103.42	310.82	519519.94
20	137.90	413.68	567741.87
21	20.68	102.15	197872.63
22	41.37	207.06	315793.66
23	68.95	343.41	437755.02
24	103.42	521.20	494319.60
25	137.90	695.91	504923.74
26	20.68	143.30	174844.14
27	41.37	289.59	280506.29
28	68.95	485.35	381548.96
29	103.42	735.77	429639.89
30	137.90	972.65	405204.87

Table 11 Resilient modulus test result for 40% RAP1 sample containing OMC-4% tested at 20 °C

40% RAP1 Sample containing OMC-4% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.18	338504.99
2	41.37	20.91	476903.45
3	68.95	34.65	627050.57
4	103.42	52.34	808796.36
5	137.90	69.78	980448.23
6	20.68	20.84	324425.90
7	41.37	41.62	475386.60
8	68.95	69.24	622279.40
9	103.42	104.61	806645.20
10	137.90	140.36	977731.70
11	20.68	41.58	345523.85
12	41.37	83.16	486976.69
13	68.95	139.68	655712.07
14	103.42	209.49	843683.84
15	137.90	276.86	975380.59
16	20.68	62.36	344724.06
17	41.37	124.42	497394.66
18	68.95	209.51	672769.70
19	103.42	311.53	844269.89
20	137.90	415.50	944492.08
21	20.68	103.68	363277.85
22	41.37	208.29	523167.27
23	68.95	344.95	697873.51
24	103.42	518.69	818497.29
25	137.90	3.81	901489.48
26	20.68	144.60	319330.67
27	41.37	290.79	484735.89
28	68.95	484.27	657773.61
29	103.42	726.56	804190.67
30	137.90	971.06	851157.75

Table 12 Resilient modulus test result for 60% RAP1 sample containing OMC-4% tested at 20 °C

60% RAP1 Sample containing OMC-4% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	9.74	1004635.04
2	41.37	20.89	948690.98
3	68.95	34.96	1025774.37
4	103.42	51.78	1136883.38
5	137.90	69.98	1378220.56
6	20.68	20.61	571244.41
7	41.37	40.97	643198.09
8	68.95	68.98	758843.85
9	103.42	103.68	964300.71
10	137.90	138.91	1102037.27
11	20.68	42.06	399337.43
12	41.37	82.37	527931.54
13	68.95	136.94	710697.76
14	103.42	206.74	852647.02
15	137.90	275.19	955771.90
16	20.68	61.27	332796.13
17	41.37	122.76	537529.05
18	68.95	206.59	697266.78
19	103.42	311.24	809354.84
20	137.90	412.60	876047.82
21	20.68	102.99	338139.57
22	41.37	204.04	483674.10
23	68.95	342.75	635758.65
24	103.42	514.07	727465.81
25	137.90	687.40	823406.35
26	20.68	143.26	315979.82
27	41.37	287.66	468547.00
28	68.95	481.05	628781.15
29	103.42	719.95	745316.34
30	137.90	946.42	846448.63

Table 13 Resilient modulus test result for 0% RAP1 sample containing OMC-2% tested at 20 °C

0% RAP1 Sample containing OMC-2% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	9.35	166232.59
2	41.37	21.12	223886.55
3	68.95	35.00	303907.10
4	103.42	52.68	424565.35
5	137.90	70.26	565721.71
6	20.68	19.51	152291.39
7	41.37	41.95	222231.81
8	68.95	69.55	310808.75
9	103.42	105.21	439864.81
10	137.90	139.65	559964.58
11	20.68	40.56	154470.14
12	41.37	83.52	238227.64
13	68.95	139.16	343310.64
14	103.42	209.52	481281.62
15	137.90	277.48	585378.66
16	20.68	61.83	162033.68
17	41.37	125.07	256050.59
18	68.95	209.39	369896.82
19	103.42	312.01	486170.00
20	137.90	412.46	570030.93
21	20.68	103.17	171189.92
22	41.37	207.66	275266.28
23	68.95	345.61	378949.63
24	103.42	518.73	472449.43
25	137.90	699.67	552552.72
26	20.68	141.48	149650.70
27	41.37	291.17	258339.65
28	68.95	486.02	373399.35
29	103.42	732.29	471925.43
30	137.90	975.78	549436.29

Table 14 Resilient modulus test result for 20% RAP1 sample containing OMC-2% tested at 20 °C

20% RAP1 Sample containing OMC-2% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	9.61	133772.08
2	41.37	20.86	187475.34
3	68.95	34.92	272604.90
4	103.42	52.75	391043.04
5	137.90	70.14	501821.10
6	20.68	19.80	130042.01
7	41.37	41.86	191488.09
8	68.95	69.42	284856.89
9	103.42	104.91	408500.56
10	137.90	139.71	519257.94
11	20.68	41.07	127773.64
12	41.37	83.15	221728.49
13	68.95	138.28	341076.73
14	103.42	209.26	463975.78
15	137.90	277.38	546733.55
16	20.68	62.94	143190.31
17	41.37	124.62	234097.68
18	68.95	208.59	350956.92
19	103.42	311.86	458659.92
20	137.90	411.53	529999.97
21	20.68	107.00	162219.84
22	41.37	207.46	262462.71
23	68.95	344.17	361836.85
24	103.42	518.82	454688.54
25	137.90	697.35	531813.29
26	20.68	143.87	159179.25
27	41.37	291.77	282919.46
28	68.95	485.71	393263.15
29	103.42	731.82	480281.88
30	137.90	972.74	571451.25

Table 15 Resilient modulus test result for 40% RAP1 sample containing OMC-2% tested at 20 °C

40% RAP1 Sample containing OMC-2% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	9.26	150036.81
2	41.37	20.59	222528.28
3	68.95	34.69	320571.73
4	103.42	52.42	444291.25
5	137.90	70.09	562357.07
6	20.68	19.17	146134.37
7	41.37	41.71	230939.89
8	68.95	69.48	335947.03
9	103.42	104.64	463555.20
10	137.90	139.45	581041.86
11	20.68	40.29	152973.97
12	41.37	82.94	252161.95
13	68.95	138.49	372447.88
14	103.42	208.51	499952.62
15	137.90	277.89	575657.05
16	20.68	61.91	164888.11
17	41.37	124.62	269212.68
18	68.95	208.21	390739.67
19	103.42	311.66	499194.20
20	137.90	411.86	577084.27
21	20.68	102.75	181573.43
22	41.37	207.21	293785.60
23	68.95	345.81	403177.81
24	103.42	517.26	487528.27
25	137.90	695.97	570086.09
26	20.68	143.98	179932.47
27	41.37	289.84	300873.41
28	68.95	483.00	414030.16
29	103.42	726.40	515769.19
30	137.90	970.44	612364.74

Table 16 Resilient modulus test result for 60% RAP1 sample containing OMC-2% tested at 20 °C

60% RAP1 Sample containing OMC-2% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	9.56	163192.00
2	41.37	20.92	246901.25
3	68.95	34.92	353314.93
4	103.42	52.31	484660.05
5	137.90	69.70	604194.45
6	20.68	19.62	151333.02
7	41.37	41.68	248080.25
8	68.95	69.13	370648.35
9	103.42	104.83	502882.89
10	137.90	139.01	615494.96
11	20.68	41.56	162047.47
12	41.37	83.14	274218.28
13	68.95	138.53	400619.86
14	103.42	209.00	521698.68
15	137.90	278.10	598878.59
16	20.68	61.40	169714.44
17	41.37	124.40	284787.94
18	68.95	208.30	407114.72
19	103.42	310.79	511556.50
20	137.90	411.30	610503.15
21	20.68	102.62	189757.50
22	41.37	206.86	309553.91
23	68.95	344.07	415064.37
24	103.42	515.10	507626.48
25	137.90	689.54	602477.66
26	20.68	143.31	193142.83
27	41.37	289.35	317296.72
28	68.95	479.51	433714.69
29	103.42	730.38	524711.69
30	137.90	969.95	632814.59

Table 17 Resilient modulus test result for 0% RAP1 sample containing OMC tested at 60 °C

0% RAP1 Sample containing OMC tested at 60 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.20	160751.26
2	41.37	20.75	212351.62
3	68.95	35.25	286346.15
4	103.42	52.86	390153.61
5	137.90	69.71	502076.20
6	20.68	20.86	158979.31
7	41.37	41.98	220832.17
8	68.95	69.58	305127.47
9	103.42	104.89	422634.81
10	137.90	140.23	549243.24
11	20.68	41.80	158269.15
12	41.37	83.54	237427.85
13	68.95	139.84	347288.91
14	103.42	211.00	468016.11
15	137.90	278.13	563605.02
16	20.68	62.73	169238.71
17	41.37	125.04	259477.28
18	68.95	211.02	372799.51
19	103.42	312.46	484915.15
20	137.90	413.30	550904.87
21	20.68	104.57	184455.43
22	41.37	209.15	287642.37
23	68.95	347.03	395152.31
24	103.42	519.06	485142.68
25	137.90	691.74	559054.48
26	20.68	146.12	183490.17
27	41.37	292.06	297322.61
28	68.95	485.36	405666.82
29	103.42	729.40	511032.49
30	137.90	973.07	597899.54

Table 18 Resilient modulus test result for 20% RAP1 sample containing OMC tested at 60 °C

20% RAP1 Sample containing OMC tested at 60 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.44	114384.02
2	41.37	20.97	147816.70
3	68.95	34.78	200665.01
4	103.42	52.45	258001.81
5	137.90	71.86	364353.43
6	20.68	20.93	109530.11
7	41.37	41.70	146251.59
8	68.95	69.65	210145.30
9	103.42	106.22	297239.87
10	137.90	139.96	393483.78
11	20.68	41.71	115025.23
12	41.37	83.30	168735.39
13	68.95	139.21	254368.27
14	103.42	210.79	351039.66
15	137.90	277.82	419215.02
16	20.68	62.31	122506.04
17	41.37	124.53	190440.08
18	68.95	210.88	279665.13
19	103.42	310.04	347619.86
20	137.90	412.08	409203.83
21	20.68	104.40	130490.17
22	41.37	208.84	211606.99
23	68.95	344.01	271487.95
24	103.42	520.11	330562.23
25	137.90	696.15	405439.29
26	20.68	147.13	117893.45
27	41.37	288.79	206573.81
28	68.95	484.12	290483.01
29	103.42	730.47	571699.46
30	137.90	965.27	396180.92

Table 19 Resilient modulus test result for 40% RAP1 sample containing OMC tested at 60 °C

40% RAP1 Sample containing OMC tested at 60 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.19	185303.49
2	41.37	20.70	270963.95
3	68.95	34.49	374847.25
4	103.42	52.28	479164.93
5	137.90	69.89	581579.65
6	20.68	20.86	183331.59
7	41.37	41.44	263627.93
8	68.95	69.13	368835.03
9	103.42	104.50	485197.84
10	137.90	139.13	579132.01
11	20.68	41.47	176147.25
12	41.37	82.63	277824.23
13	68.95	138.61	379839.06
14	103.42	208.69	488707.27
15	137.90	276.93	562777.65
16	20.68	61.69	176050.73
17	41.37	124.15	267847.52
18	68.95	208.50	380611.27
19	103.42	309.88	478771.93
20	137.90	413.96	550043.03
21	20.68	103.21	181973.32
22	41.37	207.88	289979.69
23	68.95	344.54	387788.71
24	103.42	515.64	472883.80
25	137.90	689.08	567576.40
26	20.68	144.56	190984.77
27	41.37	289.48	306051.37
28	68.95	479.88	422779.60
29	103.42	721.80	508295.28
30	137.90	965.89	683828.89

Table 20 Resilient modulus test result for 60% RAP1 sample containing OMC tested at 60 °C

60% RAP1 Sample containing OMC tested at 60 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.21	301549.09
2	41.37	20.57	436934.54
3	68.95	34.60	629994.63
4	103.42	51.91	896787.25
5	137.90	69.78	1123149.02
6	20.68	20.75	271646.53
7	41.37	41.39	373737.20
8	68.95	68.58	489644.96
9	103.42	103.58	693653.92
10	137.90	138.85	886086.59
11	20.68	40.81	222652.39
12	41.37	81.71	335478.19
13	68.95	137.40	500145.67
14	103.42	207.62	625961.20
15	137.90	276.82	711525.13
16	20.68	61.03	211282.93
17	41.37	123.43	324356.95
18	68.95	206.54	463934.41
19	103.42	310.73	540514.48
20	137.90	412.22	598223.59
21	20.68	103.58	224748.39
22	41.37	206.04	320819.94
23	68.95	343.94	444842.83
24	103.42	501.65	522519.16
25	137.90	673.40	672038.86
26	20.68	142.29	229464.41
27	41.37	288.64	378329.11
28	68.95	477.07	500538.67
29	103.42	714.90	583517.07
30	137.90	945.99	700010.89

Table 21 Resilient modulus test result for 0% RAP1 sample containing OMC tested at - 20 °C

0% RAP1 Sample containing OMC tested at -20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.30	13644469.00
2	41.37	21.65	29482222.25
3	68.95	35.81	21089386.24
4	103.42	53.06	25501906.61
5	137.90	69.82	25784012.49
6	20.68	21.45	22895185.15
7	41.37	42.11	24337340.79
8	68.95	69.60	24685270.91
9	103.42	105.34	27160399.04
10	137.90	140.20	26243589.41
11	20.68	42.25	29039523.69
12	41.37	83.07	26880740.80
13	68.95	141.63	27354789.82
14	103.42	209.66	26864379.54
15	137.90	275.78	26986644.27
16	20.68	62.36	29404435.60
17	41.37	125.13	27383237.59
18	68.95	209.32	27410520.14
19	103.42	310.59	26389978.89
20	137.90	412.38	26314915.67
21	20.68	103.73	30034313.02
22	41.37	207.46	27752189.82
23	68.95	344.11	26736985.12
24	103.42	517.60	26152095.99
25	137.90	701.20	26078977.09
26	20.68	146.03	29143696.57
27	41.37	290.37	27426736.61
28	68.95	482.60	26839868.68
29	103.42	728.86	25665912.20
30	137.90	950.57	25141359.08

Table 22 Resilient modulus test result for 20% RAP1 sample containing OMC tested at - 20 °C

20% RAP1 Sample containing OMC tested at -20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.00	12134937.79
2	41.37	22.04	31479460.98
3	68.95	35.43	30013318.49
4	103.42	51.61	29427926.04
5	137.90	68.80	32013652.97
6	20.68	29.24	31923917.70
7	41.37	41.65	28317670.21
8	68.95	70.09	30327002.35
9	103.42	109.76	31871476.18
10	137.90	142.07	31171258.45
11	20.68	41.80	33309481.17
12	41.37	85.01	31482667.04
13	68.95	142.44	31262393.35
14	103.42	208.09	30216155.34
15	137.90	276.34	29021204.32
16	20.68	62.07	30870964.20
17	41.37	128.45	30937291.77
18	68.95	207.46	30310441.14
19	103.42	310.98	28701901.23
20	137.90	410.12	29421148.49
21	20.68	106.46	33606714.15
22	41.37	207.50	28687656.66
23	68.95	344.12	28195502.01
24	103.42	515.59	28072547.81
25	137.90	691.88	27434224.31
26	20.68	149.72	31439981.60
27	41.37	290.55	28436956.40
28	68.95	480.59	27490561.37
29	103.42	726.14	27463340.87
30	137.90	967.05	26970607.06

Table 23 Resilient modulus test result for 40% RAP1 sample containing OMC tested at - 20 °C

40% RAP1 Sample containing OMC tested at -20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.21	10777629.04
2	41.37	21.97	22933326.94
3	68.95	35.89	18595118.26
4	103.42	51.96	26657047.30
5	137.90	67.36	21846230.61
6	20.68	22.06	16679085.97
7	41.37	42.15	21413074.39
8	68.95	69.46	24969658.95
9	103.42	110.43	26094848.82
10	137.90	143.18	25748704.44
11	20.68	42.38	25600936.01
12	41.37	84.81	24031592.79
13	68.95	142.72	25087359.35
14	103.42	208.15	24426152.15
15	137.90	274.97	24622645.83
16	20.68	61.28	23984480.91
17	41.37	131.66	25170710.06
18	68.95	207.44	25095012.53
19	103.42	309.40	24809038.69
20	137.90	411.60	24817753.66
21	20.68	108.63	25132340.74
22	41.37	206.66	23866966.67
23	68.95	342.76	24279624.77
24	103.42	517.30	24126657.70
25	137.90	693.43	24607373.94
26	20.68	153.32	25398071.57
27	41.37	288.95	24202113.92
28	68.95	483.87	24382756.55
29	103.42	727.65	24270813.28
30	137.90	968.27	24129098.44

Table 24 Resilient modulus test result for 60% RAP1 sample containing OMC tested at -20 °C

60% RAP1 Sample containing OMC tested at -20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	11.16	13755398.74
2	41.37	21.99	17295346.25
3	68.95	36.17	23559715.62
4	103.42	53.10	24744614.08
5	137.90	69.44	24504807.54
6	20.68	21.84	17969453.54
7	41.37	42.71	27518064.56
8	68.95	72.57	24612124.43
9	103.42	108.08	24099526.83
10	137.90	146.35	24157787.52
11	20.68	43.53	24042941.56
12	41.37	83.94	25585546.91
13	68.95	144.78	23901288.77
14	103.42	209.06	23543430.20
15	137.90	274.69	23797495.10
16	20.68	63.74	25516426.97
17	41.37	128.91	23481632.49
18	68.95	207.66	22823748.57
19	103.42	311.08	22817825.97
20	137.90	410.23	22381346.49
21	20.68	104.64	24323599.53
22	41.37	205.13	22511464.34
23	68.95	346.14	22374251.78
24	103.42	514.31	21824712.07
25	137.90	689.82	21233645.24
26	20.68	148.24	24167481.55
27	41.37	287.22	22357807.79
28	68.95	480.06	21629128.50
29	103.42	726.34	21277426.94
30	137.90	965.71	20734699.25

Table 25 Resilient modulus test result for 0% RAP1 sample containing OMC tested after FT conditioning

0% RAP1 Sample containing OMC tested after freeze-thaw conditioning			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.34	149057.75
2	41.37	20.93	205353.44
3	68.95	35.10	286249.63
4	103.42	53.34	410293.20
5	137.90	71.03	546188.86
6	20.68	20.48	126112.00
7	41.37	42.06	193370.35
8	68.95	69.84	283146.99
9	103.42	105.36	422648.60
10	137.90	139.03	547340.28
11	20.68	40.32	134337.45
12	41.37	82.45	219991.01
13	68.95	138.02	332520.34
14	103.42	207.70	468305.68
15	137.90	277.53	564411.70
16	20.68	62.50	153401.45
17	41.37	124.11	246859.88
18	68.95	208.79	357348.36
19	103.42	312.43	468995.16
20	137.90	414.42	556400.00
21	20.68	101.91	168776.76
22	41.37	206.37	280837.24
23	68.95	345.85	376846.73
24	103.42	517.40	474193.81
25	137.90	689.10	551828.77
26	20.68	144.58	172299.98
27	41.37	289.28	279968.50
28	68.95	482.32	388698.82
29	103.42	722.54	490879.12
30	137.90	959.83	576546.48

Table 26 Resilient modulus test result for 20% RAP1 sample containing OMC tested after FT conditioning

20% RAP1 Sample containing OMC tested after freeze -thaw conditioning			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.37	186365.28
2	41.37	21.11	266434.09
3	68.95	35.24	365098.07
4	103.42	52.52	501083.36
5	137.90	69.86	642122.51
6	20.68	20.95	182345.64
7	41.37	42.38	264600.09
8	68.95	69.56	376826.05
9	103.42	103.85	533468.03
10	137.90	138.16	664054.73
11	20.68	42.11	187034.07
12	41.37	82.88	293578.75
13	68.95	137.37	422552.08
14	103.42	206.39	570561.83
15	137.90	275.99	677265.09
16	20.68	62.61	203491.86
17	41.37	123.80	306561.58
18	68.95	205.94	435989.96
19	103.42	310.96	571713.25
20	137.90	413.73	646824.73
21	20.68	103.65	210834.77
22	41.37	205.48	328045.64
23	68.95	345.18	451165.32
24	103.42	515.47	552132.14
25	137.90	0.26	651692.43
26	20.68	144.74	206187.71
27	41.37	287.75	331941.18
28	68.95	481.85	467967.84
29	103.42	726.02	588260.67
30	137.90	962.29	682746.42

Table 27 Resilient modulus test result for 40% RAP1 sample containing OMC tested after FT conditioning

40% RAP1 Sample containing OMC tested after freeze -thaw conditioning			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	8.74	638151.13
2	41.37	20.45	572051.09
3	68.95	34.75	706236.85
4	103.42	52.01	982006.45
5	137.90	69.89	1214752.76
6	20.68	20.19	322950.42
7	41.37	41.42	433659.53
8	68.95	68.83	586916.19
9	103.42	103.54	845138.63
10	137.90	137.48	1057841.88
11	20.68	41.38	282485.09
12	41.37	82.72	415864.16
13	68.95	137.27	597058.38
14	103.42	207.44	775611.90
15	137.90	275.25	859500.41
16	20.68	62.09	252520.48
17	41.37	124.01	382224.64
18	68.95	206.47	557999.58
19	103.42	309.05	671218.38
20	137.90	412.48	758430.16
21	20.68	102.75	247370.09
22	41.37	206.73	384761.91
23	68.95	344.17	501641.84
24	103.42	514.83	598575.22
25	137.90	661.37	698756.04
26	20.68	143.20	231477.68
27	41.37	285.22	368586.81
28	68.95	455.00	512887.18
29	103.42	693.88	627029.89
30	137.90	930.51	729913.45

Table 28 Resilient modulus test result for 60% RAP1 sample containing OMC tested after FT conditioning

60% RAP1 Sample containing OMC tested after freeze -thaw conditioning			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.29	558558.05
2	41.37	20.78	701424.31
3	68.95	34.47	899979.53
4	103.42	51.83	1246441.07
5	137.90	69.35	1542674.30
6	20.68	20.50	399020.27
7	41.37	41.62	545547.65
8	68.95	68.75	750053.04
9	103.42	103.24	971629.84
10	137.90	137.79	1151362.37
11	20.68	40.49	334154.40
12	41.37	81.87	503730.95
13	68.95	135.93	692861.03
14	103.42	206.69	860803.52
15	137.90	274.03	944816.13
16	20.68	61.76	320502.78
17	41.37	122.79	459025.34
18	68.95	204.91	646431.73
19	103.42	306.98	783154.76
20	137.90	410.52	846414.16
21	20.68	102.03	300170.14
22	41.37	201.43	448048.89
23	68.95	339.42	599037.17
24	103.42	505.88	723370.33
25	137.90	680.31	827474.26
26	20.68	142.35	285808.36
27	41.37	284.70	446207.99
28	68.95	477.89	617060.07
29	103.42	714.05	730127.19
30	137.90	953.90	837313.08

Table 29 Resilient modulus test result for 0% RAP2 sample containing OMC tested at 20 °C

0% RAP2 Sample containing OMC tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.29	86170.67
2	41.37	21.04	139791.20
3	68.95	35.01	212392.99
4	103.42	52.58	311036.28
5	137.90	70.11	414181.84
6	20.68	20.91	88659.68
7	41.37	41.60	145582.79
8	68.95	69.47	227023.66
9	103.42	104.74	338387.78
10	137.90	139.58	436617.38
11	20.68	41.98	108268.37
12	41.37	83.47	177009.10
13	68.95	139.88	275369.70
14	103.42	210.19	384982.55
15	137.90	277.18	465630.52
16	20.68	62.27	121830.36
17	41.37	124.82	206256.66
18	68.95	209.45	304941.31
19	103.42	311.99	394200.84
20	137.90	416.42	453130.32
21	20.68	103.55	147540.91
22	41.37	207.81	231422.52
23	68.95	347.08	313490.81
24	103.42	518.39	392111.73
25	137.90	1.63	455943.39
26	20.68	145.06	152849.87
27	41.37	289.47	242819.55
28	68.95	483.57	340311.42
29	103.42	727.35	407728.35
30	137.90	942.86	521154.00

Table 30 Resilient modulus test result for 20% RAP2 sample containing OMC tested at 20 °C

20% RAP2 Sample containing OMC tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.25	131503.70
2	41.37	20.85	179691.16
3	68.95	34.44	270136.58
4	103.42	52.36	376770.89
5	137.90	70.12	488714.17
6	20.68	20.58	123809.15
7	41.37	41.69	188095.87
8	68.95	69.11	284222.57
9	103.42	104.36	401185.23
10	137.90	139.94	509667.33
11	20.68	41.71	134034.08
12	41.37	82.98	214882.00
13	68.95	138.81	326280.59
14	103.42	209.71	443670.72
15	137.90	276.89	526435.38
16	20.68	62.18	142149.21
17	41.37	124.32	232870.42
18	68.95	208.66	348343.81
19	103.42	310.45	454854.01
20	137.90	414.78	525270.17
21	20.68	103.55	163529.85
22	41.37	207.36	266220.36
23	68.95	345.17	375019.62
24	103.42	515.01	462576.14
25	137.90	688.72	540576.53
26	20.68	144.29	172196.56
27	41.37	289.81	284856.89
28	68.95	482.56	400047.59
29	103.42	724.95	490513.70
30	137.90	968.20	584571.97

Table 31 Resilient modulus test result for 40% RAP2 sample containing OMC tested at 20 °C

40% RAP2 Sample containing OMC tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.21	163516.06
2	41.37	20.82	240758.02
3	68.95	34.70	330872.49
4	103.42	52.39	446463.09
5	137.90	69.91	551042.77
6	20.68	20.67	151401.97
7	41.37	41.35	234283.84
8	68.95	68.92	342952.11
9	103.42	104.43	458590.97
10	137.90	138.01	550808.35
11	20.68	41.47	157752.04
12	41.37	82.96	255064.64
13	68.95	137.75	367366.44
14	103.42	208.97	472628.70
15	137.90	275.70	532420.03
16	20.68	61.83	159868.73
17	41.37	123.63	259284.23
18	68.95	208.35	366897.60
19	103.42	308.97	449593.31
20	137.90	411.08	500738.62
21	20.68	102.71	167694.28
22	41.37	206.14	265330.93
23	68.95	341.77	347675.02
24	103.42	512.63	411451.52
25	137.90	650.23	494078.29
26	20.68	143.11	174340.83
27	41.37	252.78	274625.07
28	68.95	447.01	378866.90
29	103.42	680.07	444201.61
30	137.90	918.01	547740.18

Table 32 Resilient modulus test result for 60% RAP2 sample containing OMC tested at 20 °C

60% RAP2 Sample containing OMC tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.30	210855.46
2	41.37	20.80	300859.62
3	68.95	34.59	413657.84
4	103.42	52.04	546044.07
5	137.90	70.09	668853.48
6	20.68	20.91	183138.54
7	41.37	41.50	295633.39
8	68.95	68.95	419242.59
9	103.42	103.87	555027.94
10	137.90	137.45	650672.01
11	20.68	41.40	183028.22
12	41.37	82.12	304562.10
13	68.95	135.92	436017.54
14	103.42	206.10	548843.34
15	137.90	274.17	617873.65
16	20.68	61.49	188778.45
17	41.37	122.42	313035.76
18	68.95	206.23	438347.97
19	103.42	303.51	536205.25
20	137.90	408.21	598816.54
21	20.68	102.26	201354.48
22	41.37	202.82	328059.43
23	68.95	340.85	439382.18
24	103.42	477.72	528614.12
25	137.90	645.97	613791.95
26	20.68	140.78	208614.66
27	41.37	285.84	345427.33
28	68.95	443.25	472828.65
29	103.42	677.35	553738.62
30	137.90	907.89	1555298.60

Table 33 Resilient modulus test result for 80% RAP2 sample containing OMC tested at 20 °C

80% RAP2 Sample containing OMC tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.06	584241.02
2	41.37	20.77	925786.60
3	68.95	34.58	1295056.00
4	103.42	51.83	1726743.63
5	137.90	69.84	2025286.61
6	20.68	20.74	553614.51
7	41.37	41.29	712076.71
8	68.95	68.74	809830.58
9	103.42	104.07	1001160.08
10	137.90	139.68	1097631.52
11	20.68	41.09	371972.14
12	41.37	82.33	527869.49
13	68.95	138.48	691240.76
14	103.42	208.28	811140.58
15	137.90	277.15	873717.40
16	20.68	61.67	340442.42
17	41.37	123.11	482171.04
18	68.95	206.50	637730.55
19	103.42	310.08	742006.85
20	137.90	411.95	813484.80
21	20.68	102.24	304796.52
22	41.37	205.68	470732.64
23	68.95	344.61	614205.64
24	103.42	513.47	685876.64
25	137.90	684.20	774563.90
26	20.68	143.61	293723.54
27	41.37	289.05	455577.96
28	68.95	480.69	602263.92
29	103.42	722.58	690123.81
30	137.90	953.14	789463.47

Table 34 Resilient modulus test result for 0% RAP2 sample containing OMC+2% tested at 20 °C

0% RAP2 Sample containing OMC+2% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.01	107751.26
2	41.37	20.74	126608.42
3	68.95	34.65	190964.08
4	103.42	52.30	293840.75
5	137.90	69.91	418311.80
6	20.68	20.73	101235.72
7	41.37	41.52	143907.37
8	68.95	69.01	220101.33
9	103.42	104.75	333478.71
10	137.90	139.61	451227.37
11	20.68	41.09	117976.19
12	41.37	82.51	179001.68
13	68.95	138.78	273204.75
14	103.42	210.03	393938.84
15	137.90	277.17	482860.52
16	20.68	62.04	136433.45
17	41.37	123.34	209407.56
18	68.95	207.69	297701.82
19	103.42	310.07	383734.60
20	137.90	411.89	461762.56
21	20.68	103.09	141728.62
22	41.37	206.70	213116.94
23	68.95	343.33	275121.49
24	103.42	512.52	361547.27
25	137.90	665.13	456494.97
26	20.68	142.96	143148.94
27	41.37	289.43	229884.99
28	68.95	453.49	311263.80
29	103.42	723.95	382085.78
30	137.90	965.27	408382.24

Table 35 Resilient modulus test result for 20% RAP2 sample containing OMC+2% tested at 20 °C

20% RAP2 Sample containing OMC+2% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.18	129090.54
2	41.37	20.85	185641.33
3	68.95	35.01	261918.03
4	103.42	52.81	357548.31
5	137.90	70.15	440499.13
6	20.68	20.58	120154.93
7	41.37	41.62	184745.01
8	68.95	69.35	266909.83
9	103.42	104.63	369214.24
10	137.90	139.41	456074.39
11	20.68	41.74	129497.33
12	41.37	82.93	201547.54
13	68.95	138.40	299859.88
14	103.42	208.45	410403.52
15	137.90	275.65	477579.13
16	20.68	62.49	139742.93
17	41.37	123.87	228099.25
18	68.95	207.98	333078.82
19	103.42	309.93	420387.12
20	137.90	413.23	473035.49
21	20.68	103.30	150760.76
22	41.37	205.97	244577.72
23	68.95	344.21	336057.35
24	103.42	515.08	398317.01
25	137.90	687.19	463141.51
26	20.68	143.47	146789.38
27	41.37	288.71	245736.03
28	68.95	481.25	342193.68
29	103.42	710.83	401212.80
30	137.90	956.71	507785.06

Table 36 Resilient modulus test result for 40% RAP2 sample containing OMC+2% tested at 20 °C

40% RAP2 Sample containing OMC+2% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.27	141039.15
2	41.37	20.90	231677.62
3	68.95	34.90	332361.76
4	103.42	52.54	443388.03
5	137.90	70.24	538390.89
6	20.68	20.90	143438.52
7	41.37	41.64	237503.69
8	68.95	68.94	340849.21
9	103.42	104.67	460225.03
10	137.90	138.54	550698.03
11	20.68	41.27	149595.54
12	41.37	82.77	253534.00
13	68.95	137.90	369862.34
14	103.42	204.86	475159.07
15	137.90	275.52	549043.29
16	20.68	61.62	162647.32
17	41.37	123.64	268019.89
18	68.95	207.48	383086.49
19	103.42	309.02	474593.70
20	137.90	409.89	535060.72
21	20.68	102.57	197121.10
22	41.37	205.79	303645.10
23	68.95	342.17	396813.95
24	103.42	513.97	475317.65
25	137.90	682.11	558509.79
26	20.68	143.62	195397.41
27	41.37	288.46	316951.98
28	68.95	478.78	427957.57
29	103.42	682.74	521643.53
30	137.90	911.58	594907.21

Table 37 Resilient modulus test result for 60% RAP2 sample containing OMC+2% tested at 20 °C

60% RAP2 Sample containing OMC+2% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.26	179863.53
2	41.37	20.48	284670.73
3	68.95	34.63	398323.90
4	103.42	52.51	539349.26
5	137.90	69.75	656732.50
6	20.68	20.70	166577.33
7	41.37	41.73	280306.35
8	68.95	68.85	411092.99
9	103.42	103.98	550318.82
10	137.90	137.69	661014.14
11	20.68	41.41	178691.42
12	41.37	82.32	299432.40
13	68.95	134.81	436072.70
14	103.42	205.84	556427.57
15	137.90	272.78	633448.90
16	20.68	61.26	189957.45
17	41.37	122.70	313828.65
18	68.95	204.55	445518.51
19	103.42	308.43	553897.20
20	137.90	408.12	622162.19
21	20.68	102.47	204732.91
22	41.37	202.10	330989.70
23	68.95	342.34	453219.96
24	103.42	511.44	533840.35
25	137.90	683.53	606249.09
26	20.68	143.80	209352.40
27	41.37	287.47	342214.37
28	68.95	478.51	465396.10
29	103.42	716.95	549567.29
30	137.90	933.58	635089.86

Table 38 Resilient modulus test result for 80% RAP2 sample containing OMC+2% tested at 20 °C

80% RAP2 Sample containing OMC+2% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.31	260166.76
2	41.37	20.80	411913.47
3	68.95	34.80	538921.79
4	103.42	52.23	678906.04
5	137.90	69.73	796089.33
6	20.68	20.67	252003.37
7	41.37	41.03	396669.16
8	68.95	68.32	540500.69
9	103.42	104.13	675065.66
10	137.90	135.41	766200.56
11	20.68	41.13	254513.06
12	41.37	82.22	402743.44
13	68.95	136.03	539438.89
14	103.42	205.65	648451.90
15	137.90	272.74	717116.78
16	20.68	61.50	262111.08
17	41.37	122.59	400302.70
18	68.95	204.77	531282.40
19	103.42	304.53	631690.74
20	137.90	409.40	695563.77
21	20.68	101.98	274680.22
22	41.37	201.89	410899.94
23	68.95	340.07	528483.12
24	103.42	509.17	597934.01
25	137.90	679.06	677989.03
26	20.68	143.20	266027.30
27	41.37	284.15	410189.78
28	68.95	474.78	539687.10
29	103.42	679.50	624816.67
30	137.90	906.84	756444.47

Table 39 Resilient modulus test result for 0% RAP2 sample containing OMC-4% tested at 20 °C

0% RAP2 Sample containing OMC-4% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.33	198824.11
2	41.37	20.97	282140.35
3	68.95	34.83	373495.88
4	103.42	53.15	499931.94
5	137.90	70.46	628946.63
6	20.68	20.78	199051.63
7	41.37	41.79	278899.82
8	68.95	70.42	386947.55
9	103.42	105.37	518954.57
10	137.90	139.56	658332.08
11	20.68	41.76	205429.28
12	41.37	83.94	310091.70
13	68.95	139.15	443036.40
14	103.42	209.25	597072.17
15	137.90	277.22	723715.06
16	20.68	63.10	215730.05
17	41.37	124.41	334312.98
18	68.95	207.92	483763.73
19	103.42	312.08	634510.70
20	137.90	415.86	744654.44
21	20.68	104.81	245977.35
22	41.37	206.83	382541.80
23	68.95	345.58	541383.21
24	103.42	516.33	669474.01
25	137.90	686.32	758423.27
26	20.68	144.53	242467.92
27	41.37	291.00	384024.18
28	68.95	483.06	541976.16
29	103.42	717.69	675796.50
30	137.90	936.72	752976.41

Table 40 Resilient modulus test result for 20% RAP2 sample containing OMC-4% tested at 20 °C

20% RAP2 Sample containing OMC-4% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.36	515114.19
2	41.37	20.72	509150.23
3	68.95	34.76	632221.64
4	103.42	52.70	801867.13
5	137.90	70.16	974194.69
6	20.68	20.89	336905.41
7	41.37	41.68	442236.61
8	68.95	69.21	586212.92
9	103.42	104.01	778914.49
10	137.90	138.28	949504.57
11	20.68	41.10	301783.51
12	41.37	82.60	430791.31
13	68.95	138.05	596741.22
14	103.42	207.87	776011.80
15	137.90	276.67	896807.94
16	20.68	62.51	288242.21
17	41.37	123.65	416429.53
18	68.95	206.53	579104.43
19	103.42	308.78	735525.78
20	137.90	411.12	833534.75
21	20.68	103.35	270391.69
22	41.37	205.60	412561.57
23	68.95	340.96	568810.56
24	103.42	492.40	686062.80
25	137.90	685.86	749529.03
26	20.68	143.52	256953.80
27	41.37	289.28	389608.93
28	68.95	481.30	533771.40
29	103.42	722.22	653195.49
30	137.90	956.90	737159.84

Table 41 Resilient modulus test result for 40% RAP2 sample containing OMC-4% tested at 20 °C

40% RAP2 Sample containing OMC-4% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.34	297239.87
2	41.37	20.62	387078.55
3	68.95	34.75	496408.71
4	103.42	52.66	654022.86
5	137.90	70.24	820510.56
6	20.68	20.66	253775.32
7	41.37	41.47	358699.73
8	68.95	69.51	490065.54
9	103.42	104.61	649548.16
10	137.90	139.25	810106.37
11	20.68	41.51	241819.81
12	41.37	82.95	360126.95
13	68.95	138.41	519085.57
14	103.42	206.66	679126.67
15	137.90	275.76	786519.40
16	20.68	62.14	247059.83
17	41.37	123.77	374985.15
18	68.95	207.03	522512.26
19	103.42	310.64	655905.13
20	137.90	409.29	736966.79
21	20.68	103.25	244488.08
22	41.37	205.77	382645.22
23	68.95	344.15	522298.53
24	103.42	513.66	632793.90
25	137.90	684.24	715427.57
26	20.68	144.16	241957.71
27	41.37	288.27	378025.74
28	68.95	479.98	531709.87
29	103.42	717.46	636241.28
30	137.90	959.18	705319.85

Table 42 Resilient modulus test result for 60% RAP2 sample containing OMC-4% tested at 20 °C

60% RAP2 Sample containing OMC-4% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.10	566087.13
2	41.37	20.93	696522.14
3	68.95	35.31	1233520.29
4	103.42	52.68	1687409.04
5	137.90	71.08	1609401.76
6	20.68	20.96	469946.64
7	41.37	42.05	801639.61
8	68.95	69.98	985343.51
9	103.42	104.31	1163435.09
10	137.90	137.67	1253970.14
11	20.68	41.42	445470.25
12	41.37	83.43	708381.12
13	68.95	136.73	929385.66
14	103.42	207.49	1017879.87
15	137.90	276.23	1108097.77
16	20.68	62.36	543086.22
17	41.37	123.49	711132.13
18	68.95	206.91	869208.23
19	103.42	310.82	975615.01
20	137.90	415.13	1064247.11
21	20.68	104.41	547257.55
22	41.37	205.79	769123.93
23	68.95	345.96	863395.95
24	103.42	515.74	882542.69
25	137.90	688.69	916078.78
26	20.68	142.71	422055.65
27	41.37	287.17	554565.99
28	68.95	479.43	715868.83
29	103.42	688.74	824171.67
30	137.90	916.64	876509.77

Table 43 Resilient modulus test result for 80% RAP2 sample containing OMC-4% tested at 20 °C

80% RAP2 Sample containing OMC-4% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.31	1380075.25
2	41.37	20.74	3729856.69
3	68.95	34.36	5751737.29
4	103.42	52.08	906129.65
5	137.90	69.62	5225798.33
6	20.68	20.67	1328716.20
7	41.37	41.35	2245318.99
8	68.95	68.72	2823906.31
9	103.42	103.77	3402169.58
10	137.90	138.64	3003163.10
11	20.68	40.73	1070266.23
12	41.37	81.14	1195592.23
13	68.95	136.14	1245634.38
14	103.42	206.75	1320732.07
15	137.90	274.42	1353744.17
16	20.68	61.47	687572.75
17	41.37	122.72	801798.19
18	68.95	205.08	927041.45
19	103.42	307.11	1069349.23
20	137.90	408.92	1050981.60
21	20.68	102.31	488307.38
22	41.37	204.62	623127.45
23	68.95	339.78	792621.26
24	103.42	507.76	873558.82
25	137.90	684.67	898959.10
26	20.68	142.32	402536.60
27	41.37	289.12	556262.10
28	68.95	479.46	722529.17
29	103.42	715.99	819972.77
30	137.90	953.32	876082.30

Table 44 Resilient modulus test result for 0% RAP2 sample containing OMC-2% tested at 20 °C

0% RAP2 Sample containing OMC-2% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.07	138026.14
2	41.37	20.08	188123.44
3	68.95	34.51	267357.99
4	103.42	52.57	361519.69
5	137.90	69.94	405322.08
6	20.68	20.20	145762.06
7	41.37	41.27	220618.43
8	68.95	69.40	314331.97
9	103.42	104.62	412678.79
10	137.90	139.07	436403.64
11	20.68	40.56	142162.99
12	41.37	82.70	228009.61
13	68.95	138.03	329638.33
14	103.42	207.65	438685.81
15	137.90	278.00	464775.57
16	20.68	61.20	143817.74
17	41.37	123.81	226734.08
18	68.95	205.58	335147.24
19	103.42	309.84	449765.68
20	137.90	410.09	460618.03
21	20.68	97.66	143293.73
22	41.37	185.33	227657.98
23	68.95	344.59	377026.00
24	103.42	513.55	424186.13
25	137.90	649.00	481495.36
26	20.68	140.14	152477.55
27	41.37	241.12	233932.21
28	68.95	441.20	382121.22
29	103.42	683.08	477903.19
30	137.90	908.14	471194.59

Table 45 Resilient modulus test result for 20% RAP2 sample containing OMC-2% tested at 20 °C

20% RAP2 Sample containing OMC-2% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	9.88	172568.87
2	41.37	20.82	237469.22
3	68.95	34.78	332892.66
4	103.42	52.58	445428.88
5	137.90	69.15	568114.19
6	20.68	20.51	157462.46
7	41.37	41.45	234642.37
8	68.95	68.98	337953.41
9	103.42	104.57	473221.65
10	137.90	137.89	581814.07
11	20.68	41.71	164591.64
12	41.37	82.77	248555.99
13	68.95	135.60	369538.29
14	103.42	206.24	491161.80
15	137.90	276.91	567638.45
16	20.68	62.18	175623.25
17	41.37	123.35	269012.73
18	68.95	207.03	384355.12
19	103.42	311.49	483212.15
20	137.90	411.47	546181.97
21	20.68	100.19	183607.38
22	41.37	204.25	287607.89
23	68.95	344.14	397337.95
24	103.42	510.91	485149.58
25	137.90	684.22	573133.57
26	20.68	143.92	192618.83
27	41.37	288.83	316883.03
28	68.95	478.15	421917.76
29	103.42	720.74	519244.15
30	137.90	949.81	601981.23

Table 46 Resilient modulus test result for 40% RAP2 sample containing OMC-2% tested at 20 °C

40% RAP2 Sample containing OMC-2% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	8.96	161482.10
2	41.37	19.57	230450.36
3	68.95	34.56	340221.78
4	103.42	52.68	464037.83
5	137.90	70.14	589225.93
6	20.68	19.75	140811.62
7	41.37	41.30	241992.18
8	68.95	69.29	355514.36
9	103.42	103.46	491223.86
10	137.90	137.92	607779.72
11	20.68	41.22	179118.89
12	41.37	82.87	276100.54
13	68.95	136.16	411906.57
14	103.42	207.04	523925.69
15	137.90	274.47	599119.91
16	20.68	61.85	167239.23
17	41.37	123.08	275879.91
18	68.95	207.29	406308.03
19	103.42	308.09	511832.29
20	137.90	411.31	586550.77
21	20.68	102.69	186641.07
22	41.37	203.30	302617.78
23	68.95	341.65	420690.49
24	103.42	512.80	507902.27
25	137.90	669.91	599423.28
26	20.68	142.54	202767.91
27	41.37	287.06	324584.48
28	68.95	479.87	445173.78
29	103.42	709.61	541162.58
30	137.90	913.13	639426.66

Table 47 Resilient modulus test result for 60% RAP2 sample containing OMC-2% tested at 20 °C

60% RAP2 Sample containing OMC-2% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.08	299618.56
2	41.37	20.92	396634.69
3	68.95	34.96	537142.94
4	103.42	51.71	75063.22
5	137.90	69.73	829060.06
6	20.68	20.63	249259.26
7	41.37	41.93	372261.72
8	68.95	69.21	518051.36
9	103.42	104.49	659531.77
10	137.90	138.48	777321.80
11	20.68	42.46	248618.04
12	41.37	83.01	378522.16
13	68.95	137.82	521850.37
14	103.42	208.68	647907.21
15	137.90	275.75	734201.99
16	20.68	62.83	234442.42
17	41.37	123.25	369655.50
18	68.95	207.91	506088.95
19	103.42	308.51	620872.87
20	137.90	412.18	704044.32
21	20.68	103.08	276810.70
22	41.37	205.06	395193.68
23	68.95	342.60	522698.42
24	103.42	513.84	609820.57
25	137.90	687.30	692743.81
26	20.68	142.14	225313.76
27	41.37	288.33	371937.67
28	68.95	481.68	520154.26
29	103.42	718.20	613171.42
30	137.90	944.02	694881.19

Table 48 Resilient modulus test result for 80% RAP2 sample containing OMC-2% tested at 20 °C

80% RAP2 Sample containing OMC-2% tested at 20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.19	367980.08
2	41.37	20.60	476179.50
3	68.95	34.25	654919.18
4	103.42	51.81	916533.84
5	137.90	69.50	1091750.30
6	20.68	20.49	323281.37
7	41.37	41.20	544823.70
8	68.95	68.54	710125.50
9	103.42	103.44	853501.97
10	137.90	139.08	987791.15
11	20.68	40.86	340421.73
12	41.37	82.12	508178.06
13	68.95	137.46	662758.52
14	103.42	206.87	767351.98
15	137.90	275.80	839112.61
16	20.68	61.54	316641.72
17	41.37	123.29	480792.09
18	68.95	205.91	613185.21
19	103.42	307.82	724680.33
20	137.90	412.06	792352.37
21	20.68	102.48	332265.23
22	41.37	203.68	469981.11
23	68.95	342.86	590377.36
24	103.42	512.59	670825.38
25	137.90	685.28	761243.23
26	20.68	142.67	298411.98
27	41.37	287.17	443856.88
28	68.95	479.37	591101.31
29	103.42	715.26	683615.16
30	137.90	943.93	770082.30

Table 49 Resilient modulus test result for 0% RAP2 sample containing OMC tested at 60 °C

0% RAP2 Sample containing OMC tested at 60 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.49	171962.13
2	41.37	21.22	213144.52
3	68.95	35.18	294785.34
4	103.42	52.97	396517.48
5	137.90	70.44	513997.24
6	20.68	21.06	147830.48
7	41.37	42.19	210290.09
8	68.95	69.64	304941.31
9	103.42	104.92	422214.23
10	137.90	140.39	544906.44
11	20.68	42.34	151381.28
12	41.37	83.82	228699.09
13	68.95	139.09	338394.67
14	103.42	210.13	454888.49
15	137.90	277.06	535495.09
16	20.68	62.88	152643.03
17	41.37	125.08	255423.17
18	68.95	210.39	364856.75
19	103.42	312.12	466120.05
20	137.90	415.93	529455.28
21	20.68	104.15	183207.48
22	41.37	209.24	273976.96
23	68.95	346.39	367924.92
24	103.42	519.41	460831.77
25	137.90	0.41	535150.35
26	20.68	145.67	178608.68
27	41.37	290.72	277403.65
28	68.95	483.96	392794.31
29	103.42	716.19	499249.35
30	137.90	926.35	591942.47

Table 50 Resilient modulus test result for 0% RAP2 sample containing OMC tested at 60 °C

20% RAP2 Sample containing OMC tested at 60 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.16	128166.64
2	41.37	20.97	177808.89
3	68.95	34.98	253864.95
4	103.42	52.72	355797.04
5	137.90	70.13	451461.79
6	20.68	20.84	115432.02
7	41.37	41.94	179898.00
8	68.95	69.18	260077.13
9	103.42	104.35	365966.81
10	137.90	139.03	470187.95
11	20.68	42.40	128525.17
12	41.37	83.12	197093.52
13	68.95	138.03	291551.69
14	103.42	208.29	396221.00
15	137.90	275.18	477268.87
16	20.68	63.71	141356.31
17	41.37	123.60	220921.80
18	68.95	208.25	316938.19
19	103.42	309.24	404391.29
20	137.90	412.71	465430.57
21	20.68	104.21	143266.16
22	41.37	206.99	231643.15
23	68.95	343.28	318916.99
24	103.42	513.06	409169.35
25	137.90	684.93	497794.56
26	20.68	144.68	152125.92
27	41.37	287.50	252106.79
28	68.95	479.91	355204.09
29	103.42	720.87	443181.19
30	137.90	918.56	667543.48

Table 51 Resilient modulus test result for 20% RAP2 sample containing OMC tested at 60 °C

40% RAP2 Sample containing OMC tested at 60 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.06	160434.10
2	41.37	20.32	203622.86
3	68.95	34.32	282760.88
4	103.42	51.92	380514.74
5	137.90	69.66	478110.03
6	20.68	20.21	139129.30
7	41.37	41.22	199672.16
8	68.95	68.58	279203.18
9	103.42	104.14	386306.34
10	137.90	138.28	478606.45
11	20.68	40.96	134130.60
12	41.37	82.64	210958.88
13	68.95	136.82	304410.42
14	103.42	206.94	398013.64
15	137.90	274.65	461031.72
16	20.68	61.56	140370.36
17	41.37	123.40	219956.54
18	68.95	207.22	316186.66
19	103.42	307.94	394097.42
20	137.90	405.67	462031.46
21	20.68	102.24	153911.66
22	41.37	205.03	244501.87
23	68.95	342.21	327273.43
24	103.42	511.71	429570.94
25	137.90	684.90	509846.60
26	20.68	143.56	166136.06
27	41.37	288.18	267426.94
28	68.95	478.46	357727.57
29	103.42	672.40	385706.50
30	137.90	965.27	546637.02

Table 52 Resilient modulus test result for 60% RAP2 sample containing OMC tested at 60 °C

60% RAP2 Sample containing OMC tested at 60 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	9.98	130641.86
2	41.37	20.31	173079.08
3	68.95	34.12	247432.14
4	103.42	51.37	422379.71
5	137.90	69.33	504075.68
6	20.68	20.35	138791.46
7	41.37	40.44	167328.86
8	68.95	67.09	313863.13
9	103.42	103.13	402267.70
10	137.90	137.70	483549.99
11	20.68	40.34	155800.82
12	41.37	81.53	231539.73
13	68.95	137.69	316510.71
14	103.42	206.28	413133.84
15	137.90	274.19	511756.44
16	20.68	60.88	159310.26
17	41.37	122.43	240109.91
18	68.95	206.60	340297.63
19	103.42	308.02	496925.82
20	137.90	410.85	515396.88
21	20.68	102.39	182924.80
22	41.37	206.22	279327.29
23	68.95	341.69	371999.72
24	103.42	515.34	529703.50
25	137.90	0.78	555682.94
26	20.68	142.96	195080.25
27	41.37	287.88	317489.77
28	68.95	480.87	425268.61
29	103.42	721.38	719095.58
30	137.90	949.88	710787.39

Table 53 Resilient modulus test result for 80% RAP2 sample containing OMC tested at 60 °C

80% RAP2 Sample containing OMC tested at 60 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.11	293061.65
2	41.37	20.32	352618.56
3	68.95	34.63	722411.95
4	103.42	51.52	817070.07
5	137.90	69.45	908522.13
6	20.68	20.57	301369.83
7	41.37	41.22	412851.15
8	68.95	68.50	530758.39
9	103.42	103.66	618811.34
10	137.90	138.31	696901.35
11	20.68	41.19	258539.60
12	41.37	82.04	348578.23
13	68.95	137.15	427164.67
14	103.42	207.65	523298.27
15	137.90	274.43	601719.23
16	20.68	61.52	219984.12
17	41.37	122.59	304920.63
18	68.95	206.31	408279.93
19	103.42	307.59	488438.38
20	137.90	410.33	558613.21
21	20.68	101.84	214957.84
22	41.37	203.48	314456.08
23	68.95	340.22	409403.78
24	103.42	512.03	489410.54
25	137.90	649.95	587957.30
26	20.68	139.29	224644.97
27	41.37	255.85	329086.75
28	68.95	447.21	441691.92
29	103.42	682.26	553573.14
30	137.90	912.79	650396.22

Table 54 Resilient modulus test result for 0% RAP2 sample containing OMC tested after FT conditioning

0% RAP2 Sample containing OMC tested after freeze-thaw conditioning			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.37	183428.12
2	41.37	20.75	255602.43
3	68.95	40.95	325832.43
4	103.42	52.63	481674.62
5	137.90	70.33	635427.70
6	20.68	20.46	170934.82
7	41.37	41.22	247714.83
8	68.95	69.28	355493.67
9	103.42	104.17	494471.29
10	137.90	138.50	638082.18
11	20.68	41.07	171644.98
12	41.37	82.73	268364.63
13	68.95	137.45	392104.83
14	103.42	207.03	541162.58
15	137.90	276.65	646011.15
16	20.68	62.02	182738.64
17	41.37	123.89	289538.43
18	68.95	206.30	420166.49
19	103.42	310.97	544927.12
20	137.90	412.22	635248.44
21	20.68	103.09	189516.19
22	41.37	205.95	307478.58
23	68.95	344.58	432928.69
24	103.42	517.18	545913.07
25	137.90	685.14	636427.44
26	20.68	144.98	196507.47
27	41.37	287.74	321647.31
28	68.95	483.26	457825.65
29	103.42	725.18	574712.47
30	137.90	933.19	690985.65

Table 55 Resilient modulus test result for 20% RAP2 sample containing OMC tested after FT conditioning

20% RAP2 Sample containing OMC tested after freeze-thaw conditioning			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.40	230691.67
2	41.37	20.86	285525.68
3	68.95	34.76	370724.19
4	103.42	52.37	505116.79
5	137.90	70.70	656311.92
6	20.68	21.02	183517.75
7	41.37	41.78	251989.58
8	68.95	69.46	340056.31
9	103.42	104.55	493905.92
10	137.90	139.87	646086.99
11	20.68	42.17	192115.51
12	41.37	83.47	281147.51
13	68.95	138.91	412561.57
14	103.42	209.37	567059.29
15	137.90	277.70	691164.92
16	20.68	63.11	181401.06
17	41.37	124.72	291172.48
18	68.95	208.86	426330.40
19	103.42	312.45	563777.39
20	137.90	415.03	665171.68
21	20.68	104.41	193301.41
22	41.37	205.88	315931.56
23	68.95	344.01	450965.37
24	103.42	518.31	566831.76
25	137.90	686.85	645376.83
26	20.68	146.84	191205.40
27	41.37	288.57	319378.93
28	68.95	483.52	454826.44
29	103.42	723.18	564956.39
30	137.90	963.63	633793.64

Table 56 Resilient modulus test result for 40% RAP2 sample containing OMC tested after FT conditioning

40% RAP2 Sample containing OMC tested after freeze-thaw conditioning			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.44	201657.85
2	41.37	21.08	273521.90
3	68.95	34.94	364036.27
4	103.42	52.34	491010.12
5	137.90	70.22	628105.47
6	20.68	20.66	158117.46
7	41.37	41.80	249948.73
8	68.95	68.98	360154.53
9	103.42	103.32	489817.33
10	137.90	138.35	602477.66
11	20.68	42.09	157683.09
12	41.37	82.52	279361.76
13	68.95	138.12	399247.80
14	103.42	206.93	513100.92
15	137.90	274.81	597823.70
16	20.68	62.31	176319.62
17	41.37	123.96	280664.87
18	68.95	205.97	404287.87
19	103.42	309.23	508288.38
20	137.90	412.40	574229.84
21	20.68	103.17	190902.03
22	41.37	204.91	301121.62
23	68.95	344.23	416753.59
24	103.42	514.76	500883.41
25	137.90	680.28	583916.97
26	20.68	143.38	206635.87
27	41.37	286.13	320744.10
28	68.95	483.09	441947.03
29	103.42	722.16	539949.10
30	137.90	934.33	653512.65

Table 57 Resilient modulus test result for 60% RAP2 sample containing OMC tested after FT conditioning

60% RAP2 Sample containing OMC tested after freeze-thaw conditioning			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.17	268605.94
2	41.37	20.51	385368.65
3	68.95	34.43	515024.56
4	103.42	52.49	661379.57
5	137.90	70.53	815380.86
6	20.68	20.38	237800.17
7	41.37	41.20	365560.02
8	68.95	69.85	511397.92
9	103.42	104.86	675527.61
10	137.90	138.79	807086.46
11	20.68	40.97	235986.85
12	41.37	83.28	375922.84
13	68.95	138.38	529220.86
14	103.42	206.90	678492.35
15	137.90	275.43	779162.70
16	20.68	61.06	251258.73
17	41.37	124.88	386726.92
18	68.95	207.70	534109.25
19	103.42	309.91	664027.15
20	137.90	412.63	753845.15
21	20.68	103.27	257464.02
22	41.37	207.05	404701.55
23	68.95	343.32	549718.98
24	103.42	515.60	658021.82
25	137.90	684.26	757416.64
26	20.68	144.96	267564.83
27	41.37	287.39	417077.64
28	68.95	481.21	574912.42
29	103.42	718.69	691799.23
30	137.90	929.74	791883.53

Table 58 Resilient modulus test result for 80% RAP2 sample containing OMC tested after FT conditioning

80% RAP2 Sample containing OMC tested after freeze-thaw conditioning			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.26	436617.38
2	41.37	20.82	587881.46
3	68.95	34.54	742372.28
4	103.42	52.03	979248.55
5	137.90	69.80	1248543.97
6	20.68	20.68	351522.29
7	41.37	41.51	569968.88
8	68.95	69.03	707995.02
9	103.42	104.21	927875.71
10	137.90	138.85	1140420.39
11	20.68	40.53	326880.43
12	41.37	81.81	505558.06
13	68.95	137.23	687165.96
14	103.42	206.24	930054.46
15	137.90	275.40	990011.26
16	20.68	61.74	319227.25
17	41.37	123.09	507357.59
18	68.95	196.52	694281.35
19	103.42	309.55	871786.86
20	137.90	411.09	948173.88
21	20.68	100.50	333485.61
22	41.37	204.83	523725.74
23	68.95	344.40	697432.25
24	103.42	513.32	815732.49
25	137.90	684.37	883397.64
26	20.68	140.87	329362.54
27	41.37	286.95	524222.16
28	68.95	476.81	717413.26
29	103.42	711.80	822806.51
30	137.90	950.60	909714.92

Table 59 Resilient modulus test result for 0% RAP2 sample containing OMC tested at - 20 °C

0% RAP2 Sample containing OMC tested at -20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.38	19821654.16
2	41.37	20.44	20008446.92
3	68.95	34.30	29041247.38
4	103.42	53.06	28618329.88
5	137.90	70.35	30186411.36
6	20.68	20.34	21427932.60
7	41.37	41.09	26747920.20
8	68.95	70.14	30108107.60
9	103.42	104.75	30769638.85
10	137.90	137.90	31735552.94
11	20.68	40.89	25945453.22
12	41.37	82.44	30157170.70
13	68.95	138.27	28409556.64
14	103.42	201.58	27038196.37
15	137.90	263.26	25281301.97
16	20.68	61.98	28245054.63
17	41.37	123.10	30040559.67
18	68.95	199.35	26995724.66
19	103.42	296.52	25414184.62
20	137.90	397.39	23916912.29
21	20.68	103.13	28835211.36
22	41.37	197.62	26560830.97
23	68.95	329.33	24792484.38
24	103.42	501.59	22927714.61
25	137.90	672.83	21678081.27
26	20.68	144.08	28106856.12
27	41.37	272.63	25257060.00
28	68.95	465.67	22728966.35
29	103.42	706.73	21342720.29
30	137.90	940.49	20437149.12

Table 60 Resilient modulus test result for 20% RAP2 sample containing OMC tested at -20 °C

20% RAP2 Sample containing OMC tested at -20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.43	12659663.28
2	41.37	21.30	14637879.38
3	68.95	35.96	19098925.05
4	103.42	53.13	17958173.71
5	137.90	69.77	19748431.84
6	20.68	20.34	16209897.76
7	41.37	42.49	18000424.78
8	68.95	69.25	20512543.29
9	103.42	104.57	20820263.19
10	137.90	138.21	20258030.23
11	20.68	42.26	17708480.09
12	41.37	82.50	19292757.35
13	68.95	136.50	19829783.08
14	103.42	202.49	20946464.82
15	137.90	267.07	20711195.03
16	20.68	63.06	19917601.60
17	41.37	122.80	20191875.03
18	68.95	200.42	20030551.51
19	103.42	300.59	20486839.63
20	137.90	403.12	19799639.20
21	20.68	103.19	19436623.35
22	41.37	197.57	20190702.93
23	68.95	333.37	19759029.08
24	103.42	505.46	19568202.89
25	137.90	679.19	19038795.87
26	20.68	142.89	20003806.75
27	41.37	273.77	19788180.12
28	68.95	469.82	19432376.18
29	103.42	713.41	18989029.52
30	137.90	951.04	18219553.95

Table 61 Resilient modulus test result for 40% RAP2 sample containing OMC tested at - 20 °C

40% RAP2 Sample containing OMC tested at -20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	12.86	13507525.33
2	41.37	20.51	13709259.03
3	68.95	35.67	15959431.92
4	103.42	53.23	18995289.96
5	137.90	71.00	18571793.30
6	20.68	20.73	13714664.52
7	41.37	41.40	18375168.62
8	68.95	69.46	18113891.80
9	103.42	105.32	19345191.98
10	137.90	139.85	19288523.97
11	20.68	41.35	15967395.37
12	41.37	83.05	18808262.78
13	68.95	138.27	18539456.89
14	103.42	206.06	18625186.30
15	137.90	266.77	18288453.26
16	20.68	62.29	17843679.38
17	41.37	124.21	18036539.52
18	68.95	202.57	18651103.69
19	103.42	299.57	18029169.03
20	137.90	401.15	18033257.62
21	20.68	102.48	17690105.56
22	41.37	198.85	17992295.87
23	68.95	332.48	18062946.44
24	103.42	505.48	17725110.24
25	137.90	678.00	17026154.25
26	20.68	144.19	17822946.85
27	41.37	273.76	17941102.30
28	68.95	469.73	17413281.07
29	103.42	711.65	16862438.25
30	137.90	946.60	16447759.98

Table 62 Resilient modulus test result for 60% RAP2 sample containing OMC tested at - 20 °C

60% RAP2 Sample containing OMC tested at -20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.60	22332117.92
2	41.37	21.49	19017608.29
3	68.95	35.74	20484750.52
4	103.42	53.08	25764065.96
5	137.90	70.04	23973042.51
6	20.68	20.97	22736350.63
7	41.37	42.08	21328372.30
8	68.95	69.80	27422248.12
9	103.42	104.59	24734671.84
10	137.90	139.18	24375710.11
11	20.68	41.61	23653332.63
12	41.37	82.83	24533110.52
13	68.95	138.75	23700699.61
14	103.42	207.95	23043787.85
15	137.90	276.82	22276980.55
16	20.68	62.30	23598346.94
17	41.37	124.13	24203747.97
18	68.95	207.44	22254351.96
19	103.42	301.27	22185507.81
20	137.90	402.54	21533050.06
21	20.68	103.17	23725265.63
22	41.37	200.09	22118083.98
23	68.95	345.72	21569702.59
24	103.42	517.31	20970886.05
25	137.90	678.49	20561854.59
26	20.68	143.98	23811615.56
27	41.37	290.27	22186018.02
28	68.95	482.81	21204763.10
29	103.42	711.13	20474787.60
30	137.90	950.59	19542519.93

Table 63 Resilient modulus test result for 80% RAP2 sample containing OMC tested at - 20 °C

80% RAP2 Sample containing OMC tested at -20 °C			
Sequence	Confining pressure (KPa)	Cyclic stress (KPa)	Resilient Modulus (KPa)
1	20.68	10.50	12800212.90
2	41.37	21.14	13136090.98
3	68.95	35.00	15323838.75
4	103.42	52.10	14621690.49
5	137.90	70.11	15398026.33
6	20.68	21.31	13451932.91
7	41.37	41.95	14888407.27
8	68.95	68.99	15568837.04
9	103.42	105.30	15804361.94
10	137.90	138.42	15361759.91
11	20.68	42.00	15107398.54
12	41.37	82.16	15350686.93
13	68.95	138.10	15188887.67
14	103.42	208.23	16061364.01
15	137.90	266.57	15474075.50
16	20.68	62.33	16102698.08
17	41.37	124.17	15554523.53
18	68.95	207.02	15324362.75
19	103.42	298.78	15136639.20
20	137.90	412.81	14792763.20
21	20.68	103.07	15390910.95
22	41.37	199.26	15229222.00
23	68.95	347.10	14978501.06
24	103.42	515.16	14546654.85
25	137.90	675.30	14351429.80
26	20.68	143.05	15482852.53
27	41.37	290.72	15437085.13
28	68.95	481.82	14548571.59
29	103.42	716.39	14132700.53
30	137.90	949.75	13640504.51