ANISOTROPIC ELASTIC PROPERTIES OF POLYMER MODIFIED ASPHALT

MR. CHALOEMCHAI TONGNUAPAD

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR
THE DEGREE OF MASTER OF ENGINEERING (CIVIL ENGINEERING)
FACULTY OF ENGINEERING
KING MONGKUT'S UNIVERSITY OF TECHNOLOGY THONBURI
2011

Anisotropic Elastic Properties of Polymer-Modified Asphalt

Mr. Chaloemchai Tongnuapad B.Eng. (Civil Engineering)

A Thesis Submitted in Partial Fulfillment
of the Requirements for
the Degree of Master of Engineering (Civil Engineering)
Faculty of Engineering
King Mongkut's University of Technology Thonburi
2011

Thesis Committee

.... (Asst. Prof. Sompote Youwai, D. Eng.)	Chairman of Thesis Committee
.... (Asst. Prof. Warat Kongkitkul, Ph.D.)	Member and Thesis Advisor
.... (Asst. Prof. Pornkasem Jongpradist, Ph.D.)	Member and Thesis Co-Advisor
.... (Poranic Jitareekul, Ph.D.)	Member

Thesis Title	Anisotropic Elastic Properties of Polymer-Modified Asphalt
Thesis Credits	12
Candidate	Mr. Chaloemchai Tongnuapad
Thesis Advisors	Asst. Prof. Dr. Warat Kongkitkul
	Asst. Prof. Dr. Pornkasem Jongpradist
Program	Master of Engineering
Field of Study	Civil Engineering (Geotechnical Engineering)
Department	Civil Engineering
Faculty	Engineering
B.E.	2554

Abstract

Due to largely increasing traffic volume and truck load, a large volume of hot-mixed asphalt (HMA) pavement in Thailand is susceptible to damage. Use of Polymer-Modified Asphalt (PMA) has become more popular in pavement construction due to its ability to support quantitatively larger traffic load than the HMA. However, PMA is prepared by compaction of aggregates to the specified density, as a result, its strength and deformation properties are anisotropic, depending on the direction of external stress application relative to the direction of compaction. This research is a study of the strength and deformation of PMA that was prepared by compaction in different directions. The strength and deformation of PMA specimen were investigated by performing unconventional unconfined compression tests. The axial and lateral strains were locally measured by means of a pair of local deformation transducers (LDTs) and a set of three clip gages to determine deformation properties which are free from bedding errors. Test results were compared with HMA specimens previously studied. It was found that: 1) the compressive strength and secant stiffness (E_{50}) of the vertically compacted PMA specimen were higher than those of the horizontally compacted PMA specimen; 2) at the same stress level, the vertical equivalent elastic Young's moduli, $E_{v,eq}$, were higher than the horizontal equivalent elastic Young's moduli, $E_{h,eq}$; and, the vertical-to-horizontal Poisson's ratios, $\nu_{vh,eq}$, were higher than the horizontal-to-vertical Poisson's ratios, $\nu_{hv,eq}$; and, 3) at the same density, the compressive strength and the stiffness of PMA were significantly higher than those of HMA.

Keywords: Polymer-Modified Asphalt / Hot-Mixed Asphalt / Anisotropy / Compressive Strength / Stiffness

หัวข้อวิทยานิพนธ์	พฤติกรรมแอนนิโซโทรปิกอีลาสติกของโพลิเมอร์โมดิฟายด์แอสฟัลต์
หน่วยกิต	12
ผู้เขียน	นายเฉลิมชัย ทองเนื้อแปด
อาจารย์ที่ปรึกษา	ผศ.ดร.วรัช ก้องกิจกุล
	ผศ.ดร.พรเกษม จงประดิษฐ์
หลักสูตร	วิศวกรรมศาสตรมหาบัณฑิต
สาขาวิชา	วิศวกรรมโยธา (วิศวกรรมเทคนิคธรณี)
ภาควิชา	วิศวกรรมโยธา
คณะ	วิศวกรรมศาสตร์
พ.ศ.	2554

บทคัดย่อ

E46291

ในปัจจุบันประเทศไทยมีถนนที่มีผิวทางแอสฟัลต์คอนกรีตเป็นจำนวนมากซึ่งต้องเผชิญกับสภาพการใช้งานที่หนักหน่วงมากขึ้น เนื่องจากปริมาณการจราจรและน้ำหนักบรรทุกที่เพิ่มมากขึ้น สาเหตุเหล่านี้นำไปสู่ปัญหาความเสียหายบนถนนผิวทางแอสฟัลต์ ด้วยเหตุนี้การสร้างถนนจึงได้มีการนำโพลิเมอร์โมดิฟายด์แอสฟัลต์มาใช้งานมากขึ้นเพื่อแก้ไขปัญหาดังกล่าว อย่างไรก็ตามการเตรียมโพลิเมอร์โมดิฟายด์แอสฟัลต์ทำโดยการบดอัดตามความหนาแน่นที่กำหนด ทำให้คุณสมบัติด้านกำลังและการเสียรูปขึ้นอยู่กับทิศทางของแรงที่กระทำที่สัมพันธ์กับทิศทางการบดอัด งานวิจัยนี้จึงศึกษาพฤติกรรมด้านกำลังและการเสียรูปของโพลิเมอร์โมดิฟายด์แอสฟัลต์ที่มีการบดอัดในทิศทางที่แตกต่างกันโดยทำการทดสอบแบบแรงอัดแกนเดียว การวัดการเสียรูปของโพลิเมอร์โมดิฟายด์แอสฟัลต์เป็นการวัดแบบเฉพาะที่โดยใช้เครื่องมือวัดการเคลื่อนที่เฉพาะจุด (LDT) สำหรับวัดการเสียรูปในแนวแกนและเครื่องมือวัดการขยายตัว (clip gage) สำหรับวัดการเสียรูปด้านข้าง ทำให้ผลที่ได้จากการวัดด้วยวิธีดังกล่าวไม่ได้รับผลกระทบเนื่องจากความไม่สม่ำเสมอบริเวณหัวตัวอย่าง เมื่อนำผลการทดลองที่ได้มาเปรียบเทียบกับผลของแอสฟัลต์ติกคอนกรีตธรรมดาที่ได้ทำการวิจัยมาแล้ว พบว่าค่ากำลังรับแรงอัดของตัวอย่างที่ได้รับการบดอัดในแนวตั้งมีค่ามากกว่าตัวอย่างที่ได้รับการบดอัดในแนวนอน ค่าโมดูลัสสมมูลย์และอัตราส่วนปัวซองสมมูลย์ของตัวอย่างที่ได้รับการบดอัดในแนวตั้งมีค่ามากกว่าค่าโมดูลัสสมมูลย์และอัตราส่วนปัวซองสมมูลย์ของตัวอย่างที่ได้รับการบดอัดในแนวนอน คุณสมบัติด้านกำลังและการเสียรูปของโพลิเมอร์โมดิฟายด์แอสฟัลต์ดีกว่าแอสฟัลต์ติกคอนกรีตธรรมดาอย่างชัดเจน

คำสำคัญ: โพลิเมอร์โมดิฟายด์แอสฟัลต์ / แอสฟัลต์ติกคอนกรีต / แอนนิโซโทรปี / กำลังรับแรงอัด / ความแข็ง

ACKNOWLEDGEMENTS

The author would like to express his gratitude to my advisor and co-advisor, Asst. Prof. Dr. Warat Kongkitkul and Asst. Prof. Dr. Pornkasem Jongpradist for excellent guidance and strong support throughout this study. Without their help in both academic and personal concerns, this thesis work could not have been completed.

Sincere appreciation is also extended to the other members of the committees, Asst. Dr. Sompote Youwai and Dr. Poranic Jitareekul for their help, encouragement, suggestions, constructive comments and serving as members of my thesis examination committees.

Thanks are also extended to Mr. Noppadon Musika, Mrs. Patcharee Issaro and my friends for their kind help and valuable encouragement.

CONTENTS

PAGE

ENGLISH ABSTRACT ii
THAI ABSTRACT iii
ACKNOWLAGEMENTS iv
CONTENTS v
LIST OF TABLES vii
LIST OF FIGTURES viii
LIST OF SYMBOLS xvii

CHAPTER

1. INTRODUCTION **1**
1.1 State of Problem 1
1.2 Objectives of Study 2
1.3 Scope and Limitation 2

2. LITERATURE REVIEW **3**
2.1 Introduction 3
2.2 Theory of elasticity 3
2.2.1 Isotropic elasticity 3
2.2.2 Soil elasticity 5
2.2.3 Anisotropic elasticity 11
2.3 Anisotropic behavior of geomaterials 15
2.3.1 Inherent anisotropy in the strength and deformation of geomaterials 17
2.3.2 Compaction-induced anisotropy on geomaterials 18
2.4 Anisotropic behavior of asphaltic concrete 19
2.5 Polymer Modified Asphalt (PMA) 21
2.5.1 Methods to incorporate polymer into asphalt 21
2.5.2 Types of Polymer Modifiers 21
2.5.3 Content of Polymer Modifiers 24
2.5.4 Performance of PMA 25
2.5.4.1 Permanent deformation Resistance 25
2.5.4.2 Thermal Cracking Resistance 28
2.5.4.3 Fatigue Cracking Resistance 28
2.6 Anisotropic behavior of polymer modified asphalt 29
2.7 Basic engineering properties of asphalt concrete 30
2.7.1 Components of asphaltic concrete 31
2.7.2 General considerations for preparing asphaltic concrete 33
2.8 Rheology of asphalt concrete 34
2.9 Factors affecting the strength and deformation of asphaltic concrete 36
2.10 Laboratory test on asphaltic concrete 36
2.10.1 Uniaxial or unconfined compaction test 36
2.10.2 Bedding error 37
2.11 Void ratio function 38

3. METHODOLOGY **39**
3.1 Introduction 39

3.2	Materials	39
3.2.1	Polymer Modified Asphaltic Cement (PM-AC)	39
3.2.2	Aggregate	40
3.3	Mould	41
3.4	Specimen Preparation	42
3.4.1	Heating	42
3.4.2	Mixing	42
3.4.3	Compaction	42
3.5	Test apparatuses	45
3.6	Measuring devices	48
3.6.1	Load cell	48
3.6.2	Displacement transducers	48
3.6.2.1	Linear Variable Displacement Transducer (LVDT)	48
3.6.2.2	Local Deformation Transducers (LDT)	49
3.6.2.3	Clip Gage	49
3.7	Test Preparations	50
3.7.1	General	50
3.7.2	Set ups of pedestal and cap	50
3.7.3	Set ups of specimen and instrument	51
3.8	Test program	52
3.8.1	Test program for studying the strength and stress-strain properties	54
3.8.2	Definition of stress and strains	56
3.8.3	Evaluation of the small-strain stress-strain properties	57
4.	**RESULT AND DISCUSSION**	**60**
4.1	Introduction	60
4.2	Continuous monotonic loading	60
4.2.1	Stress-strain relations	60
4.2.2	The maximum stress and secant modulus (E_{50})	65
4.3	Minute cyclic loading	70
4.3.1	Stress-strain relations	70
4.3.2	Equivalent modulus and Poisson's ratio	83
4.4	Comparison between the vertical stiffness and the horizontal stiffness	103
4.5	Comparison the stiffness between Polymer Modified Asphaltic Concrete (PMA) and Hot-mixed Asphaltic Concrete (HMA)	111
5.	**CONCLUSION**	**126**
	REFERENCES	**128**
	APPENDIXS	**134**
A	Equivalent elastic modulus, E_{eq} (E_v and E_h) and equivalent Poisson's ratio, ν_{eq} (ν_{vh} and ν_{hv})	134
B	Calculation of voids in mineral aggregate for PMA-1V, PMA-1H, PMA-2V, PMA-2H, PMA-3V and PMA-3H	149
C	The coefficient of determination (R^2) of equivalent stiffness	153
D	The density of PMA specimen (ρ)	155
	CURRICULUM VITAE	**158**

LIST OF TABLES

TABLE		PAGE
3.1	Properties of polymer modified asphaltic cement (PM-AC) used in this study	39
3.2	Gradation of aggregate used in this study	40
3.3	The mixed design used in this study	42
3.4	Details of vertical compactions in this study	44
3.5	Details of horizontal compactions in this study	45
3.6	Test program for studying the strength and stress-strain properties of PMA	54
4.1	Summary of maximum stress and secant modulus (E_{50}) of PMA specimens having different direction of compaction and varies densities	65
4.2	Summary of the average of maximum stress and secant modulus (E_{50}) of PMA and HMA specimens having different directions of compaction and different densities	68
4.3	Summary of voids in mineral aggregate and voids ratio of PMA in the vertical and horizontal compaction at different densities	89
C.1	Summary of determination (R^2) of equivalent stiffness for the vertical and horizontal of PMA at different densities	154
D.1	Summary of density (ρ) of the vertical and horizontal of PMA at different densities for monotonic loading test	156
D.2	Summary of density (ρ) of the vertical and horizontal of PMA at different densities for cyclic loading test	157

LIST OF FIGURES

FIGURE **PAGE**

2.1 Tensile test on metal wire: (a) test arrangement; (b) load-extension relationship; and (c) changes in diameter and length (Wood, 1990) 4

2.2 (a) Young's modulus describing change in length and Poisson's ratio describing change in width; (b) bulk modulus describing change in size at constant shape; and (c) shear modulus describing change in shape at constant volume (Wood, 1990) 5

2.3 Elastic constant deduced from conventional triaxial compression test: (a) deviator stress q and triaxial shear strain ε_q; (b) volumetric strain ε_p and triaxial shear strain ε_q; and (c) deviator stress q and axial strain ε_a (Wood, 1990) 6

2.4 Elastic constant deduced from conventional triaxial compression test: (a) deviator stress q and triaxial shear strain ε_q; (b) pore pressure u and triaxial shear strain ε_q; and (c) deviator stress q and axial strain ε_a (Wood, 1990) 8

2.5 Undrained shearing *AB* and subsequent pore pressure dissipation *BC* in conventional triaxial compression test: (a) total and effective stress paths; and (b) deviator stress q and axial strain ε_a (Wood, 1990) 9

2.6 Cylindrical soils samples taken out of the ground with their axes vertical (*A*) and horizontal (*B, C, D, E*) (Wood, 1990) 11

2.7 Effective stress paths for constant volume deformation of cross-anisotropic elastic soil (Wood, 1990) 14

2.8 Volumetric strain: triaxial shear strain path for compression of cross-anisotropic elastic soil under isotropic stresses (Wood, 1990) 14

2.9 Relationships between the ratio of vertical and horizontal elastic Young's modulus values and the principal stress ratio for cross-anisotropic sand and gravels (Kohata et al., 1997, Tatsuoka et al., 1999a) 18

2.10 Illustrations of two typical directions of compaction (Kongsukprasert et al., 2005) 19

2.11 Procedure for cutting the specimens 20

2.12 Test setup: a) in the short dimension; and b) in the long dimension 20

2.13 Examples of different polymers: a) styrene butadiene styrene (SBS); b) ethylene vinyl acetate (EVA); c) latex; and d) waxes 22

2.14 Tensile Strength at various temperatures of specimens (Phromsorn, 1998) 23

2.15 LCPC wheel test result (Tayfur et al., 2005) 23

2.16 Developing process of wheel track (Lidong et al. 2008) 24

2.17 Indirect tensile strength values of polymer modified HMA (Sengoz and Isikyakar, 2007) 24

2.18 Fluorescent images of SBS PMB samples with 100x magnification (Sengoz and Isikyakar, 2007) 25

2.19 Wet Track Abrasion Losses (Holleran, 2006) 26

2.20 Loaded Wheel Test Results (Holleran, 2006) 26

2.21 Rut depth obtained from the wheel-tracking test (Chen et al., 2002) 27

2.22 Deformation of pavement obtained from the wheel-tracking test (Greater Iowa Asphalt Conference, 2008) 27
2.23 Crack propagation by number of load cycles (Kim et al., 1996) 28
2.24 Core orientation effects on the compressive strength of asphaltic concrete mixtures containing 5% SBS modified binder (PG 76-22) (Liang et al., 2006) 29
2.25 Core orientation effects on the modulus of elasticity of asphaltic concrete mixtures containing 5% SBS modified binder (PG 76-22) (Liang et al., 2006) 29
2.26 Core orientation effect on strains at peak strength of asphalt concrete mixtures containing 5% SBS modified binder (PG 76-22) (Liang et al., 2006) 30
2.27 Asphalt mixture showing net or effective asphalt, absorbed asphalt, and air voids (Atkins, 1997) 31
2.28 Mass/volume relationships in asphalt mixes 32
2.29 Schematic permanent deformation curve (modified from Graba, 2002) 34
2.30 Comparative dilational response of asphaltic concrete specimens to shear creep loading (Asphalt Research Program, 1994) 35
2.31 Effect of confining pressure on creep behavior at 40 $^{\circ}C$ (Asphalt Research Program, 1994) 35
2.32 Drained triaxial creep test on sedimentary soft mudstone; each creep period is three days (Tatsuoka et al., 1999b,2000; Hayano et al., 2001); the detail of the testing method is described in Hayano et al. (1977) 37
2.33 Relationships between Shear modulus and Void ratio (Iwasaki et al., 1978) 38
3.1 Grain size distribution curve of aggregate used in this study 40
3.2 The characteristic of mould in this study: (a) vertical mould; (b) horizontal mould 41
3.3 The specimen preparation: a) heating PM-AC; b) add PM-AC in aggregates; c) PM-AC and aggregates after mixed; d) add the mixture into the mold; e) compaction specimen; and f) the specimen after prepared 43
3.4 Vertical compaction for the PMA specimen 44
3.5 Horizontal compaction for the PMA specimen 45
3.6 Apparatuses used in performing unconfined compression test in this study: a) picture of Apparatus A; b) picture of Apparatus B; and c) air-circuit of Apparatus B 46
3.7 Detail of load cell: a) the body of load cell; and b) attachment of four strain gages on the top surface of load cell's body 48
3.8 LVDT having capacity of 10 mm for global vertical displacement measurement 48
3.9 LDT having capacity of about 2.5 mm for local displacement measurement: a) the body LDT; and b) details of the internal connections 49
3.10 Clip gage having capacity of about 1.5 mm for local horizontal displacement measurement 49
3.11 Diagram for preparing the top and bottom ends of a specimen (Kawabe, 2008) 50

3.12 3M Scotch™ tape encircling the top cap 51

3.13 Local deformation transducers (LDTs) and clip gages (CGs) on asphaltic concrete specimen: a) plan view; b) side view; and c) installed their appearance 52

3.14 Schematic diagram showing various loading histories employed in this study: a) continuous monotonic loading (ML) at a constant strain rate by apparatus A; and b) continuous monotonic loading (ML) at a constant stress rate, sustained loading (SL), and cyclic loading at constant stress rate by apparatus B 53

3.15 Continuous monotonic loading (ML) at a constant strain rate by apparatus A; 56

3.16 The result from instruments (LDTs and clip gages): a) from vertical specimen; and b) from horizontal specimen 57

3.17 Equivalent parameters during cycles of unload and reload (Abdelrahman et al., 2008): a) vertical parameter; and b) horizontal parameter 59

4.1(a) Continuous monotonic loading test results on PMA specimens compacted in vertical and horizontal directions at the density of 1.90 g/cm^3 61

4.1(b) Continuous monotonic loading test results on PMA specimens compacted in vertical and horizontal directions at the density of 2.15 g/cm^3 61

4.1(c) Continuous monotonic loading test results on PMA specimens compacted in vertical and horizontal directions at the density of 2.37 g/cm^3 62

4.2(a) Comparison of the relationships between vertical stress and vertical strain of the vertically compacted PMA specimens at different densities 63

4.2(b) Vertical stress and vertical strain of the vertically compacted PMA specimens at different densities normalized by maximum vertical stress and maximum vertical strain 63

4.3(a) Comparison of the relationship between horizontal stress and horizontal strain of the horizontally compacted PMA specimens at different densities 64

4.3(b) Horizontal stress and horizontal strain of the horizontally compacted PMA specimens at different densities normalized by maximum vertical stress and maximum vertical strain 64

4.4 Relationships between the maximum stress ($\sigma_{v,max}$ and $\sigma_{h,max}$) and the density of PMA specimen 67

4.5 Relationships between the elastic modulus (E_{50}) and the density of PMA specimen 67

4.6 Comparison of the maximum stresses among PMA and HMA specimens prepared by vertical and horizontal compactions for different densities 69

4.7 Comparison of the secant modulus (E_{50}) among PMA and HMA specimens prepared by vertical and horizontal compactions for different densities 69

4.8(a) Relationship between vertical stress and vertical strain obtained from minute-amplitude cyclic loading test on PMA-1V from test VSC-01, density = 1.90 g/cm^3 and VMA = 31.369 % 71

4.8(b) Close-up of σ_v - ε_v relations obtained from minute-amplitude cyclic loading test on PMA-1V from test VSC-01, density = 1.90 g/cm^3 and VMA = 31.369 % 71

4.9(a) Relationship between vertical stress and vertical strain obtained from minute-amplitude cyclic loading test on PMA-2V from test VMC-01, density = 2.15 g/cm^3 and VMA = 22.339 % 72

4.9(b) Close-up of σ_v - ε_v relations obtained from minute-amplitude cyclic loading test on PMA-2V from test VMC-01, density = 2.15 g/cm^3 and VMA = 22.339 % 72

4.10(a) Relationship between vertical stress and vertical strain obtained from minute-amplitude cyclic loading test on PMA-3V from test VLC-01, density = 2.37 g/cm^3 and VMA = 14.392 % 73

4.10(b) Close-up of σ_v - ε_v relations obtained from minute-amplitude cyclic loading test on PMA-3V from test VLC-01, density = 2.37 g/cm^3 and VMA = 14.392 % 73

4.11(a) Relationship between horizontal stress and horizontal strain obtained from minute-amplitude cyclic loading test on PMA-1H from test HSC-01, density = 1.90 g/cm^3 and VMA = 31.369 % 74

4.11(b) Close-up of σ_h - ε_h relations obtained from minute-amplitude cyclic loading test on PMA-1H from test HSC-01, density = 1.90 g/cm^3 and VMA = 31.369 % 74

4.12(a) Relationship between horizontal stress and horizontal strain obtained from minute-amplitude cyclic loading test on PMA-2H from test HMC-01, density = 2.15 g/cm^3 and VMA = 22.339 % 75

4.12(b) Close-up of σ_h - ε_h relations obtained from minute-amplitude cyclic loading test on PMA-2H from test HMC-01, density = 2.15 g/cm^3 and VMA = 22.339 % 75

4.13(a) Relationship between horizontal stress and horizontal strain obtained from minute-amplitude cyclic loading test on PMA-3H from test HLC-01, density = 2.37 g/cm^3 and VMA = 14.392 % 76

4.13(b) Close-up of σ_h - ε_h relations obtained from minute-amplitude cyclic loading test on PMA-3H from test HMC-01, density = 2.37 g/cm^3 and VMA = 14.392 % 76

4.14(a) Relationship between horizontal strain and vertical strain obtained from minute-amplitude cyclic loading test on PMA-1V from test VSC-01, density = 1.90 g/cm^3 and VMA = 31.369 % 77

4.14(b) Close-up of ε_h - ε_v relations obtained from minute-amplitude cyclic loading test on PMA-1V from test VSC-01, density = 1.90 g/cm^3 and VMA = 31.369 % 77

4.15(a) Relationship between horizontal strain and vertical strain obtained from minute-amplitude cyclic loading test on PMA-2V from test VMC-01, density = 2.15 g/cm^3 and VMA = 22.339 % 78

4.15(b) Close-up of ε_h - ε_v relations obtained from minute-amplitude cyclic loading test on PMA-2V from test VMC-01, density = 2.15 g/cm^3 and VMA = 22.339 % 78

4.16(a) Relationship between horizontal strain and vertical strain obtained from minute-amplitude cyclic loading test on PMA-3V from test VLC-03, density = 2.37 g/cm^3 and VMA = 14.392 % 79

4.16(b) Close-up of ε_h - ε_v relations obtained from minute-amplitude cyclic loading test on HMA-3V from test VLC-03, density = 2.37 g/cm^3 and VMA = 14.392 % 79

4.17(a) Relationship between vertical strain and horizontal strain obtained from minute-amplitude cyclic loading test on PMA-1H from test HSC-01, density = 1.90 g/cm^3 and VMA = 31.369 % 80

4.17(b) Close-up of ε_v - ε_h relations obtained from minute-amplitude cyclic loading test on PMA-1H from test HSC-01, density = 1.90 g/cm^3 and VMA = 31.369 % 80

4.18(a) Relationship between vertical strain and horizontal strain obtained from minute-amplitude cyclic loading test on PMA-2H from test HMC-01, density = 2.15 g/cm^3 and VMA = 22.339 % 81

4.18(b) Close-up of ε_v - ε_h relations obtained from minute-amplitude cyclic loading test on PMA-2H from test HMC-01, density = 2.15 g/cm^3 and VMA = 22.339 % 81

4.19(a) Relationship between vertical strain and horizontal strain obtained from minute-amplitude cyclic loading test on PMA-3H from test HLC-01, density = 2.37g/cm^3 and VMA = 14.392 % 82

4.19(b) Close-up of ε_v - ε_h relations obtained from minute-amplitude cyclic loading test on PMA-3H from test HLC-01, density = 2.37 g/cm^3 and VMA = 14.392 % 82

4.20(a) Definition of equivalent elastic modulus for vertically compacted specimen 85

4.20(b) Definition of equivalent elastic modulus for horizontally compacted specimen 85

4.21(a) Definition of equivalent Poisson's ratio for vertically compacted specimen 86

4.21(b) Definition of equivalent Poisson's ratio for horizontally compacted Specimen 86

4.22(a) For example, to evaluations of equivalent elastic modulus at unloading from the sixth to the tenth loops at σ equal to 217 kPa 87

4.22(b) For example, to evaluations of equivalent Poisson's ration at unloading from the sixth to the tenth loops 87

4.23 For example, to evaluations of equivalent Poisson's ration which determined from the ratio of the $d\varepsilon_h / dt$ to the $d\varepsilon_v / dt$ or the $d\varepsilon_v / dt$ to the $d\varepsilon_h / dt$ 88

4.24 Relationships between void ratio function and void ratio for PMA-1V, PMA-1H, PMA-2V, PMA-2H, PMA-3V and PMA-3H 89

4.25(a) Relationships between equivalent elastic modulus and vertical stress for PMA-1V from tests VSC-01, VSC-02 and VSC-03 90

4.25(b) Relationships between equivalent elastic modulus and vertical stress for PMA-2V from tests VMC-01, VMC-02 and VMC-03 90

4.25(c) Relationships between equivalent elastic modulus and vertical stress for PMA-3V from tests VLC-01, VLC-02, VLC-03 and VLC-04 91

4.26(a) Relationships between equivalent elastic modulus and horizontal stress for PMA-1H from tests HSC-01, HSC-02 and HSC-03 92

4.26(b) Relationships between equivalent elastic modulus and horizontal stress for PMA-2H from tests HMC-01, HMC-02 and HMC-03 92

4.26(c) Relationships between equivalent elastic modulus and horizontal stress for PMA-3H from tests HLC-01, HLC-02 and HLC-03 93

4.27(a) Relationships between equivalent Poisson's ratio and vertical stress for PMA-1V from tests VSC-01, VSC-02 and VSC-03 94

4.27(b) Relationships between equivalent Poisson's ratio and vertical stress for PMA-2V from tests VMC-01, VMC-02 and VMC-03 94

4.27(c) Relationships between equivalent Poisson's ratio and vertical stress for PMA-3V from tests VLC-01, VLC-02, VLC-03 and VLC-04 95
4.28(a) Relationships between equivalent Poisson's ratio and horizontal stress for PMA-1H from tests HSC-01, HSC-02 and HSC-03 96
4.28(b) Relationships between equivalent Poisson's ratio and horizontal stress for PMA-2H from tests HMC-01, HMC-02 and HMC-03 96
4.28(c) Relationships between equivalent Poisson's ratio and horizontal stress for PMA-3H from tests HLC-01, HLC-02 and HLC-03 97
4.29(a) Comparisons of equivalent elastic modulus among PMA-1V, PMA-2V and PMA-3V as a function of vertical stress 98
4.29(b) Comparisons of equivalent elastic modulus among PMA-1H, PMA-2H and PMA-3H as a function of horizontal stress 98
4.30(a) Comparison of equivalent Poisson's ratio among PMA-1V, PMA-2V and PMA-3V as a function of vertical stress 99
4.30(b) Comparison of equivalent Poisson's ratio among PMA-1H, PMA-2H and PMA-3H as a function of horizontal stress 99
4.31(a) Equivalent elastic modulus for all densities of PMA-1V, PMA-2V and PMA-3V as a function of normalized vertical stress 100
4.31(b) Equivalent elastic modulus for all densities of PMA-1H, PMA-2H and PMA-3H as a function of normalized horizontal stress 100
4.32(a) Equivalent elastic modulus for all densities of PMA-1V, PMA-2V and PMA-3V as a function of normalized vertical stress with e_0 and $e_{current}$ 101
4.32(b) Equivalent elastic modulus for all densities of PMA-1H, PMA-2H and PMA-3H as a function of normalized horizontal stress with e_0 and $e_{current}$ 101
4.33(a) Equivalent Poisson's ratio for all densities of PMA-1V, PMA-2V and PMA-3V as a function of normalized vertical stress 102
4.33(b) Equivalent Poisson's ratio for all densities of PMA-1H, PMA-2H and PMA-3H as a function of normalized horizontal stress 102
4.34(a) Comparisons between vertical and horizontal equivalent elastic modulus for PMA-1V and PMA-1H at density of 1.90 g/cm^3 105
4.34(b) Comparisons between vertical and horizontal equivalent elastic modulus for PMA-2V and PMA-2H at density of 2.15 g/cm^3 105
4.34(c) Comparisons between vertical and horizontal equivalent elastic modulus for PMA-3V and PMA-3H at density of 2.37 g/cm^3 106
4.35(a) Comparisons between vertical and horizontal equivalent Poisson's ratio for PMA-1V and PMA-1H at density of 1.90 g/cm^3 107
4.35(b) Comparisons between vertical and horizontal equivalent Poisson's ratio for PMA-2V and PMA-2H at density of 2.15 g/cm^3 107
4.35(c) Comparisons between vertical and horizontal equivalent Poisson's ratio for PMA-3V and PMA-3H at density of 2.37 g/cm^3 108
4.36(a) Comparisons between vertical and horizontal normalized equivalent elastic modulus for all densities 109
4.36(b) Comparisons between vertical and horizontal normalized equivalent elastic modulus for all densities, linear fitted with the average m-power 109
4.37(a) Comparisons between vertical and horizontal equivalent Poisson's ratio for all densities, linear fitted with different *m*-power values 110
4.37(b) Comparisons between vertical and horizontal equivalent Poisson's ratio for all densities, linear fitted with the average *m*-power 110

4.38(a) Comparisons for equivalent elastic modulus between PMA and HMA specimen as a function of vertical stress at density of 1.90 g/cm^3 113
4.38(b) Comparisons for equivalent elastic modulus between PMA and HMA specimen as a function of vertical stress at density of 2.15 g/cm^3 113
4.38(c) Comparisons for equivalent elastic modulus between PMA and HMA specimen as a function of vertical stress at density of 2.37 g/cm^3 114
4.39(a) Comparisons for equivalent elastic modulus between PMA and HMA specimen as a function of horizontal stress at density of 1.90 g/cm^3 115
4.39(b) Comparisons for equivalent elastic modulus between PMA and HMA specimen as a function of horizontal stress at density of 2.15 g/cm^3 115
4.39(c) Comparisons for equivalent elastic modulus between PMA and HMA specimen as a function of horizontal stress at density of 2.37 g/cm^3 116
4.40(a) Comparisons for equivalent Poisson's ratio between PMA and HMA specimen as a function of vertical stress at density of 1.90 g/cm^3 117
4.40(b) Comparisons for equivalent Poisson's ratio between PMA and HMA specimen as a function of vertical stress at density of 2.15 g/cm^3 117
4.40(c) Comparisons for equivalent Poisson's ratio between PMA and HMA specimen as a function of vertical stress at density of 2.37 g/cm^3 118
4.41(a) Comparisons for equivalent Poisson's ratio between PMA and HMA specimen as a function of horizontal stress at density of 1.90 g/cm^3 119
4.41(b) Comparisons for equivalent Poisson's ratio between PMA and HMA specimen as a function of horizontal stress at density of 2.15 g/cm^3 119
4.41(c) Comparisons for equivalent Poisson's ratio between PMA and HMA specimen as a function of horizontal stress at density of 2.37 g/cm^3 120
4.42(a) Comparisons of equivalent elastic modulus for all densities of PMA and HMA as a function of normalized vertical stress 121
4.42(b) Comparisons of equivalent elastic modulus for all densities of PMA and HMA as a function of normalized horizontal stress 121
4.43(a) Comparisons of equivalent Poisson's ratio for all densities of PMA and HMA as a function of normalized vertical stress 122
4.43(b) Comparisons of equivalent Poisson's ratio for all densities of PMA and HMA as a function of normalized horizontal stress 122
4.44(a) Comparisons of equivalent elastic modulus of PMA, HMA, Hime gravel and Toyoura sand as a function of normalized vertical stress 123
4.44(b) Comparisons of equivalent elastic modulus of PMA, HMA, Hime gravel and Toyoura sand as a function of normalized horizontal stress 123
4.45(a) Comparisons between vertical and horizontal normalized equivalent elastic modulus of HMA, linear fitted with the average m-power 124
4.45(b) Comparisons between vertical and horizontal normalized equivalent elastic modulus of Hime gravel, linear fitted with the average m-power 124
4.45(c) Comparisons between vertical and horizontal normalized equivalent elastic modulus of Toyoura sand, linear fitted with the average m-power 125
A.1(a) Relationship between vertical stress and vertical strain obtained from minute cyclic loading test on PMA-1V from test VSC-02, density = 1.89 g/cm^3 and VMA = 31.731 % 135
A.1(b) Relationship between horizontal strain and vertical strain obtained from minute cyclic loading test on PMA-1V from test VSC-02, density = 1.89 g/cm^3 and VMA = 31.731 % 135

A.2(a) Relationship between vertical stress and vertical strain obtained from minute cyclic loading test on PMA-1V from test VSC-03, density = 1.90 g/cm^3 and VMA = 31.369 % 136
A.2(b) Relationship between horizontal strain and vertical strain obtained from minute cyclic loading test on PMA-1V from test VSC-03, density = 1.90 g/cm^3 and VMA = 31.369 % 136
A.3(a) Relationship between vertical stress and vertical strain obtained from minute cyclic loading test on PMA-2V from test VMC-02, density = 2.15 g/cm^3 and VMA = 22.339 % 137
A.3(b) Relationship between horizontal strain and vertical strain obtained from minute cyclic loading test on PMA-2V from test VMC-02, density = 2.15 g/cm^3 and VMA = 22.339 % 137
A.4(a) Relationship between vertical stress and vertical strain obtained from minute cyclic loading test on PMA-2V from test VMC-03, density = 2.13 g/cm^3 and VMA = 23.061 % 138
A.4(b) Relationship between horizontal strain and vertical strain obtained from minute cyclic loading test on PMA-2V from test VMC-03, density = 2.13 g/cm^3 and VMA = 23.061 % 138
A.5(a) Relationship between vertical stress and vertical strain obtained from minute cyclic loading test on PMA-3V from test VLC-02, density = 2.35 g/cm^3 and VMA = 15.114 % 139
A.5(b) Relationship between horizontal strain and vertical strain obtained from minute cyclic loading test on PMA-3V from test VLC-02, density = 2.35 g/cm^3 and VMA = 15.114 % 139
A.6(a) Relationship between vertical stress and vertical strain obtained from minute cyclic loading test on PMA-3V from test VLC-03, density = 2.35 g/cm^3 and VMA = 15.114 % 140
A.6(b) Relationship between horizontal strain and vertical strain obtained from minute cyclic loading test on PMA-3V from test VLC-03, density = 2.35 g/cm^3 and VMA = 15.114 % 140
A.7(a) Relationship between vertical stress and vertical strain obtained from minute cyclic loading test on PMA-3V from test VLC-04, density = 2.36 g/cm^3 and VMA = 14.753 % 141
A.7(b) Relationship between horizontal strain and vertical strain obtained from minute cyclic loading test on PMA-3V from test VLC-04, density = 2.36 g/cm^3 and VMA = 14.753 % 141
A.8(a) Relationship between horizontal stress and horizontal strain obtained from minute cyclic loading test on PMA-1H from test HSC-02, density = 1.92 g/cm^3 and VMA = 30.646 % 142
A.8(b) Relationship between vertical strain and horizontal strain obtained from minute cyclic loading test on PMA-1H from test HSC-02, density = 1.92 g/cm^3 and VMA = 30.646 % 142
A.9(a) Relationship between horizontal stress and horizontal strain obtained from minute cyclic loading test on PMA-1H from test HSC-03, density = 1.90 g/cm^3 and VMA = 31.369 % 143
A.9(b) Relationship between vertical strain and horizontal strain obtained from minute cyclic loading test on PMA-1H from test HSC-03, density = 1.90 g/cm^3 and VMA = 31.369 % 143

A.10(a) Relationship between horizontal stress and horizontal strain obtained from minute cyclic loading test on PMA-2H from test HMC-02, density = 2.14 g/cm^3 and VMA = 22.411 % 144
A.10(b) Relationship between vertical strain and horizontal strain obtained from minute cyclic loading test on PMA-2H from test HMC-02, density = 2.14 g/cm^3 and VMA = 22.411 % 144
A.11(a) Relationship between horizontal stress and horizontal strain obtained from minute cyclic loading test on PMA-2H from test HMC-03, density = 2.14 g/cm^3 and VMA = 22.411 % 145
A.11(b) Relationship between vertical strain and horizontal strain obtained from minute cyclic loading test on PMA-2H from test HMC-03, density = 2.14 g/cm^3 and VMA = 22.411 % 145
A.12(a) Relationship between horizontal stress and horizontal strain obtained from minute cyclic loading test on PMA-3H from test HLC-02, density = 2.36 g/cm^3 and VMA = 14.753 % 146
A.12(b) Relationship between vertical strain and horizontal strain obtained from minute cyclic loading test on PMA-3H from test HLC-02, density = 2.36 g/cm^3 and VMA = 14.753 % 146
A.13(a) Relationship between horizontal stress and horizontal strain obtained from minute cyclic loading test on PMA-3H from test HLC-03, density = 2.35 g/cm^3 and VMA = 15.114 % 147
A.13(b) Relationship between vertical strain and horizontal strain obtained from minute cyclic loading test on PMA-3H from test HLC-03, density = 2.35 g/cm^3 and VMA = 15.114 % 147
A.14(a) Equivalent elastic modulus for all densities and direction as a function of normalized stress (Assumed isotropic behaviors) 148
A.14(b) Equivalent Poisson's ratio for all densities and direction as a function of normalized stress (Assumed isotropic behaviors) 148

LIST OF SYMBOLS

A	=	temperature susceptibility
AC	=	asphaltic cements
AV	=	air voids
A_o	=	cross-sectional area of specimen before shearing
C	=	cohesion
CD	=	consolidated drained
CG	=	clip gage transducers
CL	=	cyclic loading
CRS	=	constant rate of strain
CTC	=	conventional triaxial compression
CTE	=	conventional triaxial extension
E	=	modulus of elasticity or Young's modulus
EP	=	electro pneumatic
E_{eq}	=	equivalent Young's modulus
E_h	=	horizontal elastic Young's moduli
E_v	=	vertical elastic Young's moduli
$E_{h,eq}$	=	equivalent horizontal elastic Young's moduli
$E_{v,eq}$	=	equivalent vertical elastic Young's moduli
E_0	=	initial Young's modulus
E_{50}	=	Elastic Young's modulus defined by the slope of relation between the stress and strain at the half of maximum stress
F	=	vertical force measured by load cell
e	=	void ratio
f(e)	=	void ratio function = $(2.17-e)^2/(1+e)$
G	=	shear modulus
G_s	=	specific gravity
g	=	acceleration due to gravity
H_0, L_0	=	initial height and length of the specimen
HMA	=	hot-mixed asphalt
ΔH, ΔL	=	changes in height and length of the specimen
IC	=	isotropic compression
K	=	bulk modulus
LDT	=	local deformation transducers
LVDT	=	Linear variable displacement transducer
M	=	total mass
M_B	=	mass of asphalt (binder)
M_{BA}	=	mass of absorbed asphalt, absorbed into the pores of the aggregate particles
M_{BE}	=	mass of effective asphalt, the asphalt binder between particles
M_G	=	mass of aggregate
ML	=	monotonic loading
m_h	=	slope of E_h / f(e) and σ_h / σ_0
m_v	=	slope of E_v / f(e) and σ_v / σ_0
OGFC	=	open-graded friction courses
P_B	=	asphalt content
P_{BE}	=	asphalt content

P_{BA}	=	asphalt absorption
PCC	=	Portland cement concrete
PI	=	penetration index
PSC	=	plane strain compression tests
p	=	mean stress
p'	=	mean effective stress
q	=	deviator stress
SL	=	sustained loading
SBS	=	styrene butadiene styrene
T	=	temperature
TC	=	triaxial compression
TE	=	triaxial extension
t	=	time
u	=	pore pressure
V	=	total volume of compacted mix
V_A	=	volume of air between the coated aggregate particles in the mix
V_B	=	volume of asphalt
V_{BA}	=	volume of absorbed asphalt
V_{BE}	=	volume of effective asphalt
V_G	=	volume of aggregate, the bulk volume including the aggregate pores
V_{GE}	=	effective volume of aggregate
V_{MM}	=	volume of voidless mix (maximum mix volume)
VFA	=	voids filled with asphalt
VMA	=	voids mineral aggregates
ρ	=	Density
σ_v	=	vertical stress
$\sigma_{v, max}$	=	maximum vertical stress
$\dot{\sigma}_v$	=	vertical stress rate
σ_h	=	horizontal stress
$\sigma_{h, max}$	=	maximum horizontal stress
$\dot{\sigma}_h$	=	horizontal stress rate
$\Delta\sigma_v$	=	vertical stress increments
$\Delta\sigma_h$	=	horizontal stress increments
ε	=	strain
ε_a	=	axial strain
ε_p	=	volumetric strain
ε_v	=	vertical strain
ε_h	=	horizontal strain
ε_q	=	triaxial shear strain
ε_r	=	lateral strain
ε_{vol}	=	volumetric strain in percentage
$\dot{\varepsilon}_v$	=	vertical strain rate
$\dot{\varepsilon}_h$	=	horizontal strain rate
$\Delta\varepsilon_v$	=	vertical strain increments
$\Delta\varepsilon_h$	=	horizontal strain increments
τ	=	shear strength
σ	=	normal stress
ν	=	Poisson's ratio
ν_{eq}	=	equivalent Poisson's ratio

ν_0	=	initial Poisson's ratio
ν_{vh}	=	Poisson's ratio for horizontal strain due to vertical strain
ν_{hv}	=	Poisson's ratio for vertical strain due to horizontal strain
$\nu_{vh,eq}$	=	equivalent Poisson's ratio for horizontal strain due to vertical strain
$\nu_{hv,eq}$	=	equivalent Poisson's ratio for vertical strain due to horizontal strain
ν_{hh}	=	Poisson's ratio for strain in any horizontal direction due to direct horizontal strain in the perpendicular direction
γ	=	bulk unit weight of soil