Anisotropy in hydraulic properties of unsaturated soils

Priono

2017

Priono. (2017). Anisotropy in hydraulic properties of unsaturated soils. Doctoral thesis, Nanyang Technological University, Singapore.

<http://hdl.handle.net/10356/69565>

<https://doi.org/10.32657/10356/69565>

NANYANG
TECHNOLOGICAL
UNIVERSITY

**ANISOTROPY IN
HYDRAULIC PROPERTIES OF UNSATURATED SOILS**

PRIONO
INTERDISCIPLINARY GRADUATE SCHOOL
RESIDUES AND RESOURCE RECLAMATION CENTRE
NANYANG ENVIRONMENT AND WATER RESEARCH
INSTITUTE
2017

**ANISOTROPY IN
HYDRAULIC PROPERTIES OF UNSATURATED SOILS**

PRIONO

**Interdisciplinary Graduate School
Residues and Resource Reclamation Centre
Nanyang Environment and Water Research Institute**

A thesis submitted to the Nanyang Technological University
in partial fulfilment of the requirement for the degree of
Doctor of Philosophy

2017

ACKNOWLEDGEMENTS

This thesis would not have been delivered without the guidance and the assistance of several individuals who contributed and extended their valuable support and help during my study.

I would like to express my sincere gratitude to my supervisor (Professor Harianto Rahardjo), my co-supervisor (Associate Professor Kim Neil Irvine), my former (retired) co-supervisor (Associate Professor Kalyani Chatterjea) and my mentor (Associate Professor Leong Eng Choon) for their patience, guidance, encouragement kindness and inspiration, which continuously shed some light during my study. The assistance and support from Associate Professor Wang-Jing Yuan are also greatly appreciated.

I would like to thank Mr. Vincent Heng Hiang Kim, Mr. Eugene Tan Hiap Guan and Mrs. Susie Lim-Ding for being very helpful and kind technicians in Geotechnics Laboratory, Geotechnics Research Laboratory and Geotechnics Workshop of School of Civil and Environmental Engineering (CEE).

I would like to express my gratitude to my parents (Fok Wasono and Lo Indrawati) and my brother (Fok Sugiono) for their support, encouragement and understanding throughout my study.

I would like to thank all my graduate friends and lab-mates, especially Dr. Alfrendo, Dr. Daryl, Dr. Zhai Qian, Dr. Nurly, Dr. Sugeng, Dr. Rozy, Dr. Arezoo, Dr. Reto, Dr. Zhuoyuan, Kevin, Nickanor, Jeremy, Yangyang, Nina, Wijjarni, Richard, Wengui, Martin and other friends, for their support and assistance.

Finally, I would like to acknowledge the research scholarship provided by Interdisciplinary Graduate School (IGS) and Residues and Resource Reclamation Centre (R3C), Nanyang Environment and Water Research Institute (NEWRI), Nanyang Technological University (NTU), Singapore.

ABSTRACT

Most of the rainfall-induced slope failures occurred in the unsaturated zone. A rainfall-induced slope failure preventive measure termed the Capillary Barrier System (CBS) has attracted significant interests over the past decade. A good understanding of the hydraulic properties of soil is essential in improving the performance of CBS. One aspect of the hydraulic properties of soil that is not fully understood is anisotropy, which indicates the directional-dependence. Hydraulic anisotropy is calculated by comparing the coefficient of permeability in the major and minor directions of water flow. There were no comprehensive laboratory measurements of hydraulic anisotropy behavior of soils under the saturated and unsaturated conditions.

The main objective of this research is to investigate hydraulic anisotropy behavior of soil, specifically the coefficient of permeability and soil-water characteristic curve (SWCC) of soil under the saturated and unsaturated conditions. This research focuses on studying hydraulic anisotropy behavior of homogeneous soil in two principal directions, i.e. the major (represented by vertical-layering specimens) and the minor (represented by horizontal-layering specimens) directions, under the saturated conditions and following the drying and wetting paths of unsaturated conditions.

Hydraulic anisotropy behavior of statically compacted sand-kaolin mixtures having different initial conditions and mica contents was observed following the drying and wetting paths of unsaturated conditions using direct permeability tests and indirect determination from the corresponding SWCC tests. In addition, the characteristics of both the drying and wetting SWCCs with regards to hydraulic anisotropy were observed using various measurement apparatuses (Tempe cell and pressure plate, modified triaxial SWCC and unsaturated triaxial permeameter).

The experimental results show that the initial conditions and mica content of the specimen can affect the hydraulic anisotropy measured under the saturated conditions. It was concluded that a high hydraulic anisotropy under the saturated conditions is achieved when a specimen has a high initial dry density, is compacted at a wet of optimum water content and has a moderate amount of coarse mica. In each drying and wetting path of unsaturated conditions, both the direct measurement using

permeability tests and the indirect determination from the corresponding SWCC tests agree on the observed hydraulic anisotropy values, which are consistent for all applied matric suctions. Moreover, the ratio of equilibrium times between horizontal-layering (HL) and vertical-layering (VL) of a soil measured during unsaturated permeability and SWCC tests reasonably reflects the measured hydraulic anisotropy at the corresponding matric suction. These behaviors are observed in each drying and wetting path of unsaturated conditions for each specimen, regardless the initial conditions, mica content, shape of the measured data or measurement apparatus.

By comparing the experimental results of hydraulic anisotropy under the saturated conditions and following the drying and wetting paths of unsaturated conditions, it was concluded that similar hydraulic anisotropy values are observed under the saturated conditions and drying path of unsaturated conditions. Smaller values of hydraulic anisotropy are observed in the wetting path compared to those observed in the drying path of unsaturated conditions. In addition, each drying and wetting SWCC should be considered as a scalar property (independent of the layering orientation) of the soil regardless the initial conditions, mica, shape of the measured data or measurement apparatus.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS.....	iii
ABSTRACT.....	iv
TABLE OF CONTENTS.....	vi
LIST OF TABLES.....	ix
LIST OF FIGURES	xv
LIST OF SYMBOLS	xxiii
CHAPTER 1 Introduction.....	1
1.1 Research Background	1
1.2 Significance of Research	5
1.3 Objective.....	6
1.4 Scope of Work	6
1.5 Organization of Thesis.....	7
CHAPTER 2 Literature Reviews.....	9
2.1 Unsaturated Soil Mechanics	9
2.2 Permeability	14
2.3 Soil-Water Characteristic Curve.....	25
2.4 Anisotropy.....	33
CHAPTER 3 Theory.....	46
3.1 Proposed Framework on Hydraulic Anisotropy Behavior in Unsaturated Conditions.....	46
3.2 Relationship between Grain-size Distribution and Drying Soil-Water Characteristic Curve.....	49
3.3 Relationship between Drying Soil-Water Characteristic Curve and Drying Unsaturated Permeability.....	53
3.4 Relationship between Hydraulic Anisotropy in Drying and Wetting Paths	59

CHAPTER 4 Research Methodology	61
4.1 Laboratory Work.....	61
4.1.1 Soil Design for Laboratory Tests.....	61
4.1.2 Standard Compaction Tests	65
4.1.3 Static Compaction Tests and Specimen Preparation	67
4.1.4 Index Properties Tests.....	77
4.1.5 Permeability Tests.....	78
4.1.5.1 Saturated Permeability Tests.....	78
4.1.5.2 Unsaturated Permeability Tests	82
4.1.6 Soil-Water Characteristic Curve Tests.....	94
4.1.6.1 Tempe Cell and Pressure Plate Tests	94
4.1.6.2 Modified Triaxial SWCC Tests	99
4.2 Numerical Modeling	101
4.3 Criteria for Evaluation Procedures.....	106
 CHAPTER 5 Presentation of Results	 108
5.1 Index Properties	108
5.2 Particle Shape.....	112
5.3 Compaction Curve	114
5.4 Saturated Permeability	117
5.5 Unsaturated Permeability.....	120
5.6 Soil-Water Characteristic Curve.....	138
5.7 Numerical Modeling	148
 CHAPTER 6 Discussion of Results.....	 153
6.1 Hydraulic Anisotropy Behavior under the Saturated Conditions	153
6.2 Hydraulic Anisotropy Behavior in the Drying Path of Unsaturated Conditions	161
6.3 Hydraulic Anisotropy Behavior in the Wetting Path of Unsaturated Conditions.....	198
6.4 Comparison between Hydraulic Anisotropy Values under the Saturated Conditions and following the Drying and Wetting Paths of Unsaturated Conditions	231

6.5 Characteristics of the Drying Soil-Water Characteristic Curve with regards to Hydraulic Anisotropy.....	239
6.6 Characteristics of the Wetting Soil-Water Characteristic Curve with regards to Hydraulic Anisotropy.....	257
 CHAPTER 7 Conclusions and Recommendations	270
7.1 Conclusions.....	270
7.2 Recommendations.....	273
7.3 Publications.....	274
 REFERENCES	275
APPENDIX A.....	285
APPENDIX B	288

LIST OF TABLES

Table 2.1 Saturated permeability testing standards	19
Table 4.1 Types of 50S50K specimens tested in the research	63
Table 4.2 Types of soil mixtures tested in the research	64
Table 4.3 List of all specimens used in the laboratory tests	76
Table 4.4 Index properties testing standards.....	77
Table 4.5 Specimens tested in the unsaturated permeability tests	82
Table 4.6 Matric suction intervals for 50S50K specimens (C).....	90
Table 4.7 Matric suction intervals for 50S50K (B) and specimens with 9% coarse mica.....	91
Table 5.1 Summary of physical properties of 50S50K soil mixtures	109
Table 5.2 Summary of physical properties of micaceous soil mixtures	110
Table 5.3 Qualitative shape parameters of each soil particle.....	114
Table 5.4 Maximum dry density and optimum water content of each soil mixture ..	116
Table 5.5 Saturated permeability and corresponding hydraulic anisotropy of each specimen	118
Table 5.6 Typical times needed to complete a cycle of drying and wetting unsaturated permeability tests using only one permeameter.....	120
Table 5.7 Typical times needed to complete a cycle of drying and wetting unsaturated permeability tests using the 1 bar permeameter (matric suction up to 90 kPa)	123
Table 5.8 Typical times needed to complete a cycle of drying and wetting unsaturated permeability tests using the 5 bar permeameter (matric suction up to 400 kPa)	125
Table 5.9 Physical properties of each specimen during initial and final conditions in the unsaturated permeability test	126
Table 5.10 Measured coefficients of unsaturated permeability of 50S50K (B)	128
Table 5.11 Measured coefficients of unsaturated permeability of 50S50K (C)	129
Table 5.12 Measured coefficients of unsaturated permeability of specimens with 9% coarse mica.....	130
Table 5.13 Equilibrium times of 50S50K (C) during the drying SWCC tests using all measurement apparatuses performed in numerical modeling.....	151

Table 5.14 Equilibrium times of 50S50K (D) having different heights during the drying SWCC tests using the Tempe cell and pressure plate apparatuses performed in numerical modeling	151
Table 6.1 Measured hydraulic anisotropy values of 50S50K (B) in the drying path of unsaturated conditions	162
Table 6.2 Measured hydraulic anisotropy values of 50S50K (C) in the drying path of unsaturated conditions	163
Table 6.3 Measured hydraulic anisotropy values of specimens with 9% coarse mica in the drying path of unsaturated conditions	164
Table 6.4 Bimodal fitting parameters of the measured drying SWCC data of 50S50K (B)	168
Table 6.5 Unimodal fitting parameters of the measured drying SWCC data of 50S50K (C)	170
Table 6.6 Bimodal fitting parameters of the measured drying SWCC data of specimens with 9% coarse mica	173
Table 6.7 Estimated drying hydraulic anisotropy values of 50S50K (B) from the measured drying SWCC using the Tempe cell and pressure plate apparatuses	176
Table 6.8 Estimated drying hydraulic anisotropy values of 50S50K (B) from the measured drying SWCC using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses	177
Table 6.9 Estimated drying hydraulic anisotropy values of 50S50K (C) from the measured drying SWCC using the Tempe cell and pressure plate apparatuses	178
Table 6.10 Estimated drying hydraulic anisotropy values of 50S50K (C) from the measured drying SWCC using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses	179
Table 6.11 Estimated drying hydraulic anisotropy values of specimens with 9% coarse mica from the measured drying SWCC using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses	180
Table 6.12 Ratio of equilibrium times observed during the drying permeability test compared to the measured hydraulic anisotropy for 50S50K (B)	187
Table 6.13 Ratio of equilibrium times observed during the drying permeability test compared to the measured hydraulic anisotropy for 50S50K (C)	187

Table 6.14 Ratio of equilibrium times observed during the drying permeability test compared to the measured hydraulic anisotropy for specimens with 9% coarse mica	188
Table 6.15 Ratio of equilibrium times observed during the drying SWCC test using the Tempe cell and pressure plate compared to the measured hydraulic anisotropy for 50S50K (B)	191
Table 6.16 Ratio of equilibrium times observed during the drying SWCC test using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses compared to the measured hydraulic anisotropy for 50S50K (B)	192
Table 6.17 Ratio of equilibrium times observed during the drying SWCC test using the Tempe cell and pressure plate apparatuses compared to the measured hydraulic anisotropy for 50S50K (C)	193
Table 6.18 Ratio of equilibrium times observed during the drying SWCC test using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses compared to the measured hydraulic anisotropy for 50S50K (C)	194
Table 6.19 Ratio of equilibrium times observed during the drying SWCC test using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses compared to the measured hydraulic anisotropy for specimens with 9% coarse mica	196
Table 6.20 Measured hydraulic anisotropy values of 50S50K (B) in the wetting path of unsaturated conditions	200
Table 6.21 Measured hydraulic anisotropy values of 50S50K (C) in the wetting path of unsaturated conditions	201
Table 6.22 Measured hydraulic anisotropy values of specimens with 9% coarse mica in the wetting path of unsaturated conditions	202
Table 6.23 Unimodal fitting parameters of the measured wetting SWCC data of 50S50K (B)	204
Table 6.24 Unimodal fitting parameters of the measured wetting SWCC data of 50S50K (C)	206
Table 6.25 Unimodal fitting parameters of the measured wetting SWCC data of specimens with 9% coarse mica	208
Table 6.26 Estimated wetting hydraulic anisotropy values of 50S50K (B) from the measured wetting SWCC using the Tempe cell and pressure plate apparatuses	210

Table 6.27 Estimated wetting hydraulic anisotropy values of 50S50K (B) from the measured wetting SWCC using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses	211
Table 6.28 Estimated wetting hydraulic anisotropy values of 50S50K (C) from the measured wetting SWCC using the Tempe cell and pressure plate apparatuses	212
Table 6.29 Estimated wetting hydraulic anisotropy values of 50S50K (C) from the measured wetting SWCC using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses	213
Table 6.30 Estimated wetting hydraulic anisotropy values of specimens with 9% coarse mica from the measured wetting SWCC using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses	214
Table 6.31 Ratio of equilibrium times observed during the wetting permeability test compared to the measured hydraulic anisotropy for 50S50K (B)	220
Table 6.32 Ratio of equilibrium times observed during the wetting permeability test compared to the measured hydraulic anisotropy for 50S50K (C)	221
Table 6.33 Ratio of equilibrium times observed during the wetting permeability test compared to the measured hydraulic anisotropy for specimens with 9% coarse mica	221
Table 6.34 Ratio of equilibrium times observed during the wetting SWCC test using the Tempe cell and pressure plate apparatuses compared to the measured hydraulic anisotropy for 50S50K (B).....	224
Table 6.35 Ratio of equilibrium times observed during the wetting SWCC test using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses compared to the measured hydraulic anisotropy for 50S50K (B)	225
Table 6.36 Ratio of equilibrium times observed during the wetting SWCC test using the Tempe cell and pressure plate apparatuses compared to the measured hydraulic anisotropy for 50S50K (C).....	226
Table 6.37 Ratio of equilibrium times observed during the wetting SWCC test using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses compared to the measured hydraulic anisotropy for 50S50K (C)	227
Table 6.38 Ratio of equilibrium times observed during the wetting SWCC test using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses compared to the measured hydraulic anisotropy for specimens with 9% coarse mica	229

Table 6.39 Ratio of the measured hydraulic anisotropy values in all conditions for each specimen	234
Table 6.40 Ratio of the estimated hydraulic anisotropy values from the corresponding SWCC in following the drying and wetting paths of unsaturated conditions for each specimen	235
Table 6.41 Comparison of the mean values of ratio of equilibrium times during the drying and wetting unsaturated permeability tests for each specimen	237
Table 6.42 Comparison of the mean values of ratio of equilibrium times during the drying and wetting SWCC tests for each specimen.....	237
Table 6.43 Bimodal fitting parameters of the measured drying SWCC data of 50S50K (A) and the summarized R^2 analyses	241
Table 6.44 Bimodal fitting parameters of the measured drying SWCC data of 50S50K (B) and the summarized R^2 analyses	242
Table 6.45 Unimodal fitting parameters of the measured drying SWCC data of 50S50K (C) and the summarized R^2 analyses	243
Table 6.46 Unimodal fitting parameters of the measured drying SWCC data of 50S50K (D) having different heights and the summarized R^2 analyses.....	244
Table 6.47 Bimodal fitting parameters of the measured drying SWCC data of specimens with 9% coarse mica and the summarized R^2 analyses.....	245
Table 6.48 Bimodal fitting parameters of the measured drying SWCC data of specimens with 20% coarse mica and the summarized R^2 analyses.....	246
Table 6.49 Ratio of equilibrium times observed during the drying SWCC test compared to the measured hydraulic anisotropy under the saturated conditions for 50S50K (A).....	249
Table 6.50 Ratio of equilibrium times observed during the drying SWCC test compared to the measured hydraulic anisotropy under the saturated conditions for 50S50K (D) with a 30 mm height.....	250
Table 6.51 Ratio of equilibrium times observed during the drying SWCC test compared to the measured hydraulic anisotropy under the saturated conditions for 50S50K (D) with a 50 mm height.....	251
Table 6.52 Ratio of equilibrium times observed during the drying SWCC test as compared to the measured hydraulic anisotropy under the saturated conditions for specimens with 20% coarse mica	252

Table 6.53 Relative differences between the mean ratio of equilibrium times during the drying SWCC test using various apparatuses observed in the laboratory tests and numerical modeling	256
Table 6.54 Unimodal fitting parameters of the measured wetting SWCC data of 50S50K (A) and the summarized R^2 analyses	259
Table 6.55 Unimodal fitting parameters of the measured wetting SWCC data of 50S50K (B) and the summarized R^2 analyses	259
Table 6.56 Unimodal fitting parameters of the measured wetting SWCC data of 50S50K (C) and the summarized R^2 analyses	260
Table 6.57 Unimodal fitting parameters of the measured wetting SWCC data of 50S50K (D) and the summarized R^2 analyses	261
Table 6.58 Unimodal fitting parameters of the measured wetting SWCC data of specimen with 9% coarse mica and the summarized R^2 analyses	261
Table 6.59 Unimodal fitting parameters of the measured wetting SWCC data of specimen with 20% coarse mica and the summarized R^2 analyses	262
Table 6.60 Ratio of equilibrium times observed during the wetting SWCC test compared to the measured hydraulic anisotropy under the saturated conditions for 50S50K (A).....	265
Table 6.61 Ratio of equilibrium times observed during the wetting SWCC test compared to the measured hydraulic anisotropy under the saturated conditions for 50S50K (D) with a 30 mm height.....	266
Table 6.62 Ratio of equilibrium times observed during the wetting SWCC test compared to the measured hydraulic anisotropy under the saturated conditions for 50S50K (D) with a 50 mm height.....	267
Table 6.63 Ratio of equilibrium times observed during the wetting SWCC test compared to the measured hydraulic anisotropy under the saturated conditions for specimens with 20% coarse mica	268

LIST OF FIGURES

Figure 1.1 Conceptual sketch of Capillary Barrier System (after Tami et al., 2004)	4
Figure 2.1 Conceptualized three-phases system of unsaturated soil (after Fredlund and Rahardjo, 1993).....	10
Figure 2.2 Conceptualized four-phases system of unsaturated soil (after Fredlund and Rahardjo, 1993).....	10
Figure 2.3 Illustration of typical unsaturated zone in the slope (after Rahardjo et al., 2007)	12
Figure 2.4 Capillary phenomena with different capillary tubes as analogy to different radius of curvature in a soil pore (after Janssen and Dempsey, 1980)	13
Figure 2.5 Schematic layout of flexible wall permeameter developed by Huang et al. (1998).....	21
Figure 2.6 Schematic layout of flexible wall permeameter developed by Ho (1998).....	21
Figure 2.7 Typical relationships between permeability and soil-water characteristic curve (after Rahardjo et al., 2007)	22
Figure 2.8 Typical drying and wetting SWCCs (after Satyanaga et al., 2013).....	27
Figure 2.9 Ink-bottle effect and different contact angle during drying and wetting (after Bear and Verruijt, 1987).....	28
Figure 2.10 Typical SWCC from different type of soil (modified after Fredlund et al., 1994)	29
Figure 2.11 Typical SWCCs of soil having different initial dry densities (after Yang et al., 2004)	30
Figure 2.12 Hypothesized Bridging and Ordering of the soil structure (after Lee et al., 2007).....	36
Figure 2.13 Typical soil structures as a function of water content at compaction (after Mitchell and Soga, 2005).....	38
Figure 2.14 Typical soil structure compacted on (a) dry side of optimum and (b) wet side of optimum (after Cui, 1993).....	39
Figure 2.15 Preparing specimens for hydraulic anisotropy test by cutting method (after Chapuis and Gill, 1989)	40
Figure 2.16 Special radial flow test for measuring hydraulic anisotropy (after Chapuis and Gill, 1989)	41

Figure 2.17 Conceptual sketch of possible structures of Miller-similar porous media: (a) isotropic, (b) anisotropic density of the pores and isotropic PSD, (c) isotropic density of the pores and anisotropic PSD, (d) anisotropic density of the pores and anisotropic PSD (after Ursino et al., 2000).....	43
Figure 2.18 Parallel-plate TDR and electrical conductivity measurement cells (after Blonquist et al., 2006).....	44
Figure 3.1 Illustration of unsaturated soil elements (modified after Fredlund et al., 2012).....	47
Figure 3.2 Conceptual sketch of horizontal-layering and vertical-layering specimens from a statically compacted soil mixture (after Priono et al., 2016a).....	48
Figure 3.3 Proposed framework on hydraulic anisotropy behavior of soil following the drying and wetting paths of unsaturated condition.....	49
Figure 3.4 An expected GSD of HL and VL specimens for a given soil sample	50
Figure 3.5 Expected SWCC of HL and VL specimens	52
Figure 3.6 Expected hydraulic anisotropy behavior on saturated conditions and drying path of unsaturated conditions	54
Figure 3.7 Expected equilibrium time during SWCC tests of HL and VL specimens	59
Figure 4.1 Constituents of soil mixture tested in the research.....	65
Figure 4.2 Standard compaction test performed in the research.....	66
Figure 4.3 Typical compaction curve	66
Figure 4.4 Model for calculating minimum size of compaction mould for VL specimen	68
Figure 4.5 Static compaction test performed in the research.....	69
Figure 4.6 (a) Removable disk; (b) Connection between two adjacent disks; (c) Stainless steel plug (after Ong, 1999).....	69
Figure 4.7 Static compaction setup used for HL specimen	70
Figure 4.8 Static compaction setup used for VL specimen	72
Figure 4.9 Initial block of soil sample and cutters used for preparing VL specimens	73
Figure 4.10 Cutting a rectangular section from a large block of VL sample.....	74
Figure 4.11 Cutting a circular section from a rectangular VL sample.....	74
Figure 4.12 A final VL specimen	75
Figure 4.13 Typical HL and VL specimens for a given soil mixture tested in the research	75
Figure 4.14 Particle regularity chart (after Krumbein and Sloss, 1963).....	78

Figure 4.15 Schematic diagram of saturated triaxial permeameter used	79
Figure 4.16 Saturated triaxial permeameter used in the research	80
Figure 4.17 Unsaturated triaxial permeameter used in the research	83
Figure 4.18 Modified pedestals and modified ceramic disks used in the unsaturated triaxial permeameter in the research	84
Figure 4.19 Outlets setup in the unsaturated triaxial permeameter	85
Figure 4.20 Complete setup of the unsaturated triaxial permeameter used in the research	86
Figure 4.21 Schematic diagram of the unsaturated triaxial permeameter setup	87
Figure 4.22 Pressure-temperature paths for solid-liquid-vapor phases (after Lu and Likos, 2004)	89
Figure 4.23 A three-layered system for unsaturated permeability calculation	93
Figure 4.24 Schematic diagram of Tempe cell	95
Figure 4.25 Tempe cell test performed in the research	96
Figure 4.26 Pressure plate test performed in the research	98
Figure 4.27 Modified triaxial SWCC used in the research	100
Figure 4.28 Typical initial conditions for numerical modeling of SWCC tests using conventional Tempe cell and pressure plate apparatuses	102
Figure 4.29 Typical initial conditions for numerical modeling of SWCC tests using modified triaxial SWCC and unsaturated triaxial permeameter apparatuses	102
Figure 5.1 GSD curves of all soil mixtures	111
Figure 5.2 Typical pre-test and post-test of GSD curves of the specimen	112
Figure 5.3 Overview SEM imaging of soil particles used in the research	113
Figure 5.4 SEM imaging of (a) sand, (b) coarse mica, (c) medium mica and (d) kaolin particles	113
Figure 5.5 Compaction curves of all soil mixtures used in the research obtained using Standard Proctor tests	115
Figure 5.6 Different initial compaction conditions of 50S50K specimens	116
Figure 5.7 Measured drying unsaturated permeability of 50S50K (B)	131
Figure 5.8 Measured wetting unsaturated permeability of 50S50K (B)	132
Figure 5.9 Measured drying unsaturated permeability of 50S50K (C)	132
Figure 5.10 Measured wetting unsaturated permeability of 50S50K (C)	133
Figure 5.11 Measured drying unsaturated permeability of specimens with 9% coarse mica	133

Figure 5.12 Measured wetting unsaturated permeability of specimens with 9% coarse mica.....	134
Figure 5.13 Typical water volume change curve during unsaturated permeability measurement of applied matric suction up to 75 kPa in the drying test and from 50 kPa in the wetting test.....	135
Figure 5.14 Typical water volume change curve during unsaturated permeability measurement of applied matric suction from 90 kPa in the drying test and up to 75 kPa in the wetting test.....	136
Figure 5.15 Typical volumetric strains of the specimen tested in the research	137
Figure 5.16 Measured drying SWCC data of 50S50K (A) using the Tempe cell and pressure plate apparatuses.....	139
Figure 5.17 Measured wetting SWCC data of 50S50K (A) using the Tempe cell and pressure plate apparatuses.....	140
Figure 5.18 Measured drying SWCC data of 50S50K (B) using the Tempe cell and pressure plate, modified triaxial SWCC and unsaturated triaxial permeameter apparatuses.....	140
Figure 5.19 Measured wetting SWCC data of 50S50K (B) using the Tempe cell and pressure plate, modified triaxial SWCC and unsaturated triaxial permeameter apparatuses.....	141
Figure 5.20 Measured drying SWCC data of 50S50K (C) using the Tempe cell and pressure plate, modified triaxial SWCC and unsaturated triaxial permeameter apparatuses.....	141
Figure 5.21 Measured wetting SWCC data of 50S50K (C) using the Tempe cell and pressure plate, modified triaxial SWCC and unsaturated triaxial permeameter apparatuses.....	142
Figure 5.22 Measured drying SWCC data of 50S50K (D) using the Tempe cell and pressure plate apparatuses.....	142
Figure 5.23 Measured wetting SWCC data of 50S50K (D) using the Tempe cell and pressure plate apparatuses.....	143
Figure 5.24 Measured drying SWCC data of specimens with 9% coarse mica using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses	143
Figure 5.25 Measured wetting SWCC data of specimens with 9% coarse mica using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses	144

Figure 5.26 Measured drying SWCC data of specimens with 20% coarse mica using the Tempe cell and pressure plate apparatuses	144
Figure 5.27 Measured wetting SWCC data of specimens with 20% coarse mica using the Tempe cell and pressure plate apparatuses	145
Figure 5.28 Typical water volume change curve during SWCC measurements at matric suctions higher than the AEV in the drying tests and up to 20 kPa in the wetting tests	147
Figure 5.29 Typical measured drying and wetting gravimetric SWCCs of the specimen	148
Figure 5.30 Typical volumetric water content outputs from numerical modeling of the drying SWCC test at matric suction less than the AEV	149
Figure 5.31 Typical volumetric water content outputs from numerical modeling of the drying SWCC test at matric suctions higher than the AEV	150
Figure 6.1 Measured saturated permeability values of the specimens without mica content having different initial water content	154
Figure 6.2 Regression analysis between hydraulic anisotropy values measured under the saturated conditions and initial water content during compaction	155
Figure 6.3 Measured saturated permeability values of the specimens without mica content plotted at initial and final void ratio	157
Figure 6.4 Measured saturated permeability values of the specimens having 9% and 20% mica content	158
Figure 6.5 Regression analysis between hydraulic anisotropy values measured under the saturated conditions and mica contents in the specimens	159
Figure 6.6 Measured hydraulic anisotropy of 50S50K (B) under the saturated conditions and following the drying path of unsaturated conditions	165
Figure 6.7 Measured hydraulic anisotropy of 50S50K (C) under the saturated conditions and following the drying path of unsaturated conditions	165
Figure 6.8 Best fitting for the measured drying SWCC data of 50S50K (B) based on the Tempe cell and pressure plate measurements	169
Figure 6.9 Best fitting for the measured drying SWCC data of 50S50K (B) based on the modified triaxial SWCC measurements	169
Figure 6.10 Best fitting for the measured drying SWCC data of 50S50K (B) based on the unsaturated triaxial permeameter measurements	170

Figure 6.11 Best fitting for the measured drying SWCC data of 50S50K (C) based on the Tempe cell and pressure plate measurements	171
Figure 6.12 Best fitting for the measured drying SWCC data of 50S50K (C) based on the modified triaxial SWCC measurements.....	171
Figure 6.13 Best fitting for the measured drying SWCC data of 50S50K (C) based on the unsaturated triaxial permeameter measurements	172
Figure 6.14 Best fitting for the measured drying SWCC data of specimens with 9% coarse mica based on the modified triaxial SWCC measurements.....	174
Figure 6.15 Best fitting for the measured drying SWCC data of specimens with 9% coarse mica based on the unsaturated triaxial permeameter measurements	174
Figure 6.16 Comparison between the measured and the estimated unsaturated coefficients of permeability of 50S50K (B) in the drying path of unsaturated conditions.....	183
Figure 6.17 Comparison between the measured and the estimated unsaturated coefficients of permeability of 50S50K (C) in the drying path of unsaturated conditions.....	184
Figure 6.18 Comparison between the measured and the estimated unsaturated coefficients of permeability of specimens with 9% coarse mica in the drying path of unsaturated conditions	184
Figure 6.19 Relative differences between the mean values of drying hydraulic anisotropy obtained using the direct measurement and the indirect determination from the corresponding measured drying SWCC obtained using various apparatuses for each specimen	185
Figure 6.20 Comparison between the measured hydraulic anisotropy and the corresponding measured ratio of equilibrium times during the drying SWCC tests for 50S50K (B).....	190
Figure 6.21 Comparison between the measured hydraulic anisotropy and the corresponding measured ratio of equilibrium times during the drying SWCC tests for 50S50K (C)	193
Figure 6.22 Comparison between the measured hydraulic anisotropy and the corresponding measured ratio of equilibrium times during the drying SWCC tests for specimens with 9% coarse mica	195
Figure 6.23 Best fitting for the measured wetting SWCC data of 50S50K (B) based on the Tempe cell and pressure plate measurements	204

Figure 6.24 Best fitting for the measured wetting SWCC data of 50S50K (B) based on the modified triaxial SWCC measurements.....	205
Figure 6.25 Best fitting for the measured wetting SWCC data of 50S50K (B) based on the unsaturated triaxial permeameter measurements	205
Figure 6.26 Best fitting for the measured wetting SWCC data of 50S50K (C) based on the Tempe cell and pressure plate measurements	206
Figure 6.27 Best fitting for the measured wetting SWCC data of 50S50K (C) based on the modified triaxial SWCC measurements.....	207
Figure 6.28 Best fitting for the measured wetting SWCC data of 50S50K (C) based on the unsaturated triaxial permeameter measurements	207
Figure 6.29 Best fitting for the measured wetting SWCC data of specimens with 9% coarse mica based on the modified triaxial SWCC measurements.....	208
Figure 6.30 Best fitting for the measured wetting SWCC data of specimens with 9% coarse mica based on the unsaturated triaxial permeameter measurements	209
Figure 6.31 Comparison between the measured and the estimated unsaturated coefficients of permeability of 50S50K (B) in the wetting path of unsaturated conditions.....	217
Figure 6.32 Comparison between the measured and the estimated unsaturated coefficients of permeability of 50S50K (C) in the wetting path of unsaturated conditions.....	217
Figure 6.33 Comparison between the measured and the estimated unsaturated coefficients of permeability of specimens with 9% coarse mica in the wetting path of unsaturated conditions	218
Figure 6.34 Relative differences between the mean values of wetting hydraulic anisotropy obtained using the direct measurement and the indirect determination from the corresponding measured wetting SWCC obtained using various apparatuses for each specimen	218
Figure 6.35 Comparison between the measured hydraulic anisotropy and the corresponding measured ratio of equilibrium times during the wetting SWCC tests for 50S50K (B).....	223
Figure 6.36 Comparison between the measured hydraulic anisotropy and the corresponding measured ratio of equilibrium times during the wetting SWCC tests for 50S50K (C).....	226

Figure 6.37 Comparison between the measured hydraulic anisotropy and the corresponding measured ratio of equilibrium times during the wetting SWCC tests for specimens with 9% coarse mica	228
Figure 6.38 Comparison of the measured hydraulic anisotropy values in all conditions for each specimen	233
Figure 6.39 Comparison between the estimated hydraulic anisotropy values from the corresponding SWCC in following the drying and wetting paths of unsaturated conditions for each specimen.....	234
Figure 6.40 Comparison between the ratio of equilibrium times during the drying SWCC tests using various measurement apparatuses observed in the laboratory tests and numerical modeling for 50S50K (C).....	255
Figure 6.41 Comparison between the ratio of equilibrium times during the drying SWCC tests using various measurement apparatuses observed in the laboratory tests and numerical modeling for 50S50K (D) with heights of 30 mm and 50 mm	255
Figure A.1 Best fitting for the measured drying SWCC data of 50S50K (A) based on the Tempe cell and pressure plate measurements	285
Figure A.2 Best fitting for the measured drying SWCC data of 50S50K (D) based on the Tempe cell and pressure plate measurements on 50S50K (D) with a 30 mm height	286
Figure A.3 Best fitting for the measured drying SWCC data of 50S50K (D) based on the Tempe cell and pressure plate measurements on 50S50K (D) with a 50 mm height	286
Figure A.4 Best fitting for the measured drying SWCC data of specimens with 20% coarse mica based on the modified triaxial SWCC measurements.....	287
Figure B.1 Best fitting for the measured wetting SWCC data of 50S50K (A) based on the Tempe cell and pressure plate measurements	288
Figure B.2 Best fitting for the measured wetting SWCC data of 50S50K (D) based on the Tempe cell and pressure plate measurements on 50S50K (D) with a 30 mm height	289
Figure B.3 Best fitting for the measured wetting SWCC data of 50S50K (D) based on the Tempe cell and pressure plate measurements on 50S50K (D) with a 50 mm height	289
Figure B.4 Best fitting for the measured wetting SWCC data of specimens with 20% coarse mica based on the modified triaxial SWCC measurements.....	290

LIST OF SYMBOLS

A	= cross-sectional area
α	= contact angle between soil particle and water
AEV	= air-entry value
ARD	= average relative difference
b	= coefficient of water volume change
c_v^w	= coefficient of consolidation with respect to water phase
d	= diameter of soil particle
D	= diffusivity coefficient
Δ_r	= relative difference
e	= void ratio
E	= Young's modulus
E_{total}	= total energy
ε	= normal strain
ε_v	= volumetric strain
g	= gravitational acceleration
G	= shear modulus
G_s	= specific gravity
γ	= shear strain
$\gamma_{a,o}$	= unit weight of dry air
γ_w	= unit weight of water
h	= hydraulic head
h_l	= head loss
H_{dr}	= drainage path length
i	= hydraulic gradient

η	= kinematic viscosity
K	= intrinsic permeability
k_a	= air coefficient of permeability
k_d	= air coefficient of permeability at dry condition
$k_{a,diffusion}$	= air diffusion permeability
k_f	= fluid permeability
k_s	= saturated coefficient of permeability
k_w	= water coefficient of permeability
L	= length
LL	= liquid limit
μ	= absolute viscosity
m_s	= mass of soil solids
m_w	= mass of water
m_2^w	= coefficient of volume change with respect to water phase
μ	= viscosity of water
N	= total number of data
P	= pressure
PI	= plasticity index
PL	= plastic limit
q	= volumetric rate of water flow
Q	= volumetric water flow
Q_f	= applied flux boundary
θ_a	= volumetric air content
θ_s	= saturated volumetric water content
θ_w	= volumetric water content

r	= pore radius
R	= molar constant of dry air
R^2	= coefficient of determination
R_{shape}	= roundness of particle shape
r_h	= hydraulic radius
r_{max}	= maximum pore size radius
$\rho_{a,o}$	= density of dry air
ρ_d	= dry density
$\rho_{d, \text{max}}$	= maximum dry density
ρ_{shape}	= regularity of particle shape
ρ_w	= density of water
S	= degree of saturation
S_{shape}	= sphericity of particle shape
SSE	= sum of squared errors
SST	= total sum of squares
σ	= normal stress
t	= time
t_{eq}	= equilibrium time
t_{90}	= time required to achieve 90% consolidation
T_{90}	= time factor corresponding to 90% consolidation
T	= temperature
τ	= shear stress
u_a	= pore-air pressure
$u_{a, \text{abs}}$	= absolute air pressure
u_w	= pore-water pressure

ν	= Poisson's ratio
v	= average velocity of water flow
V	= volume of soil
V_w	= volume of water
w	= gravimetric water content
w_{opt}	= optimum water content
w_{sat}	= saturated water content
WEV	= water-entry value
ψ	= $(u_a - u_w)$ = matric suction
ψ_r	= matric suction corresponding to residual volumetric water content
z	= elevation head

CHAPTER 1 INTRODUCTION

In this chapter, the motivation to do this research is firstly explained. Next, the objectives and the scope of the work carried out are defined. The main results are then elaborated and, lastly, the organization of the thesis is presented.

1.1 Research Background

Climate change has attracted vast attention from all over the world in the past decade (Priono et al., 2013). Many aspects of life are affected by this phenomenon. In geo-environmental aspects, climate change contributes significantly towards one of the most frequently occurring failures around the world: that is rainfall-induced slope failure (Rahardjo et al., 2012a). Climate change has triggered a longer dry season and more extreme precipitation during the wet season than ever before in the United Kingdom (Mendes, 2011). In the United States (Kunkel, 2003), China (Zhai et al., 2005), Japan (Fujibe, 2008) and Australia (Gallant et al., 2007), the same trend of rainfall has been widely reported to become even more extreme. In Singapore, more rainy days with a higher rainfall intensity over a shorter period has also been observed (National Environmental Agency, 2010). Due to its location in the humid tropics, climatic conditions in Singapore are generally characterized by abundant rainfalls. Global warming and the urban heat island effect could play a significant role in enhancing the volume and intensity of precipitation as recorded by National Environmental Agency (2010), which has subsequently become a major concern in Singapore.

Springman et al. (2003) suggested that the most detrimental factors for slope failures in Switzerland were snowmelt and rainfall infiltration. Evangelista et al. (2008) and Papa et al. (2008) showed the significance of rainfall infiltration on slope failures in

Naples, Italy. In Singapore, previous research by Chatterjea (1989), Toll et al. (1999), Rahardjo et al. (2001) and Rahardjo et al. (2013) illustrated that many natural slopes failed during heavy rainfalls. Most of the rainfall-induced slope failures occurred in the unsaturated zone, i.e. in soil above the ground water table (Ng et al., 2008; Fredlund et al., 2012; Rahardjo et al., 2013). Cases of slope failure almost always have significant consequences, such as the loss of life, loss of infrastructure and slope restoration costs. Hence, there is a need to develop rainfall-induced slope failure preventive measures.

A rainfall-induced slope failure preventive measure termed the Capillary Barrier System (CBS) has attracted significant interests over the past decade (Tami et al., 2004; Krisdani et al., 2006; Rahardjo et al., 2012b; Harnas et al., 2014). CBS is an environmentally-friendly and sustainable slope cover system which has advantages such as reducing surface runoff (the root cause of flash flooding) and the possibility of using recycled materials (recycled asphalt or concrete) with vegetation on top of the CBS. Principally, CBS is a slope cover system that consists of a fine-grained soil layer overlying a coarse-grained soil layer in order to prevent rainfall infiltration into the slope. Rainfall infiltration into the unsaturated zone of the slope should be prevented because it will cause the buildup of pore-water pressure in the slope, decrease the matric suction as well as the unsaturated shear strength of the slope and, when the Factor of Safety is less than one, rainfall-induced slope failure will occur. This concept of CBS has also been used in landfill covers and mine waste cover systems to control the infiltration of water and the ingress of oxygen in order to prevent adverse contamination (Bussiere, 2004; Aubertin et al., 2009).

Rainfall-induced slope failure preventive measures, especially CBS, require a good understanding of unsaturated soil mechanics. Soils exhibit different behaviors during

unsaturated conditions as compared to saturated conditions. Matric suction (negative pore-water pressure) is present in unsaturated soils, and the water content of such soils varies according to the matric suction. The relationship between matric suction and water content is termed the soil-water characteristic curve (SWCC) and it is closely related to water flow in a soil, which is indicated by the unsaturated coefficient of permeability. Both SWCC and permeability are fundamental hydraulic properties of a soil (Fredlund and Rahardjo, 1993).

CBS uses the concept of different coefficients of unsaturated permeability between fine-grained and coarse-grained soils. Fine-grained soil can have higher coefficients of unsaturated permeability than coarse-grained soil under unsaturated conditions. As a consequence, rainfalls can only infiltrate and flow along the fine-grained soil as shown in Figure 1.1. Volumetric water content of the fine-grained soil increases and consequently, the coefficient of permeability of the fine-grained soil increases as the infiltration continues. When the infiltrating water reaches the interface between fine-grained and coarse-grained soils, matric suction of the coarse-grained soil will decrease. A breakthrough condition starts to occur when the matric suction reaches water-entry value of the coarse-grained soil and subsequently, water starts to flow into the coarse-grained layer. This breakthrough condition must be avoided in order to maintain effectiveness of CBS as a slope cover system.

Figure 1.1 Conceptual sketch of Capillary Barrier System (after Tami et al., 2004)

A good understanding of SWCC and unsaturated permeability is essential in improving the performance of CBS. One aspect of the SWCC and unsaturated permeability of soil that is not fully understood is anisotropy, which indicates the directional-dependence of a property. In the case of hydraulic properties (SWCC and permeability), hydraulic anisotropy is defined as the ratio between the coefficient of permeability in the major and the minor directions of water flow. In other words, it means that permeability of a soil is expected to be different in the two principal directions (i.e. anisotropic), whereas SWCC of a soil needs to be investigated whether it is affected by the different directions (i.e. anisotropic).

Hydraulic anisotropy is not considered in the current design of CBS. Theoretically, CBS will be more effective if the fine-grained soil layer has a high hydraulic anisotropy since water will flow significantly faster in the major direction (parallel along the slope surface) than in the minor direction (perpendicular to the slope surface). The performance of CBS also depends on the storage capacity of the fine-grained soil layer which is a function of the SWCC and thickness of fine-grained soil.

Instead of increasing the thickness of fine-grained soil, another possible way to improve the performance of CBS is by reducing the required storage capacity of the fine-grained soil layer. If the fine-grained soil has a high hydraulic anisotropy, it can be expected that water will flow significantly faster in the parallel direction than in the perpendicular direction to the slope surface and subsequently, less storage capacity of the fine-grained soil is required compared to the soil having a low hydraulic anisotropy. This expected scenario can only occur if water storage capacities in the parallel and perpendicular directions are indifferent, i.e. SWCC of the fine-grained layer are isotropic. However, hydraulic anisotropy behavior (SWCC and permeability) of the soil has not been fully explored, especially under the unsaturated conditions. This research investigates the hydraulic anisotropy behavior of saturated and unsaturated soils through direct and indirect measurements in the laboratory.

1.2 Significance of Research

The main originalities of this research are as follows:

1. Hydraulic anisotropy behavior of statically compacted sand-kaolin mixtures having different initial conditions and mica contents was observed under the saturated conditions and following the drying and wetting paths of unsaturated conditions using direct laboratory measurements (unsaturated triaxial permeameter).
2. Hydraulic anisotropy behavior of statically compacted sand-kaolin mixtures having different initial conditions and mica contents was observed following the drying and wetting paths of unsaturated conditions using indirect determination from the corresponding SWCC tests (Tempe cell and pressure plate, modified triaxial SWCC and unsaturated triaxial permeameter).

3. The characteristics of both the drying and wetting SWCCs of statically compacted sand-kaolin mixtures having different initial conditions and mica contents with regards to hydraulic anisotropy was observed using various measurement apparatuses (Tempe cell and pressure plate, modified triaxial SWCC and unsaturated triaxial permeameter).

1.3 Objective

The main objective of this study is to investigate hydraulic anisotropy behavior of soil, specifically the coefficient of permeability and soil-water characteristic curve (SWCC) of soil under the saturated and unsaturated conditions. In this study, only inherent anisotropy is investigated on several artificial soils having different initial conditions and mica contents.

1.4 Scope of Work

This research focuses on studying hydraulic anisotropy behavior of homogeneous soil in two principal directions, i.e. the major (represented by vertical-layering specimens) and the minor (represented by horizontal-layering specimens) directions. The scope of the work performed in this research is as follows:

- To develop a conceptual framework of hydraulic anisotropy behavior of soil.
- To investigate the effect of different initial compaction conditions and mica contents of the specimens on the hydraulic anisotropy measured under the saturated conditions using saturated triaxial permeameter.
- To investigate the hydraulic anisotropy behavior of the specimens following the drying and wetting paths of unsaturated conditions using direct measurement (unsaturated triaxial permeameter) and indirect determination

from the corresponding drying and wetting SWCC tests (Tempe cell and pressure plate, modified triaxial SWCC and unsaturated triaxial permeameter).

- To compare the hydraulic anisotropy behavior observed under the saturated conditions and the hydraulic anisotropy behavior following the drying and wetting paths of unsaturated conditions.
- To investigate the characteristics of the drying and wetting SWCCs with regards to hydraulic anisotropy using various measurement apparatuses (Tempe cell and pressure plate, modified triaxial SWCC and unsaturated triaxial permeameter) as well as through numerical simulation using GeoStudio 2007 finite element software.

1.5 Organization of Thesis

This thesis consists of seven chapters. The content of each chapter is as follows:

Chapter 2 reviews the unsaturated soil mechanics, permeability, SWCC and anisotropy. Various existing models for permeability and SWCC are described. The current understanding of anisotropy is presented as well.

Chapter 3 presents the conceptual framework of hydraulic anisotropy behavior of unsaturated soil. This framework is developed to understand hydraulic anisotropy behavior during unsaturated conditions from basic soil properties such as grain-size distribution.

Chapter 4 presents the research methodology. The research methodology describes the laboratory work, numerical modeling and evaluation criteria for the measured data. The laboratory work includes criteria for soil selection, standard compaction tests, static compaction tests and specimen preparation, index properties tests, testing procedures for saturated and unsaturated permeability and SWCC tests using various

apparatuses. Procedures for the numerical modeling using GeoStudio 2007 finite element software and evaluating the data are presented as well.

Chapter 5 presents the results of all laboratory measurements carried out in this research. The results include index properties, particle shape, compaction, saturated and unsaturated permeability and SWCC tests. The results of the numerical modeling using GeoStudio 2007 finite element software are presented as well.

Chapter 6 discusses the results presented in Chapter 5. The hydraulic anisotropy behavior observed under the saturated and unsaturated conditions is explained in detail. Hydraulic anisotropy behavior under the saturated conditions consists of the relationship between magnitude (value) of hydraulic anisotropy against various initial conditions and mica contents tested in this research. Hydraulic anisotropy behaviors following the drying and wetting paths of unsaturated conditions consist of the observed hydraulic anisotropy values and ratio of equilibrium times between HL and VL orientations during the permeability and SWCC tests. Furthermore, a detailed discussion of the characteristics of drying and wetting SWCCs with regards to hydraulic anisotropy is subsequently presented.

Chapter 7 presents the conclusions drawn from this research as well as recommendations for future work. In addition, publications coming from this research are listed.

CHAPTER 2 LITERATURE REVIEWS

In this chapter, reviews of the literature related to this research are presented. First, a review of unsaturated soil mechanics is presented. A review of the principles related to the flow of water through soils, the permeability of soils and their measurement and estimation is presented second. Next, a review of the soil-water characteristic curve (SWCC), its measurement and the best-fit equation is presented. Lastly, a review of anisotropy in soil is presented.

2.1. Unsaturated Soil Mechanics

In geotechnical engineering, soils are classified into two types: saturated and unsaturated. The main difference between saturated and unsaturated soils is how the pore space between the soil particles is filled (Fredlund et al., 2012). Soil below the ground water table is called saturated soil and all the pore spaces are fully filled with water. On the other hand, unsaturated soil is the typical soil above the ground water table where the pore space is partially filled with water; the smallest air void occurring in the pore space renders the soil unsaturated. This definition indicates that saturated soil consists of two phases, soil solids and water, whereas unsaturated soil consists of three phases, soil solids, water and air, as illustrated in Figure 2.1. A study by Fredlund and Morgenstern (1977) found the presence of another phase of the air-water interface in unsaturated soil known as the contractile skin. This makes unsaturated soil a four-phase system, as illustrated in Figure 2.2. The contractile skin acts like an elastic membrane with the capability to exert tensile pull. This tensile pull balances the air pressure and the water pressure in the soil, as there is a difference between the intermolecular force experienced by the molecules at the air-water

interface and the force experienced by the molecules in the interior of the water (Townsend and Rice, 1991). The contractile skin can be considered part of the water phase without causing any significant error when considering the volume-mass properties of unsaturated soil (Fredlund, 2006).

Figure 2.1 Conceptualized three-phases system of unsaturated soil (after Fredlund and Rahardjo, 1993)

Figure 2.2 Conceptualized four-phases system of unsaturated soil (after Fredlund and Rahardjo, 1993)

In contrast to saturated soil, unsaturated soil behavior can be explained using two independent stress-state variables, as studied by Bishop and Donald (1961) and Bishop and Blight (1963). Fung (1977) defined that stress-state variables should be independent of soil properties. A theoretical development of the two independent stress-state variables for unsaturated soil was proposed by Fredlund and Morgenstern (1977) who considered the presence of the contractile skin and the validity of the multiphase continuum mechanics principles. Soil particles were considered to be incompressible and chemically inert, which was similar to the assumptions of the saturated soil mechanics principles (Terzaghi, 1943). Fredlund and Morgenstern (1977) proposed three possible pairs of stress-state variables for describing unsaturated soil behaviour: $(\sigma - u_a)$ and $(u_a - u_w)$, $(\sigma - u_w)$ and $(u_a - u_w)$ and $(\sigma - u_a)$ and $(\sigma - u_w)$, where σ is normal stress (kPa), u_a is pore-air pressure (kPa) and u_w is pore-water pressure (kPa). Fredlund and Rahardjo (1993) evaluated these stress-state variable pairs and concluded that the $(\sigma - u_a)$ and $(u_a - u_w)$ pair was the most suitable and should always be used when describing unsaturated soil behavior. The terms $(\sigma - u_a)$ and $(u_a - u_w)$ are called the net normal (confining) stress and matric suction, respectively.

In unsaturated soil, the pore-air pressure is usually equal to the atmospheric pressure ($u_a = 0$) and the pore-water pressure (u_w) is negative with its magnitude being dependent on ground water table and flux boundary (precipitation, evaporation and transpiration) in the field. A net downward flux of water will result in an initially unsaturated soil becoming more saturated, whereas a net upward flux of water will cause the original soil to become more unsaturated and have more pores fill with air. Figure 2.3 illustrates typical unsaturated zone affected by possible flux boundary conditions in the slope.

Figure 2.3 Illustration of typical unsaturated zone in the slope (after Rahardjo et al., 2007)

For the stress-state variable ($\sigma - u_a$), it is simple to understand that the net confining stress only depends on the depth of the soil and any surcharge load. On the other hand, for the stress-state variable ($u_a - u_w$), the matric suction depends on the negative pore-water pressure. The concept of matric suction is explained by Figure 2.4, which illustrates the capillary phenomenon with the capillary tubes implying pores in soil (Fredlund and Rahardjo, 1993). The capillary effects cause water to rise above the water table in capillary tubes of different sizes. This is similar to the condition in the field where water rises above the ground water table because the pore-water has a negative pressure with respect to the pore-air pressure ($u_a = 0$) and the capillary effect comes from the surface tension of the water and the contact angle between the water and soil particles (Fredlund and Rahardjo, 1993).

Figure 2.4 Capillary phenomena with different capillary tubes as analogy to different radius of curvature in a soil pore (after Janssen and Dempsey, 1980)

Matric suction combined with osmotic suction produces the total suction of soil, which is usually called soil suction (Fredlund and Rahardjo, 1993). Soil suction is defined as the free energy state of water in a soil (Edlefsen and Anderson, 1943). Soil suction can be calculated using the relative humidity of the pore-water vapour present in a soil (Aitchison, 1965). The osmotic suction represents the suction component from dissolved solutes in the pore-water of a soil, and any change in osmotic suction is primarily caused by a change in salt concentration. Since changes in osmotic suction require more time and have a lower occurrence rate than changes in matric suction, changes in total suction can be taken as analogous to changes in matric suction; matric suction can then be used to represent unsaturated soil behavior for simplification (Fredlund and Rahardjo, 1993). Hillel (1998) argued that osmotic

suction could be neglected if the soil solution is significantly dilute and the contained solutes do not have an effect on matric suction.

In the design and analysis of geotechnical infrastructure, engineers commonly neglect the unsaturated zone above the ground water table in order to avoid the complexity of unsaturated soil mechanics. As a consequence, the design and analysis are not realistic since they do not accurately represent field conditions. Unsaturated conditions should be incorporated in all geotechnical design and analysis, especially on slope stability and slope cover systems. The unsaturated zone above the ground water table is the soil slope layer where rainfall infiltration occurs and, subsequently, where rainwater will infiltrate following the unsaturated permeability principle. These unsaturated flow conditions can induce variation in the pore-water pressure and stability of the slope during dry and wet periods (Fredlund et al., 2012). By understanding unsaturated soil mechanics well, an effective and efficient slope capping system, such as the Capillary Barrier System (CBS), can be used to prevent rainfall-induced slope failures. Therefore, unsaturated conditions above the ground water table play a significant role in slope stability and preventive measures.

2.2. Permeability

Water in a soil has total energy state following Equation 2.1 (Baver et al., 1972).

$$E_{total} = m_w g z + \frac{m_w u_w}{\rho_w} + \frac{m_w v_w^2}{2} \quad (2.1)$$

where:

E_{total} = total energy

m_w = mass of water

g = gravitational acceleration

z = elevation height based on the selected datum

u_w = pore-water pressure

ρ_w = density of water

v_w = velocity of water flow.

Equation 2.1 is a fundamental equation governing water flow. When the total energy is defined per unit weight of water, Equation 2.1 becomes Equation 2.2, which is commonly termed the hydraulic head equation in soil permeability.

$$h_w = z + \frac{u_w}{\rho_w g} + \frac{v_w^2}{2g} \quad (2.2)$$

where:

h_w = total head or hydraulic head.

In geotechnical problems, only the elevation and pressure head terms (first and second terms on the right hand side of the equation) are considered since the velocity head (third term on the right hand side of the equation) is significantly smaller than the elevation and pressure heads. By calculating the hydraulic heads between two points, a flow of water will be observed from a point with a higher to the point with a lower hydraulic head.

Water flow in soil is classified as a case of fluid flow in porous media (Childs, 1969).

Water flow in soil follows Newton's law of viscosity, as described in Equation 2.3.

$$\tau = \mu \left(\frac{dv}{dy} \right) \quad (2.3)$$

where:

τ = shear stress by water flow

μ = absolute viscosity of water

dv/dy = gradient of water velocity perpendicular to the direction of shear.

The pore-structure of a soil is usually assumed to be a series of smooth tubes with different sizes (Baver et al., 1972; Hillel, 1982; Marshall and Holmes, 1988). The overall flow rate of water through soil can then be calculated as the sum of each flow rate through a particular tube size and can be obtained through Poiseuille's Law, as shown in Equation 2.4.

$$q = \frac{\pi}{8\mu} \left(-\frac{dP}{dx} \right) r_0^4 \quad (2.4)$$

where:

q = volumetric rate of flow

P = pressure

x = flow direction

dP/dx = pressure gradient along water flow (x-direction)

r₀ = radius of capillary tube.

Equation 2.4 is then improved into Equation 2.5, commonly called as Hagen-Poiseuille equation. Equation 2.5 is used to estimate the velocity of water flow through pore-water channels.

$$v = - \left(\frac{r_h^2 g}{C\eta} \right) \left(\frac{dP}{dx} \right) \quad (2.5)$$

where:

v = average velocity

r_h = hydraulic radius

C = constants related to shape of the flow system

η = kinematic viscosity

However, the actual channels of water flow in soil are more complex than the assumed smooth tubes and highly tortuous flow depends on soil composition (Priono

et al., 2013). Therefore, in this research, water flow in soil is considered in macroscopic and not in microscopic detail.

A macroscopic quantification of water flow through porous media was first proposed by Henry Darcy (1856). It was observed that the flow rate of water is linearly proportional to the cross-section area of the medium and the hydraulic head difference between the inlet and outlet of water. In addition, the flow rate was found to be inversely proportional to the length of the medium as shown in Equation 2.6.

$$Q \sim At \frac{\Delta h_w}{L} \quad (2.6)$$

where:

Q = volumetric water flow

A = cross-section area of the medium

Δh_w = difference of hydraulic head in inlet and outlet points = $h_{w,i} - h_{w,o}$

L = length between inlet and outlet points of flow.

If the flow rate of water is calculated per unit cross-section area and per unit time, the water flux can be calculated as shown in Equation 2.7 and a proportionality factor is required to satisfy the physical relationship with the driving gradient of water flow.

$$\frac{Q}{At} = q = k \frac{\Delta h_w}{L} \quad (2.7)$$

The proportionality factor (k) is commonly termed the coefficient of permeability or hydraulic conductivity in geotechnical engineering. If the water properties are to be expressed in the permeability model, the intrinsic permeability of the medium can be calculated according to Equation 2.8.

$$k = \frac{\rho_w g}{\mu_w} K \quad (2.8)$$

where:

K = intrinsic permeability.

In saturated soil, the voids are full of water, which makes the permeability a constant value. Saturated permeability is arguably just a function of the void ratio, e , of the soil (Lambe and Whitman, 1979). Two methods are commonly used to measure the saturated permeability of soils: constant-head tests and falling-head tests. Both methods are in accordance with Darcy's law (Equation 2.5). The principal difference is that constant-head tests use a predetermined constant hydraulic gradient during measurement, whereas falling-head tests use a non-constant hydraulic gradient that changes with time during measurement. The coefficient of permeability can be calculated using the constant and falling-head methods using Equation 2.9 and Equation 2.10, respectively.

$$k_s = \frac{QL}{\Delta h_w A t} \quad (2.9)$$

where:

k_s = saturated coefficient of permeability

L = length of soil.

$$k_s = \frac{a_1 L}{A t} \ln \left(\frac{h_1}{h_2} \right) \quad (2.10)$$

where:

a_1 = cross-section of the water reservoir

h_1 = hydraulic head at t_1

h_2 = hydraulic heat at t_2 .

Both constant and falling-head tests can be conducted in rigid or flexible wall permeameters following the ASTM standard as summarized in Table 2.1.

Table 2.1 Saturated permeability testing standards

Saturated permeability test methods and apparatuses	ASTM
Constant-head using rigid wall permeameter	D2434-68
Constant-head using flexible wall permeameter	D5084-10
Falling-head using flexible wall permeameter	D5084-10

In contrast, the coefficient of permeability of unsaturated soil is not constant since the pore space between soil particles is filled with water as well as air. Fredlund and Rahardjo (1993) argued that the hydraulic head gradient is still the driving potential of water flow in unsaturated soils. The complexity occurs because water can only flow through pore-water in soil, yet the amount of pore-water significantly depends on the matric suction applied to the soil. For instance, when a soil is subjected to a higher matric suction, the amount of pore-water in the soil will decrease and, hence the unsaturated coefficient of permeability will significantly decrease too. For comparison, saturated permeability may vary by more than 10 orders of magnitude for a wide range of soil types with different particle sizes and shapes, whereas unsaturated permeability can have the same magnitude of variation within a single soil type subjected to different applied matric suctions (Fredlund et al., 1994). Even though the unsaturated permeability of a soil can vary by several orders of magnitude subject to the applied matric suction, Darcy's law is still applicable for water flow in unsaturated soils (Richards, 1931).

Direct measurement of the unsaturated coefficient of permeability is time-consuming and tedious compared to the measurement of the saturated permeability of soil (Samingan et al., 2005). The main advantage of using the unsteady-state method is the shorter time required to measure unsaturated permeability. Examples of the unsteady-state methods include the instantaneous profile method (Richards and Weeks, 1953; Meerdink et al., 1996; Krisdani et al., 2009) and the outflow method (Gardner, 1956; Simunek et al., 1998; To-Viet et al., 2013). However, each unsteady-state method has assumptions that must be satisfied and, consequently, the results from the unsteady-state methods are less reliable than the results from the steady-state methods. Both methods require the measurement of volume change to obtain more accurate unsaturated permeability results (Klute, 1965). One issue to be considered during unsaturated permeability measurement is the use of a high air-entry ceramic disk. The ceramic disk is required to prevent mixing between the water and air phases during measurement. ASTM D7664-10 explains that the saturated permeability of the ceramic disk should be two orders of magnitude higher than the measured permeability of the specimen in order to avoid the impedance caused by the ceramic disk. Otherwise, the impedance of the ceramic disk should be taken into account when calculating the unsaturated permeability of the specimen. Several apparatuses for unsaturated permeability measurement using the steady-state method are shown in Figure 2.5 and Figure 2.6.

Figure 2.5 Schematic layout of flexible wall permeameter developed by Huang et al. (1998)

Figure 2.6 Schematic layout of flexible wall permeameter developed by Ho (1998)

Unsaturated permeability results from direct measurement are very limited in the literature primarily due to the long duration of testing (Samingan et al., 2005; Priono et al., 2013). Hence, for practical reasons, several methods have been proposed for estimating unsaturated permeability by using the relationship between unsaturated permeability and the soil-water characteristic curve (SWCC), as shown in Figure 2.7.

Figure 2.7 Typical relationships between permeability and soil-water characteristic curve (after Rahardjo et al., 2007)

Leong and Rahardjo (1997a) reviewed that there are three models of estimation for unsaturated coefficient of permeability, specifically the empirical, macroscopic and statistical models. The degree of sophistication increases from the empirical to the statistical model, with the statistical model being the most thorough. The empirical model yields an estimation of unsaturated permeability according to the particular soil database investigated in the research. The proposed empirical model should not be assumed to be applicable for soils other than those in the database. For the macroscopic model, the unsaturated coefficient of permeability is predicted from the SWCC using the assumption that the soil is a bundle of uniform and parallel circular capillary tubes. It is also assumed that the soil has a uniform pore-size distribution. This macroscopic estimation model has a tendency to overestimate the unsaturated permeability at high matric suctions due to the simplified uniform pore-size distribution for all soils (Childs and Collis-George, 1950; Brooks and Corey, 1964). The most sophisticated unsaturated permeability estimation model is the statistical model (Leong and Rahardjo, 1997a). The statistical model improves the macroscopic model by proposing a cutting and rejoining concept for more realistic predictions from the SWCC. In this cutting and rejoining concept, parallel capillary tubes in soil are cut in cross-section at a perpendicular direction with water flow and then rejoined. The rationale behind this theory is to incorporate a random pore-size distribution in the direction of water flow in soil. The most widely-used statistical models are those proposed by Childs and Collis-George (1950), Kunze et al. (1968) and Fredlund et al. (1994), as expressed in Equation 2.11 - Equation 2.13, respectively.

$$k_w = M \sum_{\rho=0}^{\rho=r} \sum_{\sigma=0}^{\sigma=r} \sigma^2 A_{\rho \rightarrow \sigma} \quad (2.11)$$

where:

k_w = estimated unsaturated coefficient of permeability

M = empirical constant

r = pore radius at consideration

ρ and σ = pore sequence with σ is smaller than ρ

$A_{\rho \rightarrow \sigma}$ = area of cross-section devoted to the pore sequence ρ to σ .

$$k_w = \frac{k_s}{k_{sc}} A_d \sum_{j=i}^m \left[\frac{(2j+1-2i)}{(u_a - u_w)_j^2} \right] \quad (2.12)$$

where:

k_s = measured saturated coefficient of permeability

k_{sc} = calculated saturated coefficient of permeability

A_d = adjusting constant of $\frac{T_s^2 \rho_w g \theta_s^p}{2\mu_w N^2}$ considered as unity

m = total number of intervals between the saturated and lowest volumetric water content on the SWCC data

i = interval number which increases with the decreasing volumetric water content

j = a counter from “i” to “m”

$(u_a - u_w)_j$ = matric suction corresponding to the midpoint of the j^{th} interval.

$$k_w = k_s \frac{\sum_{i=j}^N \frac{\theta(e^y) - \theta(\psi)}{e^{y_i}} \theta'(e^{y_i})}{\sum_{i=1}^N \frac{\theta(e^y) - \theta_s}{e^{y_i}} \theta'(e^{y_i})} \quad (2.13)$$

where:

y = a dummy variable of integration representing logarithm of matric suction

θ' = first derivative of volumetric water content as described in SWCC function

N = total intervals between matric suction associated with air-entry value and residual volumetric water content.

j = interval number which increases as the matric suction increases

i = a counter from “ j ” to “ N ”.

Fredlund et al. (1994) improved the previous statistical models by performing integration with respect to a logarithmic matric suction plane for each interval considered in the SWCC. Fredlund et al.’s (1994) model has been incorporated into geotechnical software, such as GeoStudio 2007, in order to predict unsaturated permeability from the corresponding saturated permeability and SWCC. In this research, both direct and indirect measurements of the unsaturated coefficient of permeability over a wide range of matric suctions were carried out.

2.3. Soil-Water Characteristic Curve

The soil-water characteristic curve (SWCC) is defined as the relationship between the water content within pores of a soil subject to variation in applied matric suction (Fredlund and Rahardjo, 1993). Water content can be represented as gravimetric or volumetric water content. Gravimetric water content (w) refers to the ratio between mass of water (m_w) and mass of soil solids (m_s), whereas volumetric water content (θ_w) is the ratio between volume of water (V_w) and total volume of soil (V). Fredlund

(2006) explained that SWCC described in volumetric terms is more representative considering the change in soil volume in different matric suctions.

A typical volumetric SWCC is illustrated in Figure 2.8. Figure 2.8 shows a complete SWCC, which consists of both the drying (desorption) and wetting (adsorption) paths. Drying and wetting SWCC tests have different initial values: the drying test requires initially saturated soil and matric suction is applied incrementally, whereas the wetting test is carried out to initially dry soil and the matric suction is reduced steadily. In practice, the wetting test is carried out following the drying test (Goh et al., 2010). The matric suction where the air pressure starts to penetrate the largest pores in the soil during the drying test is termed the air-entry value (AEV or ψ_a). Similarly, in the wetting path, the matric suction where water starts to infiltrate the smallest pores causing saturation of the soil is termed the water-entry value (WEV or ψ_w). As a result, the water content of soil will decrease considerably until it reaches the residual matric suction state (ψ_r) in the drying path. In the wetting path, the water content will considerably increase until it reaches the saturated water content for the wetting process. The residual state in the drying path and boundary state in the wetting path indicate increasing and decreasing levels of matric suction in following the drying and wetting paths, respectively, and do not change the water content of the soil significantly. SWCC characteristics such as AEV and WEV are generally determined using the tangent method proposed by Brooks and Corey (1964), as illustrated in Figure 2.8. This method gives a consistent way to define the SWCC characteristics. Two tangent lines are drawn from the inflection and low matric suction states in the drying path; whereas in the wetting path, tangent lines are drawn from the inflection and high matric suction states.

Figure 2.8 Typical drying and wetting SWCCs (after Satyanaga et al., 2013)

Soil in a wetting test follows a different path than soil in a drying test, as typically illustrated in Figure 2.8, where the wetting path has a lower water content than the drying path for a corresponding matric suction. This behavior is termed hysteresis (Fredlund and Rahardjo, 1993). Hysteresis can occur due to several factors, such as irregularities in pore-geometry which is also known as the ink-bottle effect (Hillel, 1982), different contact angles between soil particles and water following the drying and wetting paths (Lu and Likos, 2004) and air trapped in pores following the wetting path (Fredlund and Rahardjo, 1993).

The non-uniformities in pore-shape consisting of narrow and wide paths (ink-bottle effect) as well as different contact angle following the drying and wetting paths, as illustrated in Figure 2.9, are regarded as the main contributing factor of hysteresis. Four different pores are considered, specifically pores having the largest radius of r_1 connected by pores with a smaller radius of r_2 , r_3 and the smallest of r_4 where r_3 is larger than r_2 . During the drying test, air will start to penetrate the largest pores (r_1),

water will subsequently flow out and will reach equilibrium at pores having radius r_2 . On the other hand, water will enter through smallest pores (r_4) during the wetting test at corresponding matric suction and will stop at pores with a larger radius of r_3 , not at the initial largest pores (r_1). In addition, the contact angles between soil particles and water (α) observed during wetting test will be different with those observed during drying test. Therefore, at corresponding matric suction, soil has lower water content in the wetting path than the drying path of SWCC.

Figure 2.9 Ink-bottle effect and different contact angle during drying and wetting
(after Bear and Verruijt, 1987)

Numerous factors have been reported to influence the shape of SWCC (Fredlund and Xing, 1994; Fredlund et al., 2012). The most widely reported factor is soil type, as illustrated in Figure 2.10. Sandy soil has a generally steeper SWCC slope compared to silty or clayey soils. This is because fewer fine-grained particles in the soil were observed to yield lower water contents under the saturated and unsaturated conditions as well as smaller SWCC characteristics, such as residual matric suction and AEV, which correspond to steeper SWCC slopes.

Figure 2.10 Typical SWCC from different type of soil (modified after Fredlund et al., 1994)

For a given soil type, the initial dry density and water content were reported to influence the measured SWCC (Aubertin et al., 1998; Vanapalli et al., 1999; Birle et al., 2008). A soil with a higher dry density indicates a lower void ratio, smaller pore sizes and, subsequently, lower permeability compared to soil with a lower dry density. The SWCC of soil with a higher dry density will consequently have a lower saturated water content and a higher AEV compared to soil with a lower dry density, as illustrated in Figure 2.11.

Figure 2.11 Typical SWCCs of soil having different initial dry densities (after Yang et al., 2004)

Furthermore, soils compacted at a higher initial water content at a given dry density, i.e. wet of optimum, were reported to have a higher air-entry value than those with a lower initial water content, i.e. dry of optimum. However, the effects of initial water content and dry density on SWCC become negligible during the application of high matric suction (Tarantino and Tombolato, 2005). Further research by Li and Zhang (2009) suggested that the shape of SWCC is closely related to the shape of pore-size distributions (PSD). Li and Zhang (2009) showed that for unsaturated compacted specimens having bimodal PSD, there were possible changes in the bimodal PSD during soil saturation and drying process. During soil saturation, the distinct bimodal PSD observed in the unsaturated compacted specimen can become significantly weaker because of the swelling of soil aggregates that results in more intra-aggregate and fewer inter-aggregate pores. During drying process, the soil may shrink and

consequently, more intra-aggregate and fewer inter-aggregate pores can be resulted until essentially, there is only one dominant pore size (unimodal PSD soil structure).

Rahardjo et al. (2012c) and Satyanaga et al. (2013) reported that the initial dry density and water content can affect the shape of SWCC, whether typically sigmoidal (unimodal) or double-humped (bimodal), even though the specimen has a bimodal grain-size distribution (GSD).

Unimodal and bimodal SWCC shapes are important characteristics to be observed and they require different fitting parameters. A best-fitted SWCC is essential for estimating unsaturated permeability, as explained in Section 2.2. For unimodal SWCCs, various best fitting models have been proposed. The early best fitting model proposed by Brooks and Corey (1964) was improved by van Genuchten (1980) and subsequently by Fredlund and Xing (1994), who proposed the modified continuous best fitting model applicable to a wide range of soil types. Fredlund and Xing's (1994) equation is shown in Equation 2.14. Leong and Rahardjo (1997b) reviewed that all unimodal SWCC fitting equations have a single generic form and, subsequently, recommended that Fredlund and Xing's (1994) equation is relatively the best fitting model among the other equations and its correction factor $C(\psi)$ can be treated as unity for practical yet accurate fitting model.

$$\theta_w = C(\psi) \frac{\theta_s}{\left\{ \ln \left[e + \left(\frac{\psi}{a} \right)^n \right] \right\}^m} \quad (2.14)$$

where:

θ_s = saturated volumetric water content

e = base of natural logarithm

ψ = matric suction

a = parameter corresponding to the AEV of soil

n = parameter corresponding to the maximum slope or inflection point of SWCC

m = parameter corresponding to the curvature of SWCC slope

$$C(\psi) = \text{correction factor related to residual water content} = \left(1 - \frac{\ln\left(1 + \frac{\psi}{\psi_r}\right)}{\ln\left(1 + \frac{10^6}{\psi_r}\right)} \right) \approx 1$$

ψ_r = matric suction corresponding to residual volumetric water content.

Compared to unimodal SWCCs, there are significantly fewer good fitting models for bimodal SWCCs. A relatively recent equation proposed by Satyanaga et al. (2013) fits the bimodal SWCC data very well and is shown in Equation 2.15.

$$\theta_w = \left(1 - \frac{\ln\left(1 + \frac{\psi}{\psi_r}\right)}{\ln\left(1 + \frac{10^6}{\psi_r}\right)} \right) \left[\theta_r + (\theta_{s1} - \theta_{s2}) \left(1 - \operatorname{erfc} \frac{\ln\left(\frac{\psi_{a1} - \psi}{\psi_{a1} - \psi_{m1}}\right)}{s_1} \right) + (\theta_{s2} - \theta_r) \left(1 - \operatorname{erfc} \frac{\ln\left(\frac{\psi_{a2} - \psi}{\psi_{a2} - \psi_{m2}}\right)}{s_2} \right) \right] \quad (2.15)$$

where:

ψ_a = parameter corresponding to the AEV of soil

ψ_m = parameter corresponding to the matric suction at the inflection point of SWCC

s = parameter corresponding to the geometric standard deviation of SWCC.

Subscripts 1 and 2 indicate subcurve 1 and subcurve 2, respectively.

2.4. Anisotropy

Bear and Cheng (2010) define anisotropy as the directional dependence of a given property of a particular material. Anisotropy is frequently confused with heterogeneity, which emphasizes the location dependence of the material properties. There are four possible conditions of material based on combinations between anisotropy and heterogeneity criteria: i.e. isotropic and homogeneous, isotropic and heterogeneous, anisotropic and homogeneous and anisotropic and heterogeneous. Most of the time, materials are simply assumed to be in isotropic and homogeneous conditions for practical reasons, whereas anisotropic and heterogeneous conditions represent the most complicated cases (Fredlund et al., 2012). This research will focus on anisotropy in homogeneous soil samples in order to obtain a thorough understanding of anisotropy in the hydraulic properties of soil.

There are two types of anisotropy, specifically inherent and induced anisotropy (Oda et al., 1985; Leroueil and Hight, 2002; Mitchell and Soga, 2005; Hu et al., 2010; Meng and Chu, 2011; Nishimura, 2014). Inherent anisotropy is associated with the structure of material, whereas induced anisotropy is a consequence from the application of different stresses or strains in different directions to the material. This study focuses only on inherent type of hydraulic anisotropy of a soil in order to provide comprehensive understanding of hydraulic anisotropy behavior with respect to different saturation conditions (saturated and following drying and wetting paths of unsaturated conditions), initial compaction conditions (dry and wet of optimum) and mica contents (with and without mica content). The inherent anisotropy of each specimen tested in this study was investigated by conducting hydraulic tests on two identical-but-different-layered specimens, which are described in Section 3.1.

Anisotropy has attracted great interest from various fields of study (Wyllie and Rose, 1950; Wyllie and Gregory, 1955; Knackstedt and Zhang, 1994; Scholes, 2007). In the

geotechnical field, anisotropy has been comprehensively studied in terms of strength related parameters such as stiffness, compressibility and shear strength of soil (Pickering, 1970; Graham and Houlsby, 1983; Lings et al., 2000; Cho et al., 2006; Nishimura, 2014). The fundamental equation of cross-anisotropy elastic stress-strain in soil is shown in Equation 2.16.

$$\begin{bmatrix} \delta\epsilon_x \\ \delta\epsilon_y \\ \delta\epsilon_z \\ \delta\gamma_{xy} \\ \delta\gamma_{yz} \\ \delta\gamma_{zx} \end{bmatrix} = \begin{pmatrix} 1/E_h & -\nu_{hh}/E_h & -\nu_{vh}/E_v & 0 & 0 & 0 \\ -\nu_{hh}/E_h & 1/E_h & -\nu_{vh}/E_v & 0 & 0 & 0 \\ -\nu_{hv}/E_h & -\nu_{hv}/E_h & 1/E_v & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{hh} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{hv} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{vh} \end{pmatrix} \begin{bmatrix} \delta\sigma'_x \\ \delta\sigma'_y \\ \delta\sigma'_z \\ \delta\tau_{xy} \\ \delta\tau_{yz} \\ \delta\tau_{zx} \end{bmatrix} \quad (2.16)$$

where:

$\delta\epsilon$ = change of normal strain

$\delta\gamma$ = change of shear strain

$\delta\sigma$ = change of normal stress

$\delta\tau$ = change of shear stress

E = Young's modulus

G = shear modulus

ν = Poisson's ratio

x, y, z = axial direction

h, v = planar direction.

There are three established relationships as described in Equation 2.17 - Equation 2.19.

$$G_{vh} = G_{hv} \quad (2.17)$$

$$\frac{v'_{vh}}{E'_v} = \frac{v'_{hv}}{E'_h} \quad (2.18)$$

$$G_{hh} = \frac{E'_h}{2(1 + v'_{hh})} \quad (2.19)$$

In addition, past research has shown that particle shape has a significant effect on shear strength parameters and their anisotropy (Harris et al., 1984; Hight, 1998; Cho et al., 2006). The presence of an additional mineral such as mica (muscovite), which has platy shape, could alter the soil structure and thus contribute to significant anisotropy in shear strength of the soil. In the field, mica is commonly found in residual soil coming from weathered granite (Lee et al., 2007). Bo et al. (2015) reported that there is a significant percentage of mica content, up to 20%, observed in marine clay at Singapore. Hight (1998) illustrated that lack of understanding in the anisotropy of micaceous sands caused a number of slips in temporary and permanent slopes during construction of West Guide Bund at Bangabandhu Bridge, Bangladesh. The slope failures had the characteristics of underwater flow slides, which would not normally be associated with typical soils at the site. A phenomenon called Bridging and Ordering of the soil structure was proposed by Lee et al. (2007), as illustrated in Figure 2.12.

Figure 2.12 Hypothesized Bridging and Ordering of the soil structure (after Lee et al., 2007).

Mica particles, illustrated as thin, flat particles in Figure 2.12, promote organized packing or “ordering” of the soil particles above them, illustrated as round particles in Figure 2.12, whereas the soil particles below mica tend to be packed more irregularly. Mica particles “bridge” over voids left by the underlying soil particles. The orientation of mica particles will cause the increase in porosity to be unequally distributed throughout the soil. During loading or compaction, mica particles are expected to align themselves in a parallel direction with their greater length perpendicular to the direction of loading (resulting into a maximum area to the direction of loading) in order to keep themselves in a minimum state of energy (Martin, 1962).

Anisotropy in hydraulic properties, commonly termed hydraulic anisotropy, is described as the ratio of water coefficients of permeability on the major to minor axis of the soil (Bear and Cheng, 2010; Fredlund et al., 2012). The major axis indicates the direction parallel to the layering of soil, whereas the minor axis indicates the direction

perpendicular to the layering. Hydraulic anisotropy of soil may equal one (isotropic), more than one or less than one. Bear and Cheng (2010) suggested that hydraulic anisotropy less than unity is a common occurrence for shallow-depth clays in the field due to root and worm holes.

Anisotropy has been studied primarily in saturated soil (Basak, 1972; Mualem, 1984; Chapuis et al., 1989; Bear and Cheng, 2010). Laboratory experiments on pure saturated rock, sand and clay indicated that inherent hydraulic anisotropy has an upper limit of four (Basak, 1972; Chapuis et al., 1989). Chapuis et al. (1989) suggested that hydraulic anisotropy at saturated conditions increased during the densification process and that using the static mode of densification yielded higher saturated hydraulic anisotropy than using the dynamic mode for same void ratio. A later study by Wheeler and Sivakumar (2000) and supported by Tarantino (2010) reported negligible effects of the compaction method, whether dynamic or static densification in the laboratory, on soil microstructures as represented by pore-size distribution (PSD) results obtained using mercury intrusion porosimetry (MIP). Basak (1972) argued that clay may have different hydraulic anisotropy ratios in different soil structures (flocculated and dispersed), as shown in Figure 2.13 and Figure 2.14.

Figure 2.13 Typical soil structures as a function of water content at compaction (after Mitchell and Soga, 2005)

Figure 2.14 Typical soil structure compacted on (a) dry side of optimum and (b) wet side of optimum (after Cui, 1993)

Chapuis and Gill (1989) reviewed various techniques for determining hydraulic anisotropy in the saturated conditions using either a rigid-wall or flexible-wall permeameter in the laboratory. For cohesive soils, hydraulic anisotropy tests are best carried out by cutting high quality or undisturbed specimens in different directions, as illustrated in Figure 2.15, then testing each one in a permeameter to obtain the corresponding water coefficient of permeability. However, horizontal permeameters are not always available in a geotechnical laboratory.

Figure 2.15 Preparing specimens for hydraulic anisotropy test by cutting method
(after Chapuis and Gill, 1989)

Other possible techniques are to perform special tests where the drainage is radial towards the central core, as illustrated in Figure 2.16, or to inject air pressure into the surroundings of a cubic clod through the glass tube sealed to the clod. For non-

cohesive soils, the only possible way is to perform laboratory tests on the remolded and recompacted samples in a permeameter.

Figure 2.16 Special radial flow test for measuring hydraulic anisotropy (after Chapuis and Gill, 1989)

Previous research works such as Mualem (1984), Ursino et al. (2000) and Assouline and Or (2006) focused on understanding hydraulic anisotropy behavior during unsaturated conditions by proposing conceptual models and subsequently, performed analytical or numerical analyses over wide range of possible scenarios. Mualem (1984) proposed conceptual “layered cake” model of soil consisting of many thin parallel layers having discrete hydraulic properties. A uniform density distribution function was used to represent the probability of saturated permeability of various layers, as shown in Equation 2.20, whereas a power function relationship was assumed between the permeability and the matric suction, as shown in Equation 2.21, in order to observe the hydraulic anisotropy behavior.

$$f(k_s) = \frac{1}{(k_{s,u} - k_{s,o})} \quad (2.20)$$

$$k(\psi) = k_s \left(\frac{\psi}{\psi_{cr}} \right)^{-\eta} \quad (2.21)$$

where:

$k_{s,u}$ = parameter corresponding to the upper limit of saturated permeability

$k_{s,o}$ = parameter corresponding to the lower limit of saturated permeability

ψ_{cr} = parameter corresponding to the critical matric suction where the permeability equal to saturated permeability if $\psi > \psi_{cr}$

η = empirical constant

Ursino et al. (2000) considered three different anisotropic configurations in Miller-similar porous media, i.e. only distribution of pore diameters was anisotropic; only density of the pores was anisotropic; both density and pore-size distribution (PSD) were anisotropic. Figure 2.17(a) – (d) illustrate four possible basic structures of different Miller-similar porous media, i.e. from isotropic to anisotropic with regards to the density and PSD. Numerical simulations were performed on the similar problem setup defined by Roth and Hammel (1996), but with considering hydraulic anisotropy caused by the different configurations. Both Mualem (1984) and Ursino et al. (2000) concluded that the hydraulic anisotropy could behave dependently or independently with regards to the saturation conditions depending on the prevailing configurations. Furthermore, Assouline and Or (2006) extended Mualem (1984)'s ‘‘layered cake’’ model to consider effects of bulk density variations within a particular soil type.

Figure 2.17 Conceptual sketch of possible structures of Miller-similar porous media:
 (a) isotropic, (b) anisotropic density of the pores and isotropic PSD, (c) isotropic density of the pores and anisotropic PSD, (d) anisotropic density of the pores and anisotropic PSD (after Ursino et al., 2000)

There is a lack of comprehensive laboratory investigation on hydraulic anisotropy behavior during unsaturated conditions. As explained in Section 2.2, unsaturated permeability tests for even one direction were rarely performed due to the long duration of the test and the need for expensive unsaturated permeameters. Blonquist et al. (2011) measured sample-scale dielectric (A_{Ka}) and electrical conductivity (A_{σ}) anisotropy using parallel-plate time domain reflectometry (TDR) and electrical conductivity cell, as shown in Figure 2.18. The purpose was to predict theoretical dielectric anisotropy (A_{ϵ}) which can be used to understand hydraulic anisotropy behavior during unsaturated conditions since according to Friedman and Seaton (1996) and Friedman and Jones (2001), hydraulic anisotropy follows the same trend as the electrical anisotropy.

Figure 2.18 Parallel-plate TDR and electrical conductivity measurement cells (after Blonquist et al., 2006)

No comprehensive laboratory measurements of hydraulic anisotropy behavior under the saturated and unsaturated conditions were available in the literature. Therefore, this study focuses on comprehensive laboratory investigation on hydraulic anisotropy behavior under the saturated conditions and following the complete drying and wetting paths of unsaturated conditions. The hydraulic anisotropy was measured directly using unsaturated triaxial permeameter as well as indirectly determined from the corresponding measured (SWCC) using various measurement apparatuses (Tempe cell and pressure plate, modified triaxial SWCC and unsaturated triaxial permeameter).

CHAPTER 3 THEORY

In this chapter, a proposed framework regarding hydraulic anisotropy behavior is presented. The proposed framework contributes to new understanding of hydraulic anisotropy behavior following drying and wetting paths of unsaturated conditions, i.e. isotropic SWCC and anisotropic permeability functions having distinct equilibrium time behavior. Several previous works by Gardner (1958), Fredlund and Rahardjo (1993), Fredlund et al. (1994) and Satyanaga et al. (2013) contributed to the fundamental relationship between grain-size distribution, SWCC and permeability used in developing the proposed hydraulic anisotropy behavior.

3.1. Proposed Framework on Hydraulic Anisotropy Behavior in Unsaturated Conditions

Different saturated coefficients of permeability measured in the major and minor directions, i.e. hydraulic anisotropy, have been recognized in the literature, as explained in Section 2.4. However, due to complexities of unsaturated soil as well as practical reasons of long test durations and expensive equipment, hydraulic anisotropy behavior of unsaturated soil has not been measured thoroughly. As illustrated in Figure 3.1, unsaturated soil has various possible arrangements and connectivity of pore-water contributing to the complexity of water flow.

Figure 3.1 Illustration of unsaturated soil elements (modified after Fredlund et al., 2012)

This research focuses on hydraulic anisotropy that was mechanically-induced by static compaction. Hydraulic tests were carried out over a wide range of matric suctions on the major and minor directions of a homogeneous soil, as represented by the vertical-layering (VL) and horizontal-layering (HL) specimens respectively. A conceptual sketch indicating the identical-but-different-layered specimens is illustrated in Figure 3.2.

Figure 3.2 Conceptual sketch of horizontal-layering and vertical-layering specimens from a statically compacted soil mixture (after Priono et al., 2016a)

In order to observe hydraulic anisotropy behavior across a wide range of unsaturated conditions, direct measurement of unsaturated permeability must be performed in a laboratory. However, it is possible to understand the hydraulic anisotropy behavior following the drying and wetting paths of unsaturated conditions through the fundamental properties of soil. The proposed framework on the understanding hydraulic anisotropy behavior from fundamental soil properties is given in Figure 3.3. In summary, by considering close relationships between grain-size distribution (GSD), soil-water characteristics curve (SWCC) and permeability functions, isotropic SWCC and anisotropic permeability functions are expected in both following the drying and wetting paths of unsaturated conditions, having different magnitudes (values) of hydraulic anisotropy but similar equilibrium time behavior. The development of the proposed framework is explained in Section 3.2 – Section 3.4.

Figure 3.3 Proposed framework on hydraulic anisotropy behavior of soil following the drying and wetting paths of unsaturated condition

3.2. Relationship between Grain-size Distribution and Drying Soil-Water Characteristic Curve

Since both HL and VL specimens are identical apart from the layering orientation, both specimens should have the same grain-size distribution (GSD) curve. GSD is a fundamental soil property that indicates the relationship between the particle size and percent passing of soil particles by mass. There is no orientation factor during the measurement of mass since mass is a scalar variable. Therefore, it is reasonable to expect that HL and VL specimens have the same GSD, as illustrated in Figure 3.4.

Figure 3.4 An expected GSD of HL and VL specimens for a given soil sample

Previous works by Fredlund et al. (2002), Hwang and Powers (2003) and Satyanaga et al. (2013) suggested that there is a relationship between GSD and the drying soil-water characteristic curve (SWCC). For example, the relationship between the GSD and SWCC proposed by Satyanaga et al. (2013) is shown in Equation 3.1 and Equation 3.2.

$$P = \left[1 - \frac{\ln\left(1 + \frac{d_r}{d}\right)}{\ln\left(1 + \frac{d_r}{d_{\min}}\right)} \right] \left[W_1 \operatorname{erfc} \frac{\ln\left(\frac{d_{\max 1} - d_{m1}}{d_{\max 1} - d}\right)}{s_{d1}} + W_2 \operatorname{erfc} \frac{\ln\left(\frac{d_{\max 2} - d_{m2}}{d_{\max 2} - d}\right)}{s_{d2}} \right] \quad (3.1)$$

where:

P = cumulative GSD of soil

d = soil particle diameter under consideration

$d_{\max}$ = parameter corresponding to the maximum diameter of soil particle

d_m = parameter corresponding to the geometric mean of soil particle diameter

W = parameter corresponding to the percentage of soil particle within coarse- or fine-grained particles

s_d = parameter corresponding to the geometric standard deviation of GSD curve

$d_{\min}$ = parameter corresponding to the minimum particle size that can be measured using hydrometer analysis

d_r = parameter corresponding to the maximum particle size of fine particles.

$$\psi = \frac{\exp \left[\ln 0.149 - \left(\frac{\ln \left(\frac{d}{10} \right) - \ln u}{v} \right) \right]}{10} \quad (3.2)$$

where:

ψ = corresponding matric suction

u = parameter corresponding to the shape of soil particle

v = parameter corresponding to the packing of soil particle.

SWCC indicates the variation in water content in a soil subjected to applied matric suction. Soils with similar compositions of soil particles, as indicated in the GSD, will have similar SWCCs. By understanding the relationship between the GSD and drying SWCC, it is expected that a GSD will produce an identical drying SWCC for HL and VL specimens that can be best-fitted using the same line. Therefore, the SWCC of HL and VL specimens is not expected to be affected by the orientation factor, as illustrated in Figure 3.5.

Figure 3.5 Expected SWCC of HL and VL specimens

Physically, it is reasonable to expect such SWCC behavior since the SWCC indicates the magnitude of water content at equilibrium, the steady-state condition, at each application of matric suction (Priono et al., 2016a). SWCC can be conceptualized as shown in Equation 3.3.

$$\theta_w(\psi) = \int_0^{r_{\max}} f(r_w) dr \quad (3.3)$$

where:

$\theta_w(\psi)$ = equilibrium water content at particular matric suction

$r_{\max}$ = maximum pore size radius corresponding to the matric suction under consideration

$f(r_w)$ = a function of available pore-water in a soil.

Every soil has a unique function of pore-water available at a particular suction. When all the pore-water is fully integrated up to the maximum pore radius, it will produce the equilibrium water content in the soil as a summation of each water contents available in different sizes of soil pores. This equilibrium water content does not

depend on the integration process, i.e. whether the summation is performed following vertical or horizontal layering intervals.

3.3. Relationship between Drying Soil-Water Characteristic Curve and Drying Unsaturated Permeability

As explained in Section 2.2, SWCC is commonly used to estimate the unsaturated permeability of a soil because SWCC indicates the amount of pore-water in a soil which dictates the permeability at a given matric suction. The most sophisticated unsaturated permeability estimation model is a statistical model as given in Equation 2.11 - Equation 2.13. The statistical model suggests the shape of SWCC should be reflected in the permeability function. Equation 2.13 is presented again as Equation 3.4 to clearly explain the relationship between the drying SWCC and unsaturated permeability.

$$k_w = k_s \frac{\sum_{i=j}^N \frac{\theta(e^y) - \theta(\psi)}{e^{y_i}} \theta'(e^{y_i})}{\sum_{i=1}^N \frac{\theta(e^y) - \theta_s}{e^{y_i}} \theta'(e^{y_i})} \quad (3.4)$$

By understanding Equation 3.4, it is expected that the magnitude (value) of the unsaturated coefficients of permeability of HL and VL specimens will not be the same; rather, there will be a difference following the one observed in the saturated conditions (Priono et al., 2016a). As previously explained in Section 3.2, HL and VL specimens have the same type of SWCC best fitting. If the fitting parameter is then inputted into Equation 3.4, the summation parameters in Equation 3.4 will yield the same results, which implies the similar shapes between HL and VL unsaturated permeability functions, and only parameter k_s contributes to the difference. Therefore, hydraulic anisotropy of soil is expected to be constant throughout the saturated conditions and along drying path in unsaturated conditions, as illustrated in Figure

3.6. This expected constant behavior of hydraulic anisotropy is supported by Mualem (1984)'s conceptual "layered cake" model of soil consisting of homogeneous thin layers and Ursino et al. (2000)'s conceptual configuration of Miller-similar porous media having anisotropic density of the pores and isotropic pore-size distribution (PSD), as described in Section 2.4.

Figure 3.6 Expected hydraulic anisotropy behavior on saturated conditions and drying path of unsaturated conditions

Another hydraulic anisotropy behavior that can be expected is the different lengths of time needed for HL and VL specimens to reach equilibrium conditions (Priono et al., 2016a). In order to obtain the equilibrium time at each application of matric suction during the SWCC tests, the transient process of coupled water and air phases is taken into consideration. Assuming that the continuum mechanics framework is valid, conservation of mass for a fluid flowing in any direction through soil is governed by Equation 3.5 (Fredlund and Rahardjo, 1993).

$$\frac{\partial(\rho_f \theta_f)}{\partial t} = \frac{\partial}{\partial y} \left[-(\rho_f k_f) \frac{\partial h_f}{\partial y} \right] + Q_f \quad (3.5)$$

where:

ρ_f = density of fluid

θ_f = volumetric fluid content

k_f = fluid permeability

h_f = total head of fluid

Q_f = applied flux boundary

t = time.

Equation 3.5 can be expanded for the respective air and water phases in soil. Equation 3.6 – Equation 3.8 show the modification of the governing equation for the water phase.

$$\frac{\partial(\rho_w \theta_w)}{\partial t} = \theta_w \frac{\partial(\rho_w)}{\partial t} + \rho_w \frac{\partial(\theta_w)}{\partial t} \quad (3.6)$$

$$\frac{\partial(\theta_w)}{\partial t} = \frac{\partial(\theta_w)}{\partial(u_a - \gamma_w h_w)} \frac{\partial(u_a - \gamma_w h_w)}{\partial t} = m_w \frac{\partial(\gamma_w h_w - u_a)}{\partial t} \quad (3.7)$$

$$\frac{\partial}{\partial y} \left[(\rho_w k_w) \frac{\partial h_w}{\partial y} \right] + Q_w = k_w \frac{\partial h_w}{\partial y} \frac{\partial \rho_w}{\partial y} + \rho_w \frac{\partial}{\partial y} \left[k_w \frac{\partial h_w}{\partial y} \right] + Q_w \quad (3.8)$$

where:

m_w = mass of water

u_a = pore-air pressure

γ_w = unit weight of water.

For the air phase, Equation 3.6 can be expanded into Equation 3.9 – Equation 3.11.

$$\frac{\partial(\rho_a \theta_a)}{\partial t} = \theta_a \frac{\partial(\rho_a)}{\partial t} + \rho_a \frac{\partial(\theta_a)}{\partial t} \quad (3.9)$$

$$\theta_a \frac{\partial \rho_a}{\partial t} = \frac{\theta_a}{RT} \frac{\partial u_a}{\partial t} + \frac{\theta_a u_a}{R} \frac{\partial(1/T)}{\partial t} \quad (3.10)$$

$$\rho_a \frac{\partial(\theta_a)}{\partial t} = -\rho_a \frac{\partial(\theta_w)}{\partial t} = \rho_a m_w \frac{\partial(\gamma_w h_w - u_a)}{\partial t} \quad (3.11)$$

where:

θ_a = volumetric air content

R = molar constant of dry air

T = temperature.

Two ultimate partial differential equations of air and water flows governing the SWCC test are described in Equation 3.12 and Equation 3.13, respectively. If the SWCC test is performed under isothermal conditions, the term involving the change in temperature over time can be omitted.

$$\left(\frac{\theta_a}{RT} + \rho_a m_w \right) \frac{\partial u_a}{\partial t} = \frac{\partial}{\partial y} \left[\frac{\rho_a k_a}{\gamma_{a,o}} \frac{\partial u_a}{\partial y} + \frac{\rho_a^2 k_a}{\rho_{a,o}} \right] - \frac{\theta_a u_a}{R} \frac{\partial}{\partial t} \left[\frac{1}{T} \right] + \rho_a m_w \gamma_w \frac{\partial h_w}{\partial t} \quad (3.12)$$

$$m_w \gamma_w \frac{\partial h_w}{\partial t} = \frac{\partial}{\partial y} \left[k_w \frac{\partial h_w}{\partial y} \right] + m_w \frac{\partial u_a}{\partial t} + Q_w \quad (3.13)$$

where:

$\gamma_{a,o}$ = unit weight of dry air

$\rho_{a,o}$ = density of dry air.

Equation 3.12 and Equation 3.13 are difficult to solve analytically and should thus be solved numerically. In order to obtain the expected trend of equilibrium time, a simplified model proposed by Gardner (1958) focusing only on the outflow of water through a soil is provided in Equation 3.14.

$$\frac{\partial u_w}{\partial t} = D_w \frac{\partial^2 u_w}{\partial y^2} \quad (3.14)$$

where:

u_w = pore-water pressure

y = soil height

D_w = water diffusivity = $\frac{k_w}{\gamma_w b}$

k_w = coefficient of water permeability

b = coefficient of water volume change.

Equation 3.14 closely resembles the governing consolidation equation shown in Equation 3.15.

$$\frac{\partial u_w}{\partial t} = c_v^w \frac{\partial^2 u_w}{\partial y^2} \quad (3.15)$$

where:

c_v^w = coefficient of consolidation with respect to water phase = $\frac{k_w}{\gamma_w m_2^w}$

m_2^w = coefficient of volume change with respect to water phase.

For consolidation time, a solution can be calculated by the root-time method using a non-dimensional time factor as described in Equation 3.16.

$$t_{90} = \frac{T_{90} H_{dr}^2}{c_v} = \frac{T_{90} H_{dr}^2 \gamma_w m_v^w}{k_w} \quad (3.16)$$

where:

t_{90} = time required to achieve 90% consolidation

T_{90} = time factor corresponding to 90% consolidation

H_{dr} = drainage path length.

Drawing similarities between Equation 3.14 and Equation 3.15, it is expected that Equation 3.16 will yield the expected trend regarding the behavior of equilibrium time during SWCC tests. Equilibrium time during SWCC tests, as implied by t_{90} in Equation 3.16, is expected to be inversely proportional to the coefficient of permeability, as implied by k_w in Equation 3.16, at each application of matric suction. In principal, SWCC in unsaturated soil is similar to consolidation behavior in saturated soil since both SWCC and consolidation involve the dissipation of excess pore-water pressure. Excess pore-water pressure is caused by loading in consolidation and by the application of air pressure in SWCC tests.

In consolidation, the magnitude of the final settlement corresponding to a specific loading is the same regardless the drainage boundary condition. Only the time rate of settlement is different since the dissipation of excess pore-water pressure will be different in various drainage boundary conditions. Using the same analogy for SWCC and knowing that hydraulic anisotropy is constant, as illustrated in Figure 3.6, the HL specimen is expected to have a different time for the dissipation of excess pore-water pressure, i.e. a longer equilibrium time during the SWCC test than the VL specimen. The ratio between the equilibrium times for the HL and VL specimens is closely related to the hydraulic anisotropy of the specimen. This concept is illustrated in Figure 3.7. This is reasonable because the transient processes of water content and pore-water pressure change during the SWCC test differ according to the compaction-induced layering direction. The VL specimen is expected to have a faster dissipation of water content and pore-water pressure change and, consequently, it will achieve equilibrium faster than the HL specimen (Priono et al., 2016a).

Figure 3.7 Expected equilibrium time during SWCC tests of HL and VL specimens

3.4. Relationship between Hydraulic Anisotropy in Drying and Wetting Paths

Unsaturated conditions can be observed in either the drying path from a saturated soil or the wetting path from a relatively dry soil. In this research, hydraulic tests in the wetting path were carried out after the drying path and, as explained in Section 2.3, hysteretic behavior of the soil is observed. Hysteretic behavior is due to several factors, such as the ink-bottle effect, and it causes irreversible change in the water content and hydraulic properties of a soil following the wetting path as compared to the drying path.

By understanding hysteretic behavior and its causal factors, it can be conceptualized that unsaturated soil has a different soil structure in the wetting path compared to the drying path. Equation 3.3 is presented again as Equation 3.17 to clearly explain the differences between soils in following the drying and wetting paths.

$$\theta_w(\psi) = \int_0^{R_{\max}} f(r_w) dr \quad (3.17)$$

Soils in following the drying and wetting paths have different $f(r_w)$ in Equation 3.17 in which $f(r_w)$ of the wetting path indicates a lower amount of pore-water and permeability than in $f(r_w)$ of the drying path. As a consequence, it is reasonable to expect that pore-water connectivity following the wetting path is also less than that following the drying path. It is plausible that the change of pore-water connectivity is not the same in all directions since there is random pore-water distribution in a soil. The smaller and disproportional pore-water connectivity observed following the wetting path will considerably decrease the hydraulic anisotropy of the soil following the wetting path compared to that following the drying path. Moreover, $R_{\max}$ at corresponding matric suction of Equation 3.17 in the wetting path is lower than in the drying path considering the hysteretic behavior. Therefore, the magnitude of hydraulic anisotropy observed in the wetting path is expected to be less than that in the drying path. On the other hand, hydraulic anisotropy behavior in the drying path is still expected to be observed in the wetting path. A VL soil specimen in the wetting path will constantly have a higher unsaturated coefficient of permeability, a similar SWCC and a faster equilibrium time during SWCC tests than the corresponding HL specimen. It is reasonable to expect such behavior because following the drying and wetting paths are just different ways to achieve the equilibrium (steady-state) condition at a corresponding matric suction where hydraulic anisotropy behavior is observed.

CHAPTER 4 RESEARCH METHODOLOGY

This chapter presents a detailed research methodology to study the hydraulic anisotropy behavior of soil, including laboratory tests, numerical modeling and evaluation procedures for the measured data. Firstly, criteria for selecting specimens to be used in the laboratory tests are described. Comprehensive laboratory tests including standard and static compaction tests, index properties tests, saturated and unsaturated permeability tests and SWCC tests are then explained. Subsequently, the procedure and criteria for numerical modeling used to validate the results of the laboratory tests are presented. Lastly, procedures to evaluate hydraulic anisotropy behavior using applicable statistical methods are described.

4.1. Laboratory Work

To obtain a better understanding of hydraulic anisotropy behavior of soil, laboratory tests of horizontal-layering (HL) and vertical-layering (VL) specimens with different initial conditions, different percentages of mica content and at different unsaturated test cycles (i.e. drying and wetting cycles) were carried out, as previously described in Section 1.4. In this section, a complete description of the laboratory work from material selection to the procedure for each test conducted is presented.

4.1.1 Soil Design for Laboratory Tests

Investigating the hydraulic anisotropy behavior of soil over a wide range of matric suctions within a reasonable timeframe required careful selection of a specific soil mixture. Several criteria for the soil mixture used in this research are as follows:

- a. The soil mixture must contain a significant percentage of fine-grained particles in order to have a significant range of hydraulic properties (permeability and SWCC) that can be observed over a wide range of matric suctions.
- b. The soil mixture must contain a significant percentage of fine-grained particles in order to provide significant cohesion for reproducible compaction purposes. As explained in Section 2.4, the best technique for hydraulic anisotropy measurement is to cut cohesive specimens in different directions.
- c. The soil mixture must contain a significant percentage of coarse-grained particles so that the timeframe for completing the various laboratory tests is reasonable.
- d. The soil mixture must have characteristics of non-collapsing and non-excessive volume change, which should ideally be an “inert” material, throughout the drying and wetting hydraulic tests.
- e. The soil mixture must be thoroughly mixed and uniformly compacted to achieve homogeneous conditions.

Considering engineering criteria (a) and (b) above, L2 grade coarse kaolin manufactured by Kaolin Malaysia SDN BHD (Malaysia) was selected as fine-grained particles in the soil mixtures tested in this study. Considering engineering criteria (c) above, ASTM 20-30 grade Ottawa sand supplied by U.S. Silica Company was selected as coarse-grained particles in the soil mixtures tested in this study. Considering engineering criteria (d) and (e) above, a specific mixture of sand and kaolin in a 1:1 ratio by dry mass, termed 50% Sand-50% Kaolin (50S50K) was selected for this study.

Four types of 50S50K specimens, as summarized in Table 4.1, were specified in order to investigate the relationships between different initial conditions and hydraulic

anisotropy behavior. 50S50K (A) and 50S50K (B) were used to compare the effect of different dry densities on the hydraulic anisotropy at the dry of optimum side, whereas 50S50K (C) and (D) were used to compare the effect of different dry densities at the corresponding wet of optimum side. Moreover, 50S50K (A) and 50S50K (D) along with 50S50K (B) and 50S50K (C) were compared in order to understand the relationship between hydraulic anisotropy behavior and different initial water contents on drier or wetter than the optimum condition for a particular initial dry density. It was deemed necessary to study specimens prepared at both dry of optimum and wet of optimum conditions since compacted soils at dry and wet of optimum conditions have different soil structures, as shown in Figure 2.13, which may affect the hydraulic anisotropy.

Table 4.1 Types of 50S50K specimens tested in the research

Types	Initial Conditions from Compaction Curve
A	90% maximum dry density at dry of optimum
B	95% maximum dry density at dry of optimum
C	95% maximum dry density at wet of optimum
D	90% maximum dry density at wet of optimum

To further investigate the effect of mineral on the hydraulic anisotropy behavior of soil, two types of mica, i.e. coarse and medium, supplied by International Scientific Private Limited (Singapore) were selected. As mentioned in Section 2.4, mica has been recognized to have significant influence on the anisotropy of soil, particularly on the strength properties. This study investigated the effect of mica content in a soil with regards to hydraulic anisotropy in order to achieve better understanding of

hydraulic anisotropy behavior of soil with and without mica contents. Coarse and medium mica were added to the original 50S50K mixture as described in Table 4.2. For meaningful comparison between micaceous and non-micaceous specimens, an initial condition of 95% maximum dry density at wet of optimum conditions was specified for all specimens. The relationship between hydraulic anisotropy behavior and mica content, whether coarse or medium mica, was observed during this research. Therefore, soil mixture tested in this research had a typical composition as shown in Figure 4.1.

Table 4.2 Types of soil mixtures tested in the research

Soil mixtures	Sand (%)	Kaolin (%)	Coarse Mica (%)	Medium Mica (%)
50S50K	50	50	0	0
Specimens with 9% coarse mica	45.5	45.5	9	NA
Specimens with 9% medium mica	45.5	45.5	NA	9
Specimens with 20% coarse mica	40	40	20	NA
Specimens with 20% medium mica	40	40	NA	20

Figure 4.1 Constituents of soil mixture tested in the research

4.1.2 Standard Compaction Tests

Standard Proctor compaction tests were used to obtain the compaction curves for the specified compositions defined in Section 4.1.1. The Standard Proctor compaction tests performed in this research, as shown in Figure 4.2, followed the procedure described in ASTM D698–12e1. Distilled water was added to the specified soil mixture and the soil mixture was then sealed in a zipped plastic bag and placed overnight in a humidity chamber to equalize the water content. The soil mixture was then compacted at various water contents and the corresponding total and dry densities were measured. The compaction curve for the soil mixture was then plotted, as illustrated in Figure 4.3.

Figure 4.2 Standard compaction test performed in the research

Figure 4.3 Typical compaction curve

4.1.3 Static Compaction Tests and Specimen Preparation

Static compaction tests were used to produce all horizontal-layering (HL) and vertical-layering (VL) specimens for the various laboratory tests performed in this research. The static compaction method was used to ensure even compaction, homogeneity and reproducibility of the identical specimens with similar initial conditions to allow for meaningful comparisons and consistent analyses with regards to hydraulic anisotropy behavior. Wheeler and Sivakumar (2000), supported by Tarantino (2010), reported negligible effects of the compaction method, whether standard or static, on the microstructure of specimens by presenting similar pore-size distribution (PSD) results obtained using a mercury intrusion porosimetry (MIP) test. In this research, the procedure for the static compaction tests was adopted from Ong (1999). Since there were two types of orientation observed for a given soil mixture, i.e. HL and VL, two sets of compaction moulds with two different inner diameters were used in this research. For HL specimens, the size of the specimen indicated the size of mould used, i.e. 50 mm diameter of mould. For VL specimens, a 50 mm diameter of mould was not sufficient to obtain a 50 mm diameter VL specimen. An optimization calculation, as illustrated in Figure 4.4, was performed to determine the size of the compaction mould for VL specimens. The objective of the optimization was to calculate the largest possible area of a rectangle ($b \times h$) inside a circle with a radius (r) equal to one unit. The largest possible area was then determined to be two units. It could be interpreted that if the rectangle was a square, the dimensions would be $\sqrt{2}$ units. Therefore, to obtain a 50 mm diameter VL specimen, a compaction mould with a minimum diameter of 70.71 mm was required. In this research, a compaction mould with a 100 mm diameter was selected.

Figure 4.4 Model for calculating minimum size of compaction mould for VL specimen

The typical static compaction device is shown in Figure 4.5. The compaction device consists of a stainless steel mould and two stainless steel plugs. The stainless steel mould is 200 mm in height and has two symmetrical parts that can be connected or disconnected by two Allen keys. The mould with a square-shaped cross-section has a cylindrical hole in the center. The stainless steel plugs include nine removable disks, each 10 mm thick, in order to compact the specimen 10 mm layer by layer. Each set of disks consists of two parts, a top and a base, with 40 mm and 50 mm diameters, respectively, and a thickness of 5 mm, as indicated in Figure 4.6(a). The disks are connected to each other via a threaded screw that sticks out from the centre of the face of one disk and the threaded hole drilled into the centre of the face of the other disk. The connection of the screw to the hole of the adjacent disk is illustrated in Figure 4.6(b). All disks and plugs were designed in a T-shape to reduce the friction between trapped soil particles in the gaps and the wall of the compaction moulds, as shown in Figure 4.6(c).

Figure 4.5 Static compaction test performed in the research

Figure 4.6 (a) Removable disk; (b) Connection between two adjacent disks; (c) Stainless steel plug (after Ong, 1999)

In this research, a mixture of sand, kaolin, water and, in some cases, mica having specific initial conditions as explained in Section 4.1 was prepared thoroughly and uniformly. The soil mixture was placed inside a zipped plastic bag and left overnight in a humidity chamber to allow for equalization of the water content in the soil mixture. The water content was evaluated by measuring three small samples from the soil mixture and a tolerance of 5% of the intended water content was satisfied. The mass of soil mixture required for each 10 mm compaction layer was measured before the soil was placed into the static compaction mould as shown in Figure 4.7.

Figure 4.7 Static compaction setup used for HL specimen

At both ends of the top and bottom plugs, flat-faced disks termed “capping disks” were used to prevent the soil from entering the threaded hole of the disk during compaction. The top plug was inserted into the mould and the axial load was applied at a constant rate until the additional layer was compressed to 10 mm height. A static

displacement rate of 1 mm/min was applied to the soil mixture using the static compression machine, as illustrated in Figure 4.5, to prevent excess pore-water pressure from building up and to obtain a uniform density throughout the specimen.

Once the specimen was successfully compacted to the designated height, the mould was turned over so that the top plug was at the bottom and the bottom plug was at the top. Then, the height of the plug at the top was reduced by 10 mm by removing one disk to allow space for the subsequent compaction layer. Prior to placing the soil mixture inside the mould, the compacted soil surface was uniformly scarified in order to ensure good bonding between each soil layer before adding the next layer. The procedure was repeated until the designated specimen height was reached. In this research, most HL and VL specimens had a height of 30 mm; a couple HL and VL 50S50K (D) had a height of 50 mm in order to investigate hydraulic anisotropy behavior in identical specimens of different sizes.

Lastly, the specimen was extruded from the compaction mould using the same steel plugs and compression machine. The specimen was then transferred to the intended hydraulic test setup for either the permeability or soil-water characteristic curve test. Meanwhile, three small samples were collected from the remaining soil mixture for verification of the designated water content and corresponding dry density. Evaluation of the water content and dry density of the compacted specimen were important in ensuring identical initial conditions of the compacted soil for the different hydraulic tests, i.e. permeability and soil-water characteristic curve. In addition, the height, diameter and weight of the specimen were recorded for calculating the initial volume of the specimen.

As illustrated in Figure 4.4, VL specimens needed a larger compaction mould than HL specimens to produce identical specimens. Thus, a compaction mould of 100 mm diameter was used to prepare VL specimens in this research as shown in Figure 4.8.

Figure 4.8 Static compaction setup used for VL specimen

The soil mixture preparation procedure and static compaction process similar to those carried out for HL specimens were used for VL specimens. The difference in preparing VL specimens only started after the compacted soil sample was extruded from the static compaction mould. The initially large blocks of soil sample and the sets of cutters used in this research are shown in Figure 4.9. There were two different types of cutters, specifically a rectangular cutter with a cross-section of 70 mm x 50 mm and a circular cutter with a diameter of 50 mm. Firstly, a rectangular section was trimmed from the large block of soil sample, as shown in Figure 4.10. The rectangular soil sample was then rotated 90 degrees on its broader face so that the soil layers were oriented vertically. Lastly, the VL specimen was prepared to the intended size, the

same as the size of the HL specimen, using the circular cutter as shown in Figure 4.11. Assurance of minimum disturbance was observed from the absence of cracks in the extruded circular specimen. The final cut VL specimen is shown in Figure 4.12.

Figure 4.13 shows the typical HL and VL specimens used in this research.

Figure 4.9 Initial block of soil sample and cutters used for preparing VL specimens

Figure 4.10 Cutting a rectangular section from a large block of VL sample

Figure 4.11 Cutting a circular section from a rectangular VL sample

Figure 4.12 A final VL specimen

Figure 4.13 Typical HL and VL specimens for a given soil mixture tested in the research

Table 4.3 shows list of all specimens used in the laboratory tests. Each specimen was prepared in HL and VL orientations so as to investigate the hydraulic anisotropy. The details of permeability and SWCC tests are presented in Section 4.1.5 and Section 4.1.6, respectively.

Table 4.3 List of all specimens used in the laboratory tests

Specimens	Size in mm (diameter x height)	$\rho_{d,initial}$ (Mg/m³)	$w_{initial}$ (%)	Permeability tests	SWCC tests
50S50K (A)	50 x 30	1.65	11.0	Saturated	TC&PP
50S50K (B)	50 x 30	1.75	12.1	Saturated Unsaturated	TC&PP Triaxial Permeameter
50S50K (C)	50 x 30	1.75	17.5	Saturated Unsaturated	TC&PP Triaxial Permeameter
50S50K (D)	50 x 30	1.65	19.8	Saturated	TC&PP
	50 x 50	1.65	19.8	Saturated	TC&PP
Specimens with 9% medium mica	50 x 30	1.68	18.0	Saturated	-
Specimens with 20% medium mica	50 x 30	1.54	21.0	Saturated	-
Specimens with 9% coarse mica	50 x 30	1.77	16.0	Saturated	Triaxial
				Unsaturated	Permeameter
Specimens with 20% coarse mica	50 x 30	1.64	19.0	Saturated	Triaxial

4.1.4 Index Properties Tests

A series of index properties tests were carried out to characterize the basic properties of soil. The index properties tests included grain-size distribution tests (dry sieving and hydrometer tests), specific gravity tests and Atterberg limit (liquid limit and plastic limit) tests. All index properties tests were conducted according to the ASTM standards summarized in Table 4.4.

Table 4.4 Index properties testing standards

Index Properties Test	ASTM
Specific gravity	D854-14
Grain-size distribution	D422-63e2
Atterberg limits	D4318-10e1
Soil Classification (Unified Soil Classification System)	D2487-11

In addition, Scanning Electron Microscope (SEM) imaging was performed to identify the shape of each soil particle used in this research, i.e. sand, coarse mica, medium mica and kaolin. The shape of each soil particle was then qualitatively determined using the particle regularity chart proposed by Krumbein and Sloss (1963), as shown in Figure 4.14. In the particle regularity chart, there are pre-determined shapes of particles that correspond to three parameters, i.e. sphericity (S_{shape}) in y-axis, roundness (R_{shape}) in x-axis and regularity (ρ_{shape}) in diagonal line. High sphericity indicates high eccentricity (spherical) and high roundness indicates small angularity, whereas regularity shows average value between sphericity and roundness parameters. Quantifying different shape parameters of each particle provides supporting facts to the reasoning for mica particle (which is widely known to have platy shape) that can induce the Bridging and Ordering soil structure. The Bridging and Ordering soil structure, as shown in Figure 2.12, was argued by Lee et al. (2007) as the main reason of significant shear strength anisotropy observed in a micaceous soil.

Figure 4.14 Particle regularity chart (after Krumbein and Sloss, 1963)

4.1.5 Permeability Tests

Two types of permeability tests were carried out in this research, namely saturated and unsaturated permeability tests, in order to directly measure the coefficient of permeability of specimens at saturated and unsaturated conditions. The equipment and procedures are described in this section.

4.1.5.1 Saturated Permeability Tests

In this research, all saturated permeability tests were conducted using the constant-head method in the flexible wall, i.e. the triaxial permeameter, as illustrated in Figure 4.15.

Figure 4.15 Schematic diagram of saturated triaxial permeameter used in the research

Eight separate saturated permeability tests were carried out for each HL and VL specimen corresponding to the different initial conditions and mica contents given in Section 4.1.1. The procedure for the saturated permeability test was in accordance with ASTM D5084-10. After the specimen was statically compacted as described in Section 4.1.4, it was placed on top of a filter paper and a saturated porous stone above the bottom pedestal of a triaxial permeameter setup. Subsequently, the specimen was capped with a filter paper, a saturated porous stone and the top cap. Filter paper was used to prevent fine particles from being trapped inside the bottom pedestal or top cap, whereas saturated porous stones were used to uniformly distribute the applied water pressure towards the specimen. An impervious rubber membrane was fixed around the specimen and fastened in place using a vacuum gauge. Lastly, a Plexiglass cover was placed over the setup and screwed in place before the entire cell was filled with de-aired distilled water. The complete setup is shown in Figure 4.16.

Figure 4.16 Saturated triaxial permeameter used in the research

The first stage of the saturated permeability test was then performed, i.e. saturating the specimen. The initial pore-water pressure of the specimen was measured by a pressure transducer connected to a valve at the bottom of the specimen. A cell pressure of 50 kPa was applied to the specimen through a valve connected to a digital pressure and volume controller (DPVC) manufactured by GDS Instruments Limited of England. The cell pressure caused pore-water pressure to build up in the soil specimen. The built up pore-water pressure was recorded and the pore-water pressure coefficient (B value) was then calculated using Equation 4.1.

$$B = \frac{\Delta u_w}{\Delta \sigma_3} \quad (4.1)$$

where:

Δu_w = change of pore-water pressure

$\Delta \sigma_3$ = change of confining pressure.

If the B value was less than 0.95, a representation of the saturated conditions recommended by Head (1998), back pressure of 40 kPa was applied through a valve at the top of specimen that was connected to another DPVC. The pore-water pressure was then recorded when it reached the equilibrium value. The procedure of applying incremental cell and back pressure with a net confining pressure of 10 kPa was repeated until a B value of 0.95 or larger was achieved.

The next stage was consolidating the specimen under a designated net confining pressure of 25 kPa. The consolidation process was considered complete if there was no excess pore-water pressure and the pore-water volume reached equilibrium. After consolidation was completed, the saturated permeability test was carried out by applying a specific pressure head gradient at the top and bottom of the specimen through two DPVCs. In this research, a higher water pressure was applied at the bottom of the specimen than at the top of the specimen in order to create an upward water flow through the specimen. The saturated permeability test was stopped when the flow rate of water was constant over a period of time. The saturated permeability of the specimen was then calculated using Equation 4.2 following Darcy's Law.

$$k_s = \frac{v}{i} = \frac{QL}{A\Delta h} \quad (4.2)$$

where:

v = velocity of water flow through specimen

i = hydraulic gradient

Q = flow rate of water through specimen

L = length of the specimen

A = cross-sectional area of specimen

Δh = pressure head gradient.

4.1.5.2 Unsaturated Permeability Tests

Three complete sets of drying and wetting unsaturated permeability tests were carried out for each HL and VL specimen in this research, as indicated in Table 4.5.

Table 4.5 Specimens tested in the unsaturated permeability tests

Specimens	Initial Conditions from Compaction Curve
50S50K (B)	95% maximum dry density at wet of optimum
50S50K (C)	95% maximum dry density at dry of optimum
Specimens with 9% coarse mica	95% maximum dry density at wet of optimum

Initial conditions of 50S50K specimens at 95% maximum dry density at dry and wet of optimum conditions were selected since both of these conditions produced the highest hydraulic anisotropy values during the saturated permeability tests in the dry and wet of optimum conditions, respectively. An initial condition of 9% coarse mica content at 95% maximum dry density at wet of optimum was selected since this condition produced the highest hydraulic anisotropy value during the saturated permeability tests of all micaceous and non-micaceous specimens tested in this research.

The unsaturated permeability tests were conducted using an unsaturated triaxial permeameter different from the permeameter used in the saturated permeability tests. In this research, the unsaturated triaxial permeameters were assembled following the modifications recommended by Goh et al. (2015) and Rahimi and Rahardjo (2016). A typical permeameter used in the laboratory is shown in Figure 4.17.

Figure 4.17 Unsaturated triaxial permeameter used in the research

The unsaturated triaxial permeameter consists of a triaxial cell, modified top and bottom pedestals and a pair of high air-entry ceramic disks. The triaxial cell has the capacity to withstand pressure up to 1700 kPa, which was deemed satisfactory for the unsaturated permeability tests in this research. The top and bottom pedestals were composed of aluminum and stainless steel, respectively. Both the top and bottom pedestals were modified for the unsaturated permeability tests by creating a protruding air pressure outlet and spiral grooves in the water compartments, as indicated in Figure 4.18.

Figure 4.18 Modified pedestals and modified ceramic disks used in the unsaturated triaxial permeameter in the research

A protruding air pressure outlet was constructed in order to apply pore-air pressure to the specimen through the attached sintered bronze in the modified ceramic disk. Sintered bronze is very porous, which allows continuity of the air phase between the air pressure line and the pore-air pressure in the specimen. Two water pressure outlets were placed at the spiral grooves to apply pore-water pressure into the water compartment and then into the specimen through the ceramic disk. The modified ceramic disk provided uniform distribution of water and air pressures to the specimen. Slow-setting epoxy was used to glue the sintered bronze to the modified ceramic disk and also to glue the ceramic disk to the modified pedestal. Therefore, the top and bottom pedestal each had three pressure outlets. The valves connecting the bottom pedestal and triaxial cell base were called the bottom pore-water pressure, bottom flushing line and bottom pore-air pressure valves. The top pedestal and triaxial cell base connection also had three corresponding valves, namely the top pore-water pressure, top flushing line and top pore-air pressure valves. Another water outlet was

located in the cell base to connect the cell pressure from the DPVC. In total, the cell base had seven outlets, as shown in Figure 4.19.

Figure 4.19 Outlets setup in the unsaturated triaxial permeameter

Two types of high air-entry ceramic disks, specifically 1 bar and 5 bar ceramic disks, with a thickness of 7.14 mm were used in this research. It was necessary to have a 1 bar triaxial permeameter, which was used to measure unsaturated permeability up to a matric suction of 90 kPa, since the unsaturated permeability of the specimens, especially VL specimens, during low matric suction conditions, could be higher than the saturated permeability of 5 bar ceramic disk. The saturated permeability of the ceramic disk represented the highest possible unsaturated permeability of a specimen that could be accurately measured due to the flow impedance consideration. There was also the need to have a 5 bar triaxial permeameter in order to obtain unsaturated permeability measurements during high matric suction conditions, i.e. 200 and 400

kPa. Since the unsaturated permeability test was expected to last longer during high matric suction conditions, two 5 bar triaxial permeameters were used in this research.

The unsaturated triaxial permeameter was connected to two DPVCs for pore-water pressure, a DPVC for cell pressure, a pore-air pressure control system, four pressure transducers, a data acquisition system and a personal computer as shown in Figure 4.20. The schematic diagram of unsaturated triaxial permeameter used in the research is illustrated in Figure 4.21.

Figure 4.20 Complete setup of the unsaturated triaxial permeameter used in the research

Figure 4.21 Schematic diagram of the unsaturated triaxial permeameter setup

Three DPVCs were required to conduct accurate unsaturated permeability tests since the water inflow and outflow during the permeability tests were measured using the base and back (top) DPVCs and the volume change of the specimen was measured by cell DPVC. The volume change of the specimen was measured by assuming negligible volumetric change in the no-leakage triaxial cell due to the application of matric suction and room temperature conditions. Hence, the volumetric change of the cell DPVC represented the volume change of the specimen. The assumption of negligible change in the triaxial cell volume is reasonable because the highest cell pressure applied in this study is 515 kPa, which is less than a third of the maximum capacity of the triaxial apparatus used in this study (1700 kPa) and all triaxial tests in this study were performed in the laboratory, where the room temperature was always controlled. This assumption has been used in previous research by Goh et al. (2010) and Rahimi and Rahardjo (2016).

For pore-air pressure control during the unsaturated permeability test, a compressor capable of supplying continuous air pressure up to 1000 kPa was used. Continuous pore-air pressure between that supplied by the compressor and that measured in the specimen was important for ensuring that the intended matric suction existed during the test. Four pressure transducers were needed to measure the cell pressure, the pore-water pressure at the top of the specimen, the pore-water pressure at the bottom of the specimen and the pore-air pressure of the specimen. Each pressure transducer was well-calibrated within the testing range with an interval of 10 kPa before the unsaturated permeability tests began. An eight-channel data logger connected to a personal computer was used to automatically collect data on the pore-water pressure, pore-air pressure, pore-water volume change and total volume change of the specimen from the pressure transducers and DPVCs. The readings were taken in five minute intervals using the embedded GDS Lab software or a Triax 4.0 data acquisition program (Toll, 1999).

The unsaturated permeability tests performed in this research involved saturation, consolidation, matric suction equalization and, lastly, unsaturated permeability measurement. Prior to the test, the ceramic disks on the top and bottom pedestals were saturated using de-aired distilled water with a pressure of 200 kPa for 24 hours. After the ceramic disks were saturated, the saturated coefficients of permeability of the top and bottom ceramic disks were then measured. A cell pressure of 500 kPa was applied to the ceramic disk and the water outflow through the disk was measured using Equation 4.2, which is similar to that used for calculating the saturated permeability of the specimen. The processes of setting up the specimen in the unsaturated permeameter, saturating and consolidating the specimen were the same as for the saturated permeability tests described in Section 4.1.5.1.

The differences in the unsaturated permeability tests compared to the saturated permeability tests started with the need to introduce matric suction. Negative pore-water pressure was difficult to establish during unsaturated permeability tests since water starts to cavitate when the pore-water pressure approaches -1 atm or about -100 kPa. Fredlund and Rahardjo (1993) explained that cavitation occurs when air starts to fill the measuring system and, as a consequence, the pore-water pressure and volume measurements are inaccurate. Lu and Likos (2004) defined cavitation as the process of phase translation from a liquid phase to vapour phase along a path of decreasing pressure at the same temperature, as indicated in Figure 4.22.

Figure 4.22 Pressure-temperature paths for solid-liquid-vapor phases (after Lu and Likos, 2004)

The cavitation of water was prevented in this research by using the axis translation technique proposed by Hilf (1956). Hilf (1956) recommended translating the reference point, i.e. the negative pore-water pressure, into the corresponding positive pore-air pressure with zero pore-water pressure in order to maintain the designated

matric suction. This technique has been successfully applied for the measurement of unsaturated permeability and SWCCs by many researchers (e.g. Fredlund and Rahardjo, 1993; Fredlund et al., 2012). At the matric suction equalization stage, the cell and pore-air pressures were kept constant, whereas the pore-water pressure was decreased incrementally in order to create the designated matric suction during the drying test. In contrast, the pore-water pressure was increased incrementally in order to create the designated matric suction during the wetting test. Frequent flushing of air bubbles was carried out during the test at each designated matric suction due to the long duration of the test.

There was a slight difference in the designated matric suction intervals during the drying and wetting tests since different shapes of unsaturated permeability function, whether unimodal or bimodal, were encountered in different specimens. Detailed intervals of the matric suction application in the complete drying and wetting tests for 50S50K (C) are shown in Table 4.6, whereas, for 50S50K (B) and specimens with 9% coarse mica, the detailed intervals of the matric suction application during the tests are shown in Table 4.7.

Table 4.6 Matric suction intervals for 50S50K specimens (C)

	Drying	Wetting
Matric suction (kPa)	5	200
	20	90
	35	75
	50	50
	75	35
	90	20
	200	5
	400	1

Table 4.7 Matric suction intervals for 50S50K (B) and specimens with 9% coarse mica

	Drying	Wetting
Matric suction (kPa)	5	200
	10	90
	20	75
	30	50
	40	35
	50	20
	75	10
	90	5
	200	1
	400	

It was necessary to define systematic and consistent criteria to determine whether a specimen achieved equilibrium condition at a particular matric suction. Graphical observation is usually used, but such observations can be very subjective. Equilibrium condition is principally achieved when the change in pore-water volume measured by DPVC is negligible. Therefore, a criterion following the central difference approximation of the Taylor Series, as described in Equation 4.3, was used in this research in addition to the usual graphical observation. The time to reach equilibrium condition, termed the “equalization time” or “equilibrium time”, was taken as the time when the gradient of the water volume change curve became zero for the first time.

$$f'(x_i) = \frac{f(x_{i+1}) - f(x_{i-1}))}{2h} + O(h^2) \quad (4.3)$$

where:

$f'(x_i)$ = gradient of water volume change curve at particular suction

i = counter

h = step size (50 intervals)

$O(h^2)$ = truncation error.

After equilibrium at a particular matric suction was achieved, the last stage of unsaturated permeability measurement was performed. Similar to the procedure used in the saturated permeability test, an upward flow of water through the specimen was created by applying a pressure head difference of 10 kPa between the top and bottom of the specimen via the base and back DPVCs, respectively. The unsaturated permeability test was stopped when a steady-state condition was achieved for a period of time. A steady-state condition, i.e. a condition where there is a constant change in water volume, is usually determined by graphical observation, similar to the equilibrium time in the matric suction equalization stage. In this research, a criterion for determining the steady-state condition specifically for unsaturated permeability tests at high matric suction is described in Equation 4.4, following that used in Equation 4.3. The steady-state condition was considered to commence when the gradients of two successive steps in water volume did not change for the first time (the change was close to 0).

$$f'(x_{i+1}) - f'(x_i) \approx 0 \quad (4.4)$$

The measured unsaturated permeability did not solely represent the permeability of the specimen since there were influences from the ceramic disks on the top and bottom pedestals. Therefore, the specimen was considered a three-layered system with

the top and bottom ceramic disks, as suggested by Samingan et al. (2003) and illustrated in Figure 4.23.

Figure 4.23 A three-layered system for unsaturated permeability calculation

In this sandwich system, the average velocities of all three layers are equal due to the continuity requirement shown in Equation 4.5.

$$v_{\text{system}} = v_b = v_{\text{soil}} = v_t \quad (4.5)$$

where:

v = average velocity.

Subscripts system, b, soil and t represent three-layered system, bottom disk, soil specimen and top disk, respectively.

Subsequently, Equation 4.5 can be expanded into Equation 4.6.

$$\begin{aligned} v_{\text{system}} &= (ki)_{\text{system}} = (ki)_b = (ki)_{\text{soil}} = (ki)_t \\ &= (ki)_{\text{system}} = (kh_l/L)_b = (kh_l/L)_{\text{soil}} = (kh_l/L)_t \end{aligned} \quad (4.6)$$

where:

k = coefficient of permeability

i = hydraulic gradient

h_l = head loss

L = length.

Permeability of the system (k_{system}) can be obtained using Equation 4.2, similar to the calculation of saturated permeability. However, permeability of the system (k_{system}) is not the same with unsaturated permeability of the soil specimen (k_{soil}). There are head losses in the top and bottom disks and these need to be considered in order to obtain k_{soil} from the measured k_{system} , as mentioned in ASTM D7664-10. The total head loss of the system is equal to the summation of head loss in each layer of soil specimen, bottom and top disks. Therefore, the ultimate form to determine the unsaturated permeability of the specimen at a particular matric suction (k_{soil}) from the measured permeability in the test (k_{system}) can be written as shown in Equation 4.7.

$$k_{\text{soil}} = \frac{L_s}{\left(\frac{L_{\text{system}}}{k_{\text{system}}} - \left(\frac{L_t}{k_t} + \frac{L_b}{k_b} \right) \right)} \quad (4.7)$$

4.1.6 Soil-Water Characteristic Curve Tests

In this research, a complete set of drying and wetting soil-water characteristic curve (SWCC) tests was carried out using three methods, namely the conventional method of combining Tempe cell and pressure plate tests, the modified triaxial SWCC method and the unsaturated triaxial permeameter method. The equipment used and the detailed procedures of each method are described in this section, except the unsaturated triaxial permeameter method (explained in Section 4.1.5).

4.1.6.1 Tempe Cell and Pressure Plate Tests

The conventional method of combining Tempe cell and pressure plate tests in order to obtain drying and wetting SWCC data over a wide range of matric suctions was adopted for each HL and VL orientation of 50S50K specimens having various initial conditions as indicated in Table 4.1. Tempe cell tests were used for measurement of SWCC up to matric suction of 90 kPa, whereas pressure plate tests were used for

measurement of SWCC up to matric suction of 400 kPa. The designated matric suction intervals during the drying and wetting SWCC tests for specimens having initial conditions of dry and wet of optimum were similar to those used in the unsaturated permeability tests, as shown in Table 4.6 and Table 4.7. Further SWCC tests of HL and VL specimens having an initial condition at 90% maximum dry density at wet of optimum and a larger size, i.e. 50 mm height, were performed in order to investigate whether hydraulic anisotropy behavior was still observed in the SWCC of identical specimens with different sizes.

The Tempe cell consists of a 1 bar air-entry value ceramic disk, three O-rings, a cell cap, a cell base, a cell ring and three screws, as illustrated in Figure 4.24.

Figure 4.24 Schematic diagram of Tempe cell

The mass of each individual part of the Tempe cell, i.e. cell base, cell ring, cell cap, O-rings and screws, was firstly measured. Prior to the Tempe cell test, the ceramic disk was placed in a vacuum chamber containing de-aired distilled water for one week in order to become fully saturated. After the ceramic disk was fully saturated, the

specimen was placed directly on top of the saturated disk inside the Tempe cell ring, which was placed in the cell base. The cell cap was then placed on top of the cell ring and tightly secured using the three screws. When the Tempe cell was fully set up, the saturation process of the specimen then took place. The specimen was saturated from the bottom of the Tempe cell by connecting the bottom of the Tempe cell to a flexible tube that was connected to a water tank filled with de-aired distilled water, as shown in Figure 4.25.

Figure 4.25 Tempe cell test performed in the research

Water flowed to the bottom of the specimen through the pre-saturated ceramic disk in order to allow all the air inside the specimen to flow upward and the specimen to efficiently become fully saturated. After the saturation process was completed, the

specimen was weighed and measured in terms of height and diameter to calculate the mass of the water and the volume of the specimen, respectively. The saturated volumetric water content of the specimen was then calculated by taking the ratio of volume of water and the total volume of the specimen.

A drying SWCC test was then carried out on the specimen by connecting the cell cap to the air pressure control system. In this SWCC test, the axis translation technique proposed by Hilf (1956) was used to introduce the designated matric suction into the specimen, as explained in Section 4.1.5.2. Air would not flow through the ceramic disk if the air pressure did not exceed the capacity of the ceramic disk (1 bar), and the ceramic disk was kept saturated by connecting the bottom of the Tempe cell to a water tank, as shown in Figure 4.25. The specimen was weighed and measured in terms of height and diameter, regularly, to calculate the change of the mass and volume of the specimen. Volumetric change of water in the specimen was plotted against time in order to closely monitor whether the equilibrium condition had been achieved. The equilibrium condition was reached if the same criterion used in the matric suction equalization stage of the unsaturated permeability test, i.e. Equation 4.3, was satisfied. The matric suction was then increased to the designated higher value and these processes were repeated until matric suction of 90 kPa was reached. After equilibrium at matric suction of 90 kPa was satisfied, the specimen was removed from the Tempe cell and transferred to the pressure plate.

The pressure plate consists of a pressure chamber, a 5 bar high air-entry value ceramic disk and a rubber membrane beneath the ceramic disk. The space between the ceramic disk and the rubber membrane was used as a water compartment. The water compartment was connected to a burette. The typical pressure plate setup used in this research is shown in Figure 4.26.

Figure 4.26 Pressure plate test performed in the research

Prior to the pressure plate test, the 5 bar ceramic disk was saturated by placing it in a vacuum desiccator filled with de-aired distilled water for one week. Once no air bubbles were observed on the ceramic disk, the disk was taken out and placed in the pressure chamber. De-aired distilled water was poured on the surface of the ceramic disk and an air pressure of 400 kPa was applied in order to ensure that the ceramic disk and the water compartment were fully saturated.

After saturation of the ceramic disk and the water compartment, the specimen from the Tempe cell test was placed directly on top of the ceramic disk. Matric suction was applied to the specimen by the same axis-translation technique (Hilf, 1956) used in the unsaturated permeability and Tempe cell tests. The water level in the burette connected to the pressure plate was maintained at the same level as the ceramic disk

in order to ensure zero water pressure. An air pressure of 200 kPa was applied to the soil specimen and the specimen was measured and weighed daily in order to accurately obtain equilibrium condition. The ceramic disk and the water compartment were flushed regularly after the readings were recorded in order to ensure they were always fully saturated. The change of water volume was plotted against time considering the volume change of the specimen. Once the specimen reached the equilibrium condition following the criterion described in Equation 4.3, the air pressure was increased to the next designated matric suction pressure, i.e. 400 kPa.

After equilibrium condition at matric suction of 400 kPa was achieved, the wetting SWCC test of the specimen then took place. In the wetting SWCC test, the air pressure was decreased in order to introduce water back into the specimen, as opposed to the process in the drying test. The intervals of designated matric suction in the wetting SWCC test were different from those in the drying SWCC test, as explained in Table 4.6 and Table 4.7. The equilibrium condition for a particular matric suction during the wetting SWCC test followed the criterion specified in Equation 4.3. After the equilibrium condition was achieved at the last matric suction of 1 kPa, the specimen was dried in an oven for 24 hours and the dry mass of the specimen was obtained. The dry mass of the specimen was important for calculating saturated water content of the specimen.

4.1.6.2 Modified Triaxial SWCC Tests

In this research, the saturated triaxial apparatus was modified following the recommendation by Goh et al. (2010) in order to measure a complete set of drying and wetting SWCCs over a wide range of matric suctions. The modified triaxial SWCC apparatus had a similar arrangement to the unsaturated triaxial permeameter described in Section 4.1.5.2. The differences were that a 5 bar ceramic disk was used

above the bottom pedestal and a porous stone was used below the top pedestal in the modified triaxial SWCC apparatus, whereas unsaturated triaxial permeameter used modified ceramic disks in the modified top and bottom pedestals, as shown in Figure 4.18. The typical setup of the modified triaxial SWCC used in the laboratory is shown in Figure 4.27.

Figure 4.27 Modified triaxial SWCC used in the research

The purpose of performing a complete set of drying and wetting SWCCs using the modified triaxial SWCC setup was to compare the results to those obtained through the matric suction equalization stage in the unsaturated permeability tests. Both drying and wetting SWCC results could then be evaluated to serve as a basis for estimating the unsaturated permeability, which can then be compared to direct measurements of unsaturated permeability data. Hence, three sets of complete drying and wetting SWCC tests were performed using the modified triaxial SWCC setup for each HL and VL specimen following those in the unsaturated permeability tests shown in Table

4.5. In addition, the measured drying and wetting SWCCs using the modified triaxial SWCC setup were compared to the SWCC results obtained using the conventional method of Tempe cell and pressure plate tests.

The specimen setup and testing procedures performed in the modified triaxial SWCC tests were similar to those used in the unsaturated permeability tests. The only difference was that there was no permeability measurement stage since the modified triaxial SWCC test was only used to obtain drying and wetting SWCCs. The modified triaxial SWCC setup allowed continuous measurement of pore-water pressure, pore-air pressure, pore-water volume change and total volume change of the specimen from both pressure transducers and DPVCs used. These values were monitored using Triax 4.0 software (Toll, 1999), similar to the procedures in the unsaturated permeability tests. The equilibrium condition at a particular matric suction was defined following Equation 4.3 in order to be consistent with the other tests in this research.

4.2. Numerical Modeling

Numerical modeling of SWCC tests of both HL and VL specimens were performed using GeoStudio 2007 finite element software, specifically Seep/W combined with Air/W package. GeoStudio finite element software has been deemed reliable for analyzing various unsaturated soil problems (Tami et al., 2004; Aubertin et al., 2009; Rahardjo et al., 2013; Priono et al., 2016a). The purpose of performing numerical modeling of the SWCC test was to verify the effect of hydraulic anisotropy on the equilibrium time of SWCC observed in the laboratory tests using both the conventional Tempe cell and pressure plate setup, modified triaxial SWCC and unsaturated triaxial permeameter setups. Typical initial conditions for the numerical modeling of SWCC tests using the Tempe cell and pressure plate setups are illustrated

in Figure 4.28, whereas the initial conditions for SWCC tests using modified triaxial SWCC and unsaturated triaxial permeameter setups are shown in Figure 4.29.

Figure 4.28 Typical initial conditions for numerical modeling of SWCC tests using conventional Tempe cell and pressure plate apparatuses

Figure 4.29 Typical initial conditions for numerical modeling of SWCC tests using modified triaxial SWCC and unsaturated triaxial permeameter apparatuses

The main difference between Figure 4.28 and Figure 4.29 is that the air boundary condition was only applied from the top of the specimen in the simulation of SWCC tests using the modified triaxial apparatus, while in the SWCC tests using the conventional apparatus the air boundary condition was applied from both the top and the side of the specimen. The hydraulic boundary (local datum) was specified as constant, whereas the air boundary condition varied according to the matric suction applied in the laboratory tests. An axisymmetric condition was specified in the numerical modeling since the specimen had a cylindrical shape that was symmetrical about its vertical axis of rotation. The specimen and ceramic disk were modeled using quadrilateral mesh elements with each element having an area of 1 x 1 mm². The finite element size was specified as 2% of the diameter of the laboratory specimens to ensure accurate and reliable modeling.

It was necessary to specify an air permeability function in the numerical modeling in order to model the SWCC tests performed in the laboratory. In this research, the air coefficient of permeability was estimated using Equation 4.8 proposed by Ba-Te et al. (2005).

$$k_a = k_d \sqrt{(1-S)} \left(1 - \sqrt[q]{S}\right)^{2q} \quad (4.8)$$

where:

k_a = air coefficient of permeability at particular degree of saturation

k_d = air coefficient of permeability at dry condition of soil

S = degree of saturation of a soil at particular matric suction

q = empirical constant depending on soil type.

Ba-Te et al. (2005) modified the air permeability model by Parker et al. (1987), which extended Brooks and Corey's (1964) concept of water permeability to the air phase, in order to be applicable for any degree of saturation. Fredlund et al. (2012)

explains that the air coefficient of permeability in the dry condition can be calculated from the intrinsic permeability of the medium, as shown in Equation 4.9, with regards to the water phase of a soil.

$$k_d = \left(\frac{\rho g}{\mu} \right)_a K = \left(\frac{\rho g}{\mu} \right)_a \left(\frac{k_s \mu}{\rho g} \right)_w \quad (4.9)$$

where:

g = gravitational acceleration

μ = absolute viscosity

K = intrinsic permeability of the medium.

To be more realistic, the air coefficient of permeability was specified to not be lower than the air diffusion permeability, which was estimated using Equation 4.10.

$$k_{a,diffusion} = \frac{Dh\rho g}{u_{a,abs}} \quad (4.10)$$

where:

$k_{a,diffusion}$ = air diffusion permeability

D = diffusivity coefficient

h = volumetric coefficient of solubility for air in water

$u_{a,abs}$ = absolute air pressure.

Parameter “q” of the specimen in Equation 4.8 was empirically found to be 3.5 as there was no previous research on the air permeability function of compacted sand-kaolin mixtures (Priono et al., 2016a). Since the laboratory tests were carried out at room temperature ($T = 20^\circ\text{C}$), $\rho_a = 1.196 \text{ kg/m}^3$, $\mu_a = 1.785 \times 10^{-5} \text{ Ns/m}^2$, $\mu_w = 1.009 \times 10^{-3} \text{ Ns/m}^2$, $D = 2 \times 10^{-9} \text{ m}^2/\text{s}$, $h = 1.868 \times 10^{-2}$ and $u_{abs} = 101.3 \text{ kPa}$ were used in Equation 4.9 and Equation 4.10 as suggested by Fredlund and Rahardjo (1993). The saturated water coefficient of permeability of the high air-entry ceramic disk was

specified at 7.56×10^{-9} and 1.21×10^{-9} m/s, corresponding to 1 bar and 5 bar ceramic disks, respectively. The ceramic disk was specified as an incompressible material having a saturated volumetric water content set to 0.31.

All numerical simulations were carried out in a transient analysis after the steady-state initial condition. Numerical modeling was carried out following the steps used in the experiment. Each simulation had a varying running time of 50 stages in order to achieve equilibrium condition at each application of matric suction. Convergence in each simulation step was reached when the computed results did not change by more than a specified tolerance of 1% in successive iterations. In addition, the overall cumulative water balance error was maintained at very low levels (zero, in ideal cases) so as to obtain reasonable results in every simulation.

On top of the graphical interpretation, the output criteria from the numerical modeling had to be defined to ensure consistent results at each application of matric suction. The criteria for the volumetric water content and equalization time of the specimen model were specified in Equation 4.11 and Equation 4.12, respectively.

$$\theta_{model} = \frac{\sum \theta_{node}}{N} \quad (4.11)$$

where:

θ_{model} = volumetric water content of the specimen model

θ_{node} = volumetric water content at each composing node of the specimen model

N = total number of nodes in the specimen model (excluding nodes at the soil-disk boundary).

$$\frac{\theta_2 - \theta_1}{\theta_2 - \theta_i} \leq 1\% \quad (4.12)$$

where:

$\theta_2 - \theta_1$ = difference between current and previous volumetric water content

$\theta_2 - \theta_i$ = difference between current and initial volumetric water content at each simulation step.

Equation 4.11 defines the average volumetric water content for the specimen model, while Equation 4.12 indicates whether the specimen model has approached equilibrium condition, i.e. equilibrium time.

4.3. Criteria for Evaluation Procedures

Statistical analyses were carried out to evaluate the measured data from the laboratory works carried out in this research. The goodness of fit of the measured experimental data and the applicable fitting equations were quantified by calculating the coefficient of determination (R^2) according to Equation 4.13. A high value of R^2 , i.e. closer to 1, indicates a good fit between the measured laboratory data and the applicable fitting equations. In addition, R^2 was used as a criterion to explain the observed trend in hydraulic anisotropy behavior under the saturated conditions, i.e. hydraulic anisotropy values against initial conditions for all specimens tested in this research.

$$R^2 = 1 - \frac{SSE}{SST} = 1 - \frac{\sum_{i=1}^N (y_i - y_p)^2}{\sum_{i=1}^N (y_i - y_m)^2} \quad (4.13)$$

where:

SSE = sum of squared errors

SST = total sum of squares

y_i = measured data

y_p = predicted data

y_m = mean of all data

N = total number of data.

To explain hydraulic anisotropy behavior following the drying and wetting paths in unsaturated conditions for all specimens in this research, calculating R^2 alone was not sufficient. Hydraulic anisotropy behavior consists of unsaturated permeability behavior (magnitude and equilibrium time) and SWCC behavior (magnitude, equilibrium time and numerical modeling results) for the respective drying and wetting paths. Therefore, relative difference (Δ_r) was calculated according to Equation 4.14, in order to quantify the difference between the observed data and the reference value such as mean value. The Δ_r and its average i.e. average relative difference (ARD) as shown in Equation 4.15 were considered satisfactory if the value was less than 20%.

$$\Delta_r(\%) = \left| \frac{y_i - y_m}{y_m} \right| \times 100\% \quad (4.14)$$

$$ARD(\%) = \frac{\sum_{i=1}^n \left| \frac{y_i - y_m}{y_m} \right|}{N} \times 100\% \quad (4.15)$$

CHAPTER 5 PRESENTATION OF RESULTS

The results of all the laboratory tests and numerical modeling carried out in this research are presented in this chapter. The results of the index properties test are presented first. Subsequently, the results of the particle shape determination, compaction, saturated and unsaturated permeability and soil-water characteristic curve (SWCC) tests are presented. The results of the numerical modeling are presented last. Parts of the results presented in this chapter have been published in Priono et al. (2016a) and Priono et al. (2016b).

5.1. Index Properties

Index properties tests including specific gravity, Atterberg limits, grain-size distribution (GSD) and soil classification based on the Unified Soil Classification System (USCS) were performed on all soil mixtures tested in this research. Table 5.1 shows the results of the index properties tests for 50S50K soil mixtures at various initial conditions, as described in Table 4.1. Table 5.2 shows the results of the index properties tests for all micaceous soil mixtures having an initial condition of 95% maximum dry density at wet of optimum, as described in Table 4.2. All 50S50K specimens were classified as SM-ML (silty sand to sandy silt with low plasticity), whereas all micaceous specimens were classified as SM (silty sand).

Table 5.1 Summary of physical properties of 50S50K soil mixtures

Index properties	50% Sand - 50% Kaolin (50S50K)			
	A	B	C	D
Dry density, ρ_d (Mg/m ³)	1.65	1.75	1.75	1.65
Water content, w (%)	11.0	12.1	17.5	19.8
Void ratio, e	0.57	0.48	0.48	0.57
Saturated water content, w_{sat} (%)	27.8	23.7	26.1	29.5
Liquid limit, LL (%)	46.7	46.7	46.7	46.7
Plastic limit, PL (%)	27.4	27.4	27.4	27.4
Plasticity index, PI (%)	19.3	19.3	19.3	19.3
Specific gravity, G_s	2.59	2.59	2.59	2.59
GSD - Sand (%)	50.0	50.0	50.0	50.0
GSD - Silt (%)	37.5	37.5	37.5	37.5
GSD - Clay (%)	12.5	12.5	12.5	12.5
Unified Soil Classification System (USCS)	SM-ML	SM-ML	SM-ML	SM-ML

Table 5.2 Summary of physical properties of micaceous soil mixtures

Index properties	Specimens with 9% medium mica	Specimens with 20% medium mica	Specimens with 9% coarse mica	Specimens with 20% coarse mica
Dry density, ρ_d (Mg/m^3)	1.68	1.54	1.77	1.64
Water content, w (%)	18.0	21.0	16.0	19.0
Void ratio, e	0.58	0.75	0.47	0.61
Saturated water content, w_{sat} (%)	28.8	32.9	25.4	31.5
Liquid limit, LL (%)	49.5	48.2	49.6	46.9
Plastic limit, PL (%)	32.3	32.2	31.9	30.3
Plasticity index, PI (%)	18.3	16.0	18.7	16.6
Specific gravity, G_s	2.65	2.69	2.61	2.63
GSD - Sand (%)	54.8	63.7	59.8	63.5
GSD - Silt (%)	36.0	27.9	29.1	28.9
GSD - Clay (%)	9.2	8.4	11.1	7.6
USCS	SM	SM	SM	SM

Figure 5.1 shows the grain-size distribution (GSD) curves of all soil mixtures tested in this research as described in Table 4.1 and Table 4.2. All GSD curves show a gap-graded distribution where coarse-grained particles predominantly consist of medium-sized sand, whereas fine-grained particles predominantly consist of silt-sized particles. It is observed that the addition of mica induces higher percentages of coarse-grained particles in the micaceous soils mixtures compared to the 50S50K soil mixture. Addition of coarse mica induces considerably more coarse-grained particles than addition of medium mica at 9% mica content, whereas at 20% mica content, a relatively similar GSD is observed in both soil mixtures with coarse mica and medium mica content.

Figure 5.1 GSD curves of all soil mixtures

In addition, the GSDs of all specimens were retested after the completion of laboratory tests. It was important to confirm that no significant breakage or soil loss occurred during laboratory tests in order to ensure that the measurement results reflect the intended initial condition. Figure 5.2 shows typical pre- and post-laboratory tests

of GSD curves of the specimens tested. It is observed that the GSDs of pre- and post-laboratory tests are relatively similar.

Figure 5.2 Typical pre-test and post-test of GSD curves of the specimen

5.2. Particle Shape

The constituents of the soil mixtures tested in the research, as explained in Section 4.1.1, i.e. sand, kaolin and mica particles, are known to have different shapes. Figure 5.3 shows overview imaging using a 1 mm unit-scale of the sand, kaolin, coarse and medium mica particles used in the research. Figure 5.4(a) – (d) show scanning electron microscope (SEM) imaging of the sand, kaolin, coarse mica and medium mica particles. Each SEM imaging of sand, coarse and medium mica particles has a 100 μm unit-scale, whereas that of kaolin has a 2 μm unit-scale due to the particle size (fine-grained).

Figure 5.3 Overview SEM imaging of soil particles used in the research

Figure 5.4 SEM imaging of (a) sand, (b) coarse mica, (c) medium mica and (d) kaolin particles

Shape parameters of each soil particle were then qualitatively identified using a modified Krumbein and Sloss chart (1963) as shown in Figure 4.13. Table 5.3 shows the qualitative shape parameters of each soil particle used in the research. It is observed that both coarse and medium mica particles are very spherical (high S_{shape}) compared to kaolin and very angular (low R_{shape}) compared to sand. In terms of the regularity parameter (ρ_{shape}), a medium mica particle is similar to a kaolin particle, whereas a coarse mica particle is in between sand and kaolin particles.

Table 5.3 Qualitative shape parameters of each soil particle

Soil particles	Sphericity (S_{shape})	Roundness (R_{shape})	Regularity (ρ_{shape})
Sand	0.9	0.9	0.9
Coarse Mica	0.9	0.1	0.5
Medium Mica	0.7	0.1	0.4
Kaolin	0.3	0.5	0.4

5.3. Compaction Curve

The compaction curves showing the relationship between dry density (ρ_d) and water content (w) were obtained using standard Proctor compaction tests. Figure 5.5 shows compaction curves of all soil mixtures tested in the research. It is shown that each soil mixture has a different compaction curve and the highest maximum dry density is achieved by the soil mixture having 9% coarse mica content. The maximum dry density and the corresponding optimum water content for each soil mixture are presented in Table 5.4. It is observed that only the soil mixture having 9% coarse mica content has a higher maximum dry density than the initial 50S50K soil mixture.

Table 5.3 shows that each particle (sand, coarse mica, medium mica and kaolin) has different particle shapes. Different particle shapes lead to possible Bridging and Ordering soil structure in a soil having mica content as illustrated in Figure 2.12. Therefore, the fact that soil mixture with 9% coarse mica having the highest dry density can be attributed to the moderate amount of mica content (9%) and more pronounced (greater in dimension) Bridging and Ordering soil structure produced by coarse mica than that by medium mica. Furthermore, the addition of coarse mica is observed to produce a higher maximum dry density and lower optimum water content than that induced by the addition of medium mica, at a given percentage.

Figure 5.5 Compaction curves of all soil mixtures used in the research obtained using Standard Proctor tests

Table 5.4 Maximum dry density and optimum water content of each soil mixture

Soil mixtures	Maximum dry density, $\rho_{d, \max}$ (Mg/m ³)	Optimum water content, w_{opt} (%)
50S50K	1.84	14.2
Specimens with 9% coarse mica	1.87	11.3
Specimens with 9% medium mica	1.77	12.0
Specimens with 20% coarse mica	1.72	14.9
Specimens with 20% medium mica	1.62	16.2

Figure 5.6 shows the different initial conditions of 50S50K specimens tested in the research as listed in Table 4.1. For comparison, all micaceous specimens had an initial compaction condition of 95% maximum dry density at wet of optimum, i.e. type C, since the highest hydraulic anisotropy value was observed for this type among all initial conditions. The hydraulic anisotropy results are presented in Section 5.4 and Section 5.5.

Figure 5.6 Different initial compaction conditions of 50S50K specimens

5.4. Saturated Permeability

Coefficients of saturated permeability of all specimens were measured according to the procedure described in Section 4.1.5.1. The constant head method was used with an effective consolidation stress ($\sigma_3 - u_b$) of 25 kPa having back pressure (u_b) of 490 kPa and subsequently, two pressure head differences of 5 kPa ($\Delta h = 0.5$ m) and 10 kPa ($\Delta h = 1$ m) was applied in the saturated permeability test of each specimen. The constant head method was deemed reliable for saturated permeability measurement of all specimens since the two applied pressure difference corroborate to a consistent saturated permeability value for each specimen. The results of the saturated permeability tests, as well as the corresponding hydraulic anisotropy, are shown in Table 5.5. In Table 5.5, subscripts “initial” and “final” refer to the initial compaction condition and the final condition during the saturated permeability measurement, respectively. Since there were two pressure head differences applied during saturated permeability measurement, there were two readings of water flow rate (Q) and the average of these water flow readings is shown as Q_{ave} for each specimen in Table 5.5. The saturated permeability of each specimen was then calculated using Equation 4.2.

Table 5.5 Saturated permeability and corresponding hydraulic anisotropy of each specimen

Specimens	$\rho_{d,initial}$ (Mg/m ³)	$W_{initial}$ (%)	$S_{initial}$	$\rho_{d,final}$ (Mg/m ³)	W_{final} (%)	S_{final}	$Q_{ave,HL}$ (m ³ /s)	$k_{s, HL}$ (m/s)	$Q_{ave,VL}$ (m ³ /s)	$k_{s, VL}$ (m/s)	Hydraulic anisotropy
50S50K (A)	1.65	11.0	0.50	1.59	22.2	0.91	4.46E-09	9.09E-08	8.18E-09	1.64E-07	1.80
50S50K (B)	1.75	12.1	0.65	1.64	20.9	0.93	8.50E-10	1.67E-08	2.63E-09	5.34E-08	3.20
50S50K (C)	1.75	17.5	0.94	1.60	22.7	0.95	9.67E-11	1.92E-09	5.50E-10	1.12E-08	5.83
50S50K (D) with 30 mm height	1.65	19.8	0.90	1.50	26.3	0.94	8.50E-10	1.73E-08	3.36E-09	6.80E-08	3.93
50S50K (D) with 50 mm height	1.65	19.8	0.90	1.52	25.8	0.93	4.83E-10	1.67E-08	1.97E-09	6.74E-08	4.04
Specimens with 9% medium mica	1.68	18.0	0.82	1.56	24.2	0.91	2.04E-09	3.88E-08	1.17E-08	2.42E-07	6.24
Specimens with 20% medium mica	1.54	21.0	0.75	1.50	26.6	0.91	1.01E-08	2.07E-07	1.25E-08	2.56E-07	1.24
Specimens with 9% coarse mica	1.77	16.0	0.89	1.62	21.6	0.92	5.25E-10	1.07E-08	5.36E-09	1.12E-07	10.47
Specimens with 20% coarse mica	1.64	19.0	0.82	1.51	25.8	0.92	3.36E-09	6.75E-08	5.92E-09	1.22E-07	1.81

Among all non-micaceous specimens, i.e. 50S50K (A) – (D), it is observed that the highest hydraulic anisotropy value under the saturated conditions is for 50S50K (C). In addition, it is observed that 50S50K (C) has a higher hydraulic anisotropy than 50S50K (B) and 50S50K (D) has a higher hydraulic anisotropy than 50S50K (A). This observation shows that, in general, specimens compacted at wet of optimum have higher hydraulic anisotropy than specimens having a similar dry density compacted at dry of optimum, even though they have lower coefficients of saturated permeability at the corresponding HL and VL orientations. Moreover, a specimen compacted at 95% maximum dry density has a higher hydraulic anisotropy, even though the coefficients of saturated permeability are lower at the corresponding HL and VL orientations, than a specimen compacted at 90% maximum dry density at the same side of optimum water content. 50S50K (B) has a higher hydraulic anisotropy than 50S50K (A) and 50S50K (C) has a higher hydraulic anisotropy than 50S50K (D). It is also observed that different heights (30 mm and 50 mm) in 50S50K (D) do not induce significant differences in the coefficients of saturated permeability of each HL and VL orientation or the corresponding hydraulic anisotropy.

Since the initial compaction condition in 50S50K (C) induced the highest hydraulic anisotropy among all conditions, all micaceous specimens were prepared in this way, i.e. at 95% maximum dry density at wet of optimum water content of their compaction curve. It is observed that the coefficients of saturated permeability of all micaceous specimens at the corresponding HL and VL orientations are higher than those of 50S50K (C). Nevertheless, the hydraulic anisotropy values of all micaceous specimens are not necessarily higher than that of 50S50K (C). Only specimens with 9% mica content, regardless if it is coarse or medium mica, have a higher hydraulic anisotropy than 50S50K (C). In general, specimens having coarse mica have higher

hydraulic anisotropy than specimens having medium mica for a given percentage of mica content.

5.5. Unsaturated Permeability

Prior to measuring the coefficients of unsaturated permeability of the specimens, the coefficients of saturated permeability of both the 1 bar and 5 bar ceramic disks used in the unsaturated triaxial permeameter were measured according to the procedure described in Section 4.1.5.2. The saturated coefficients of permeability of the 1 bar and 5 bar ceramic disks were found to be 5.60×10^{-8} and 1.75×10^{-8} m/s, respectively. After saturation of the ceramic disks inside the unsaturated triaxial permeameter was complete, the specimen was set into the permeameter and the unsaturated permeability test was carried out according to the procedure described in Section 4.1.5.2. It was expected that the complete drying and wetting unsaturated permeability tests of a particular orientation (HL or VL) of a given specimen would require a substantial testing duration. Table 5.6 shows the typical times needed for measuring a complete set of drying and wetting coefficients of unsaturated permeability using only one unsaturated triaxial permeameter.

Table 5.6 Typical times needed to complete a cycle of drying and wetting unsaturated permeability tests using only one permeameter

Stages of test	Matric suction (kPa)	Duration (days)
Sample preparation	-	2
Saturation	-	6
Consolidation	-	1
Matric suction equalization	5	1

Drying permeability test	5	3
Matric suction equalization	10	1
Drying permeability test	10	3
Matric suction equalization	20	1
Drying permeability test	20	3
Matric suction equalization	30	2
Drying permeability test	30	4
Matric suction equalization	40	2
Drying permeability test	40	4
Matric suction equalization	50	2
Drying permeability test	50	4
Matric suction equalization	75	2
Drying permeability test	75	4
Matric suction equalization	90	3
Drying permeability test	90	6
Matric suction equalization	200	6
Drying permeability test	200	8
Matric suction equalization	400	25
Drying permeability test	400	11
Matric suction equalization	200	27
Wetting permeability test	200	14
Matric suction equalization	90	6
Wetting permeability test	90	10
Matric suction equalization	75	3

Wetting permeability test	75	9
Matric suction equalization	50	3
Wetting permeability test	50	8
Matric suction equalization	35	2
Wetting permeability test	35	6
Matric suction equalization	20	2
Wetting permeability test	20	4
Matric suction equalization	10	1.5
Wetting permeability test	10	4
Matric suction equalization	5	1
Wetting permeability test	5	3
Matric suction equalization	1	1
Wetting permeability test	1	3
	Total (Months)	7.05

An approximately 7-month long test to obtain the complete drying and wetting coefficients of unsaturated permeability of just one orientation (HL or VL) of a given specimen was deemed infeasible considering the candidature time. As a result, more than one unsaturated triaxial permeameters were required for this research.

Three unsaturated triaxial permeameters were used to expedite the testing. The three permeameters consist of one 1 bar permeameter and two 5 bar permeameters, as explained in Section 4.1.5.2. Two permeameters, i.e. a pair of 1 bar and 5 bar permeameters, were used to complete a cycle of drying and wetting unsaturated permeability tests of a particular orientation (HL or VL) of a specimen, whereas the remaining permeameter was used to start the unsaturated permeability test on the

corresponding orientation (VL or HL) of the specimen. Table 5.7 shows the typical times needed for completion of the drying and wetting unsaturated permeability tests using the 1 bar permeameter. The drying unsaturated permeability test was carried out until 90 kPa and, subsequently, the wetting unsaturated permeability test was performed until the saturated conditions (approximately 1 kPa). Table 5.8 shows the typical times needed for completion of the drying and wetting unsaturated permeability tests using the 5 bar permeameter. The drying unsaturated permeability test was carried out at 200 kPa and 400 kPa of applied matric suction and, subsequently, the wetting unsaturated permeability test was performed until 90 kPa.

Table 5.7 Typical times needed to complete a cycle of drying and wetting unsaturated permeability tests using the 1 bar permeameter (matric suction up to 90 kPa)

Stages of test	Matric suction (kPa)	Duration (days)
Sample preparation	-	2
Saturation	-	6
Consolidation	-	1
Matric suction equalization	5	1
Drying permeability test	5	3
Matric suction equalization	10	1
Drying permeability test	10	3
Matric suction equalization	20	1
Drying permeability test	20	3
Matric suction equalization	30	2
Drying permeability test	30	4
Matric suction equalization	40	2

Drying permeability test	40	4
Matric suction equalization	50	2
Drying permeability test	50	4
Matric suction equalization	75	2
Drying permeability test	75	4
Matric suction equalization	90	3
Drying permeability test	90	6
Matric suction equalization	75	3
Wetting permeability test	75	9
Matric suction equalization	50	3
Wetting permeability test	50	8
Matric suction equalization	35	2
Wetting permeability test	35	6
Matric suction equalization	20	2
Wetting permeability test	20	4
Matric suction equalization	10	1.5
Wetting permeability test	10	4
Matric suction equalization	5	1
Wetting permeability test	5	3
Matric suction equalization	1	1
Wetting permeability test	1	3
	Total (Months)	3.48

Table 5.8 Typical times needed to complete a cycle of drying and wetting unsaturated permeability tests using the 5 bar permeameter (matric suction up to 400 kPa)

Stages of test	Matric suction (kPa)	Duration (days)
Sample preparation	-	2
Saturation	-	6
Consolidation	-	1
Matric suction equalization	200	6
Drying permeability test	200	8
Matric suction equalization	400	25
Drying permeability test	400	11
Matric suction equalization	200	27
Wetting permeability test	200	14
Matric suction equalization	90	6
Wetting permeability test	90	10
	Total (months)	3.87

It is observed from Table 5.7 and Table 5.8 that a cycle of drying and wetting unsaturated permeability test of one particular orientation (HL or VL) of a specimen can be completed in less than 4 months. As described in Section 4.1.5.2, three complete sets of drying and wetting unsaturated permeability tests were performed for each HL and VL orientation of 50S50K (B), 50S50K (C) and specimens with 9% coarse mica. Therefore, the unsaturated permeability tests performed in this research took almost two years for the completion.

As described in Section 4.1.5.2, there are different stages in the unsaturated permeability test compared to the saturated permeability test. Initially after the specimen was fully saturated, the specimen underwent consolidation with an effective consolidation stress ($\sigma_3 - u_b$) of 25 kPa having back pressure (u_b) of 490 kPa, similar to the conditions in the saturated permeability test. Table 5.9 shows the physical properties of each specimen at the initial compaction condition and the final condition at the start of application of matric suction in the unsaturated permeability test.

Table 5.9 Physical properties of each specimen during initial and final conditions in the unsaturated permeability test

Specimens	$\rho_{d,initial}$ (Mg/m³)	$W_{initial}$ (%)	$S_{initial}$	$\rho_{d,final}$ (Mg/m³)	W_{final} (%)	S_{final}
50S50K (B)	1.75	12.1	0.65	1.62	19.8	0.91
50S50K (C)	1.75	17.5	0.94	1.58	20.4	0.96
Specimens with 9% coarse mica	1.77	16.0	0.89	1.61	20.1	0.93

After the consolidation was completed, the intended matric suction following intervals described in Section 4.1.5.2 was applied to the specimen. A pressure head difference of 10 kPa ($\Delta h = 1$ m) was applied to the specimen when the equilibrium condition had been achieved for the applied matric suction. This procedure was repeated until the intended drying and wetting paths of unsaturated conditions were completed. For each application of matric suction, water flow rate (Q) through the specimen was measured. The permeability of the three-layered system (k_{system}) was then calculated using Equation 4.2. In order to obtain the unsaturated permeability of

the specimen, Equation 4.7 was used by incorporating the top and bottom disks (7.14 mm of thickness each). The saturated permeability of 1-bar and 5 bar ceramic disks were 5.60×10^{-8} and 1.75×10^{-8} m/s, respectively. Table 5.10 shows the results of unsaturated permeability tests for HL and VL orientations of 50S50K (B). Table 5.11 shows the results of unsaturated permeability tests for HL and VL orientations of 50S50K (C). Table 5.12 shows the results of unsaturated permeability tests for HL and VL orientations of specimens with 9% coarse mica

Table 5.10 Measured coefficients of unsaturated permeability of 50S50K (B)

Matric suction (kPa)	Q_{HL} (m³/s)	$k_{system,HL}$ (m/s)	$k_{w, HL}$ (m/s)	Q_{VL} (m³/s)	$k_{system,VL}$ (m/s)	$k_{w, VL}$ (m/s)
5	9.00E-10	2.03E-08	1.56E-08	2.25E-09	5.07E-08	4.86E-08
10	7.13E-10	1.61E-08	1.20E-08	1.84E-09	4.15E-08	3.69E-08
20	1.02E-10	2.30E-09	1.58E-09	3.87E-10	8.74E-09	6.23E-09
30	9.67E-11	2.18E-09	1.50E-09	3.41E-10	7.70E-09	5.46E-09
40	7.73E-11	1.74E-09	1.19E-09	2.62E-10	5.92E-09	4.15E-09
50	5.65E-11	1.27E-09	8.70E-10	1.82E-10	4.11E-09	2.85E-09
75	1.25E-11	2.81E-10	1.91E-10	3.88E-11	8.76E-10	5.97E-10
90	8.32E-12	1.88E-10	1.27E-10	2.69E-11	6.07E-10	4.13E-10
200	1.61E-13	3.63E-12	2.46E-12	5.56E-13	1.25E-11	8.50E-12
400	1.14E-14	2.57E-13	1.74E-13	3.67E-14	8.28E-13	5.61E-13
200	1.69E-14	3.82E-13	2.59E-13	4.24E-14	9.57E-13	6.48E-13
90	1.15E-13	2.59E-12	1.76E-12	3.24E-13	7.31E-12	4.96E-12
75	2.80E-13	6.31E-12	4.27E-12	7.50E-13	1.69E-11	1.15E-11
50	2.27E-12	5.11E-11	3.47E-11	4.86E-12	1.10E-10	7.44E-11
35	4.46E-12	1.01E-10	6.81E-11	1.02E-11	2.29E-10	1.56E-10
20	1.49E-11	3.36E-10	2.28E-10	3.85E-11	8.69E-10	5.92E-10
10	1.97E-11	4.43E-10	3.01E-10	4.71E-11	1.06E-09	7.24E-10
5	2.25E-11	5.08E-10	3.45E-10	5.21E-11	1.18E-09	8.02E-10
1	2.38E-11	5.38E-10	3.65E-10	5.25E-11	1.19E-09	8.09E-10

Table 5.11 Measured coefficients of unsaturated permeability of 50S50K (C)

Matric suction (kPa)	Q_{HL} (m³/s)	$k_{system,HL}$ (m/s)	$k_{w, HL}$ (m/s)	Q_{VL} (m³/s)	$k_{system,VL}$ (m/s)	$k_{w, VL}$ (m/s)
5	1.17E-10	2.65E-09	1.82E-09	6.38E-10	1.44E-08	1.06E-08
20	9.43E-11	2.13E-09	1.46E-09	4.89E-10	1.10E-08	7.98E-09
35	9.17E-11	2.07E-09	1.42E-09	4.46E-10	1.01E-08	7.23E-09
50	2.75E-11	6.22E-10	4.23E-10	1.66E-10	3.74E-09	2.59E-09
75	5.44E-12	1.23E-10	8.32E-11	3.13E-11	7.07E-10	4.81E-10
90	1.79E-12	4.04E-11	2.74E-11	1.02E-11	2.29E-10	1.56E-10
200	6.50E-14	1.47E-12	9.93E-13	3.88E-13	8.75E-12	5.93E-12
400	1.18E-14	2.66E-13	1.80E-13	7.02E-14	1.58E-12	1.07E-12
200	7.08E-16	1.60E-14	1.08E-14	3.10E-15	6.98E-14	4.73E-14
90	1.08E-14	2.43E-13	1.65E-13	5.09E-14	1.15E-12	7.79E-13
75	2.51E-14	5.65E-13	3.83E-13	1.08E-13	2.44E-12	1.65E-12
50	4.44E-13	1.00E-11	6.78E-12	2.09E-12	4.72E-11	3.20E-11
35	1.29E-12	2.90E-11	1.96E-11	6.10E-12	1.38E-10	9.33E-11
20	2.06E-12	4.65E-11	3.15E-11	1.00E-11	2.26E-10	1.53E-10
5	2.68E-12	6.04E-11	4.09E-11	1.29E-11	2.90E-10	1.97E-10
1	3.21E-12	7.25E-11	4.91E-11	1.46E-11	3.29E-10	2.23E-10

Table 5.12 Measured coefficients of unsaturated permeability of specimens with 9% coarse mica

Matric suction (kPa)	Q_{HL} (m³/s)	$k_{system,HL}$ (m/s)	$k_{w, HL}$ (m/s)	Q_{VL} (m³/s)	$k_{system,VL}$ (m/s)	$k_{w, VL}$ (m/s)
5	6.38E-10	1.44E-08	1.06E-08	3.68E-09	8.29E-08	1.08E-07
10	3.66E-10	8.25E-09	5.87E-09	2.66E-09	6.01E-08	6.22E-08
20	3.13E-11	7.06E-10	4.80E-10	3.10E-10	7.00E-09	4.94E-09
30	2.74E-11	6.18E-10	4.20E-10	2.66E-10	5.99E-09	4.20E-09
40	1.75E-11	3.95E-10	2.68E-10	1.91E-10	4.31E-09	3.00E-09
50	1.18E-11	2.67E-10	1.81E-10	1.23E-10	2.76E-09	1.90E-09
75	7.78E-12	1.76E-10	1.19E-10	7.78E-11	1.76E-09	1.20E-09
90	4.97E-12	1.12E-10	7.61E-11	5.34E-11	1.20E-09	8.22E-10
200	5.15E-13	1.16E-11	7.87E-12	5.29E-12	1.19E-10	8.11E-11
400	2.03E-14	4.58E-13	3.10E-13	2.17E-13	4.90E-12	3.32E-12
200	6.41E-15	1.45E-13	9.80E-14	5.55E-14	1.25E-12	8.48E-13
90	1.20E-13	2.71E-12	1.84E-12	9.63E-13	2.17E-11	1.47E-11
75	3.99E-13	9.00E-12	6.10E-12	3.36E-12	7.58E-11	5.14E-11
50	9.32E-13	2.10E-11	1.42E-11	8.30E-12	1.87E-10	1.27E-10
35	3.50E-12	7.90E-11	5.35E-11	3.11E-11	7.01E-10	4.77E-10
20	6.26E-12	1.41E-10	9.57E-11	5.49E-11	1.24E-09	8.45E-10
10	9.55E-12	2.15E-10	1.46E-10	8.50E-11	1.92E-09	1.31E-09
5	1.06E-11	2.39E-10	1.62E-10	8.95E-11	2.02E-09	1.38E-09
1	1.07E-11	2.41E-10	1.63E-10	9.12E-11	2.06E-09	1.41E-09

Figure 5.7 and Figure 5.8 respectively show the drying and wetting coefficients of unsaturated permeability of 50S50K (B) obtained using the direct measurement. Figure 5.9 and Figure 5.10 respectively show the drying and wetting coefficients of unsaturated permeability of 50S50K (C) obtained using the direct measurement. Figure 5.11 and Figure 5.12 respectively show the drying and wetting coefficients of unsaturated permeability of specimens with 9% coarse mica obtained using the direct measurement.

Figure 5.7 Measured drying unsaturated permeability of 50S50K (B)

Figure 5.8 Measured wetting unsaturated permeability of 50S50K (B)

Figure 5.9 Measured drying unsaturated permeability of 50S50K (C)

Figure 5.10 Measured wetting unsaturated permeability of 50S50K (C)

Figure 5.11 Measured drying unsaturated permeability of specimens with 9% coarse mica

Figure 5.12 Measured wetting unsaturated permeability of specimens with 9% coarse mica

In both following the drying and wetting paths of unsaturated conditions, the VL orientation is observed to have consistently higher coefficients of unsaturated permeability than the corresponding HL orientation for a given specimen. This behavior existed in all specimens tested in the research regardless the shape of the unsaturated permeability data (unimodal or bimodal), initial compaction conditions (dry or wet of optimum) or mica content (with or without mica). In addition, coefficients of unsaturated permeability measured during the wetting test are observed to be significantly smaller (almost two orders of magnitude) than those measured during the drying test at the corresponding matric suction for a given orientation of a specimen. It is also observed that the measured wetting unsaturated permeability data for all specimens have a unimodal shape regardless the shape of the drying unsaturated permeability data (unimodal or bimodal). This observation is supported

by the shape of the corresponding measured wetting SWCC, which is presented in Section 5.6.

Two typical water volume change curves are observed during the drying and wetting unsaturated permeability tests of the specimens. Figure 5.13 shows the typical water volume curve observed during the drying unsaturated permeability tests of matrix suction up to 75 kPa and from a matrix suction of 50 kPa downwards in the wetting unsaturated permeability tests.

Figure 5.13 Typical water volume change curve during unsaturated permeability measurement of applied matrix suction up to 75 kPa in the drying test and from 50 kPa in the wetting test

Figure 5.13 depicts the linear increase in water volume from the beginning of permeability measurements with the VL orientation consistently showing a higher water volume change than the corresponding HL orientation for a given specimen. This observation persists for a period of time, indicating the steady-state (equilibrium)

condition has already been achieved. It indicates that there is good connectivity between pore-water in the specimen so the rate of water flow directly corresponds to the applied pressure gradient, which is similar to the case of saturated permeability measurement.

Figure 5.14 shows another typical water volume curve observed during the drying unsaturated permeability tests from matric suction of 90 kPa upwards and in the wetting unsaturated permeability tests from matric suction of 200 kPa to 75 kPa.

Figure 5.14 Typical water volume change curve during unsaturated permeability measurement of applied matric suction from 90 kPa in the drying test and up to 75 kPa in the wetting test

The observed water volume curve is non-linear at the beginning and shows a linear trend after some period of time. This non-linear period can be considered a transient condition prior to reaching the steady-state (equilibrium) condition, as reflected by the linear period afterwards. For a given specimen, HL and VL orientations are observed

to require different durations of time to reach the steady-state condition, i.e. they have different equilibrium times, during the drying and wetting unsaturated permeability tests, although the cumulative water volume during this transient period is similar for both orientations.

During the drying and wetting unsaturated permeability tests, small volume changes are observed for the specimens and have been considered in this research. Figure 5.15 shows typical volumetric strains in the specimens observed during the drying and wetting unsaturated permeability and SWCC tests.

Figure 5.15 Typical volumetric strains of the specimen tested in the research

Volumetric strain (ϵ_v) is defined as a change in soil volume (ΔV) over initial soil volume (V_{initial}). A specimen typically undergoes shrinking (represented by negative value) and swelling (represented by positive value) during the respective drying and wetting unsaturated permeability and SWCC tests. It is observed that the cumulative volumetric strains for the specimens during each drying and wetting unsaturated permeability and SWCC tests are less than 5% of the initial volume, thus can be considered as non excessive.

5.6. Soil-Water Characteristic Curve

A series of soil-water characteristic curve (SWCC) tests was performed on soil mixtures corresponding to those used for the permeability tests as well other soil mixtures described in Table 4.1 and Table 4.2. A complete set of 12 drying and wetting SWCC tests was performed for each HL and VL orientation of the specimens. The results from the SWCC tests serve as an indirect determination of the unsaturated permeability for the corresponding specimens. In addition, the effects of hydraulic anisotropy on the drying and wetting SWCCs are observed for different initial conditions and mica contents. The SWCCs of all specimens are obtained using Tempe cell and pressure plate (represented by “TC&PP” in all relevant figures and tables), modified triaxial SWCC (represented by “Triaxial” in all relevant figures and tables) and unsaturated triaxial permeameter (represented by “Permeameter” in all relevant figures and tables) as described in Section 4.1.5.2 and Section 4.1.6. The measured SWCCs data are classified as SWCCs under zero net confining pressure if obtained from the Tempe cell and pressure plate apparatuses, and SWCCs under 25 kPa net confining pressure if obtained from the modified triaxial SWCC and unsaturated triaxial permeameter apparatus.

Figure 5.16 and Figure 5.17 show the drying and wetting SWCCs of 50S50K (A) obtained using the Tempe cell and pressure plate apparatuses. Figure 5.18 and Figure 5.19 show the drying and wetting SWCCs of 50S50K (B) obtained using all measurement apparatuses. Figure 5.20 and Figure 5.21 show the drying and wetting SWCCs of 50S50K (C) obtained using all measurement apparatuses. Figure 5.22 and Figure 5.23 show the drying and wetting SWCCs of 50S50K (D) having heights of 30 mm and 50 mm obtained using the Tempe cell and pressure plate apparatuses. Figure 5.24 and Figure 5.25 show the drying and wetting SWCCs of specimens with 9% coarse mica obtained using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses. Figure 5.26 and Figure 5.27 show the drying and wetting SWCCs of specimens with 20% coarse mica obtained using the modified triaxial SWCC apparatus.

Figure 5.16 Measured drying SWCC data of 50S50K (A) using the Tempe cell and pressure plate apparatuses

Figure 5.17 Measured wetting SWCC data of 50S50K (A) using the Tempe cell and pressure plate apparatuses

Figure 5.18 Measured drying SWCC data of 50S50K (B) using the Tempe cell and pressure plate, modified triaxial SWCC and unsaturated triaxial permeameter apparatuses

Figure 5.19 Measured wetting SWCC data of 50S50K (B) using the Tempe cell and pressure plate, modified triaxial SWCC and unsaturated triaxial permeameter apparatuses

Figure 5.20 Measured drying SWCC data of 50S50K (C) using the Tempe cell and pressure plate, modified triaxial SWCC and unsaturated triaxial permeameter apparatuses

Figure 5.21 Measured wetting SWCC data of 50S50K (C) using the Tempe cell and pressure plate, modified triaxial SWCC and unsaturated triaxial permeameter apparatuses

Figure 5.22 Measured drying SWCC data of 50S50K (D) using the Tempe cell and pressure plate apparatuses

Figure 5.23 Measured wetting SWCC data of 50S50K (D) using the Tempe cell and pressure plate apparatuses

Figure 5.24 Measured drying SWCC data of specimens with 9% coarse mica using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses

Figure 5.25 Measured wetting SWCC data of specimens with 9% coarse mica using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses

Figure 5.26 Measured drying SWCC data of specimens with 20% coarse mica using the Tempe cell and pressure plate apparatuses

Figure 5.27 Measured wetting SWCC data of specimens with 20% coarse mica using the Tempe cell and pressure plate apparatuses

The shapes of the drying and wetting SWCCs of 50S50K (B), 50S50K (C) and specimens with 9% coarse mica are observed to follow the shapes of the corresponding unsaturated permeability, as presented in Section 5.5. In addition, the shapes of the drying SWCCs of 50S50K (A) and specimens with 20% coarse mica are observed to be bimodal, whereas the shapes of their corresponding wetting SWCCs as well as the drying and wetting SWCCs of 50S50K (D) are unimodal. Regardless the shape of the drying and wetting SWCCs (unimodal or bimodal), it is observed that, for a given specimen (with or without mica content), the HL and VL orientations have similar measured SWCC data throughout the drying and wetting paths of unsaturated conditions. Different heights (30 mm and 50 mm) of 50S50K (D) also show insignificant differences in both the measured drying and wetting SWCCs data. Moreover, for a given specimen, SWCC data obtained using the Tempe cell and pressure plate apparatuses are found to be slightly higher than those obtained using

the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses. This observation can be related to the fact that there was 25 kPa net confining pressure in the SWCC measurement using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses, unlike zero confining pressure in the corresponding SWCC measurement using the Tempe cell and pressure plate apparatuses. In general, highly similar measured drying and wetting SWCCs data for HL and VL orientations are obtained for all specimens tested regardless the initial conditions (dry or wet of optimum), mica content (with or without mica), shape (unimodal or bimodal) or measurement apparatus.

There were different times needed to achieve the equilibrium (steady-state) conditions, i.e. equilibrium times differed for HL and VL orientations during the drying SWCC test of matric suctions higher than the air-entry value (AEV) and during the wetting SWCC test up to matric suction approaching saturated conditions (20 kPa) of the specimen. Figure 5.28 shows the typical water volume change during SWCC measurement of applied matric suctions higher than the AEV in the drying tests and applied matric suction up to 20 kPa in the wetting tests. The shapes of the water volume change curves for both the HL and VL orientations are observed to be similar, i.e. typical sigmoid shape. Both the HL and VL orientations are observed to have similar initial and final volumes of water at a particular application of matric suction. However, the equilibrium time for the VL orientation is faster than the equilibrium time for the corresponding HL orientation for a given specimen. This is as expected because the VL orientation has a consistently higher coefficient of unsaturated permeability than the HL orientation, as shown in Section 5.5. For other applications of matric suction, i.e. matric suction less than the AEV in the drying SWCC test or less than 20 kPa in the wetting SWCC test, there was no significant

water volume change between the initial and final water contents. Therefore, the equilibrium time was found to be relatively constant from the beginning of the test.

Figure 5.28 Typical water volume change curve during SWCC measurements at matric suctions higher than the AEV in the drying tests and up to 20 kPa in the wetting tests

During the drying and wetting SWCC tests, a small volume change was observed in each specimen similar to that observed during the drying and wetting unsaturated permeability tests as shown in Figure 5.15. The small volume change has been considered in the SWCC as presented in the form of volumetric water content in Figure 5.16 – Figure 5.27. Nonetheless, the drying and wetting SWCCs can be plotted independent of volume change, i.e. in gravimetric water content form. Figure 5.29 shows the typical drying and wetting SWCCs in gravimetric form. It is observed that the HL and VL orientations of a given specimen have similar measured SWCC data throughout the drying and wetting paths of unsaturated conditions. This observation indicates that this behavior can be observed in the drying and wetting SWCCs of both volumetric and gravimetric forms.

Figure 5.29 Typical measured drying and wetting gravimetric SWCCs of the specimen

5.7. Numerical Modeling

Numerical analyses of the SWCC tests using the Tempe cell and pressure plate, modified triaxial SWCC and unsaturated triaxial permeameter apparatuses were carried out according to the procedure described in Section 4.2. Figure 5.30 shows the typical output of volumetric water content from numerical modeling of the drying SWCC test at matric suctions less than the air-entry value (AEV). Figure 5.31 shows the typical output of volumetric water content from numerical modeling of the drying SWCC test at matric suctions higher than the AEV. Certain node locations throughout the specimen model, as described in Figure 4.27, were selected to show the variation in water content compared to the average water content from all nodes. It is observed that, at matric suctions less than the AEV, only the water content at nodes A and D is affected. On the other hand, for matric suctions higher than the AEV, all nodes (A-D as well as the average) show significant changes in water content. This behavior is expected because, for matric suctions less than the AEV, air has not entered the soil

and, as a consequence, only nodes located at the perimeter area are influenced. For the application of matric suctions higher than the AEV, air can enter into the specimen and cause significant water flow throughout the specimen, as depicted by the change in the average volumetric water content in all nodes.

Figure 5.30 Typical volumetric water content outputs from numerical modeling of the drying SWCC test at matric suction less than the AEV

Figure 5.31 Typical volumetric water content outputs from numerical modeling of the drying SWCC test at matric suctions higher than the AEV

Numerical modeling was carried out to confirm the equilibrium time behavior observed during the laboratory SWCC tests. Table 5.13 shows the numerical modeling results of equilibrium time during the drying SWCC tests using all measurement apparatuses at matric suctions higher than the AEV for HL and VL orientations of 50S50K (C). Table 5.14 shows the numerical modeling results of equilibrium time during the drying SWCC tests using the Tempe cell and pressure plate apparatuses higher than the AEV for HL and VL orientations of 50S50K (D) having heights of 30 mm and 50 mm.

Table 5.13 Equilibrium times of 50S50K (C) during the drying SWCC tests using all measurement apparatuses performed in numerical modeling

Matric suction (kPa)	TC&PP			Triaxial and Permeameter		
	$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL}/$ $t_{eq, VL}$)	$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL}/$ $t_{eq, VL}$)
75	65.59	11.91	5.51	66.78	10.98	6.08
90	76.74	12.91	5.94	121.90	20.27	6.01
200	222.60	41.48	5.37	268.97	49.33	5.45
400	956.95	186.26	5.14	1011.47	186.26	5.43

Table 5.14 Equilibrium times of 50S50K (D) having different heights during the drying SWCC tests using the Tempe cell and pressure plate apparatuses performed in numerical modeling

Matric suction (kPa)	30 mm height			50 mm height		
	$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL}/$ $t_{eq, VL}$)	$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL}/$ $t_{eq, VL}$)
75	20.27	5.46	3.71	31.48	10.11	3.11
90	25.27	6.26	4.04	34.25	11.26	3.04
200	50.46	13.84	3.65	104.59	28.90	3.62
400	189.06	48.51	3.90	401.92	106.20	3.78

It is observed that HL orientation requires a longer equilibrium time during the drying SWCC tests using a particular measurement apparatus than the corresponding VL orientation for a given specimen. The ratio of equilibrium times during the drying SWCC tests between HL and VL orientations of a given specimen is consistent for all matric suctions higher than the AEV, regardless the measurement apparatus used. In addition, 50S50K (D) model with a shorter height of 30 mm has a significantly faster equilibrium time during the SWCC test for each corresponding orientation (HL or VL) than the 50S50K (D) model with a taller height of 50 mm. However, the different heights of 30 mm and 50 mm in 50S50K (D) models are observed to induce only a small difference in the ratio of equilibrium times during the SWCC test. In general, the behavior of consistent ratio of equilibrium times during the drying SWCC tests between HL and VL orientations of a given specimen is observed regardless the measurement apparatus used or height of the specimen model. The numerical analyses in this research only focus on models with a unimodal shape for the drying SWCC, water and air permeability functions, i.e. 50S50K (C) and 50S50K (D), because for models with a bimodal shape for the SWCC, the corresponding bimodal water and air permeability functions estimated from the SWCC have not been well investigated. In addition, the hysteresis effect (drying and wetting cycle) has not been well defined in the combined Seep/W and Air/W packages of GeoStudio 2007 software. These limitations should be studied in the future and will be presented again in the recommendations section.

CHAPTER 6 DISCUSSION OF RESULTS

Discussions of the results shown in Chapter 5 are presented in this chapter. Hydraulic anisotropy behavior of the specimens under the saturated conditions and following the drying and wetting paths of unsaturated conditions are discussed in detail. Under the saturated conditions, the hydraulic anisotropy behavior discussion is primarily on the different hydraulic anisotropy values measured for different initial conditions (dry or wet of optimum) and different mica contents (with or without mica). For each drying and wetting path of unsaturated conditions, the hydraulic anisotropy behaviors consisting of hydraulic anisotropy values and ratio of equilibrium times between HL and VL orientations are discussed. Next, comparisons of the different hydraulic anisotropy values under the saturated conditions and following the drying and wetting paths of unsaturated conditions, as well as the ratio of equilibrium times following the drying and wetting paths of unsaturated conditions, are presented. A detailed discussion of the characteristics of drying and wetting SWCCs with regards to hydraulic anisotropy is subsequently presented. Parts of the discussion presented in this chapter have been published in Priono et al. (2016a) and Priono et al. (2016b).

6.1. Hydraulic Anisotropy Behavior under the Saturated Conditions

The discussion of hydraulic anisotropy behavior of various specimens under the saturated conditions, as shown in Table 4.5, is presented in this section. As described in Section 4.1.1, the statically-compacted specimens prepared in this research were intended to be tested for understanding the effect of different initial compaction conditions and different mica contents on hydraulic anisotropy behavior. Under the saturated conditions, the different values of hydraulic anisotropy measured for each

specimen were correlated with the initial conditions and the mica contents of the specimen using regression analyses. The regression analyses were carried out by finding a mathematical expression with highest possible of coefficient of determination (R^2) value.

Figure 6.1 shows saturated permeability of HL and VL orientations of each specimen without mica content, i.e. 50S50K (A – D) against the initial water content. Graphically, the distance between saturated permeability values of VL and HL for given specimen indicates hydraulic anisotropy of the specimen. It can be observed that 50S50K (C) and 50S50K (A) have the highest and the lowest hydraulic anisotropy, respectively.

Figure 6.1 Measured saturated permeability values of the specimens without mica content having different initial water content

Figure 6.2 shows a non-linear regression analysis between the initial water content and hydraulic anisotropy for specimens without mica content tested in this research, i.e. 50S50K (A – D). This analysis was performed in order to understand the relationship between the hydraulic anisotropy values measured under the saturated conditions and the different water contents at compaction without the effect of adding mica particles. A non-linear (parabolic) expression of $y = -0.162x^2 + 5.233x - 36.233$ having $R^2 = 1.000$ is observed between hydraulic anisotropy measured under the saturated conditions (represented by parameter “y”) and the initial water content at compaction (represented by parameter “x”).

Figure 6.2 Regression analysis between hydraulic anisotropy values measured under the saturated conditions and initial water content during compaction

This relationship may exist because the initial water content at compaction affects the arrangement of soil particles and, consequently, the soil structure. Specimens having an extreme amount of water content at compaction, i.e. too little water content like in

50S50K (A) or too much water content like in 50S50K (D), induce smaller hydraulic anisotropy values than specimens with intermediate water content, such as 50S50K (B) and 50S50K (C). Too little or too much water content at compaction produces a soil structure with a low initial dry density (90% maximum dry density), which indicates that water can flow with less directional-dependence (less tortuous flow between HL and VL orientations) compared to the corresponding soil structure with a high initial dry density (95% maximum dry density). The denser soil structure of 50S50K (B) and 50S50K (C) is also the main factor that induces lower coefficients of saturated permeability at each orientation (HL or VL) compared to 50S50K (A) and 50S50K (D), respectively. It is also observed that 50S50K (C) and 50S50K (D) have higher hydraulic anisotropy under the saturated conditions than 50S50K (B) and 50S50K (A), respectively. This observation means that, for a given initial dry density, the specimens compacted at wet of optimum water content have higher hydraulic anisotropy values than those with the corresponding dry of optimum water content. This may occur because specimens compacted at wet of optimum water content have the dispersed or layered soil structure, unlike the flocculated soil structure observed in specimens compacted at dry of optimum water content (Fredlund and Rahardjo, 1993; Mitchell and Soga, 2005; Tarantino, 2010).

For further understanding, saturated permeability of each specimen is plotted against both initial and final void ratio as shown in Figure 6.3. Initial and final conditions refer to the initial compaction condition and the final condition during the saturated permeability measurement, respectively. Graphically, for a given specimen, the vertical distance between saturated permeability values of VL and HL indicates hydraulic anisotropy of the specimen, whereas the horizontal distance indicates the change in void ratio of the specimen during the saturation and the consolidation of

saturated permeability test. It can be observed that for a given dry density, soils having initial conditions at the wet of optimum, i.e. 50S50K (C) and 50S50K (D), have a larger change in void ratio and a higher hydraulic anisotropy than those in soils having initial conditions at the dry of optimum, i.e. 50S50K (B) and 50S50K (A).

Figure 6.3 Measured saturated permeability values of the specimens without mica content plotted at initial and final void ratio

Figure 6.4 shows saturated permeability values of HL and VL orientations of each micaceous specimen against the mica content. Graphically, the distance between saturated permeability values of VL and HL for a given specimen indicates hydraulic anisotropy of the specimen. It can be observed that the specimens with 9% mica content have a higher hydraulic anisotropy than the specimens with 20% mica content.

Figure 6.4 Measured saturated permeability values of the specimens having 9% and 20% mica content

Figure 6.5 shows the regression analysis between hydraulic anisotropy values measured under the saturated conditions and mica contents of the specimens. This analysis was performed in order to understand the relationship between hydraulic anisotropy values measured under the saturated conditions and different mica contents without the effect of different initial compaction conditions. All specimens considered in Figure 6.5 were prepared at 95% maximum dry density at wet of optimum water content. Non-linear (parabolic) expressions of $y = -0.065x^2 + 1.101x + 5.830$ having $R^2 = 1.000$ and $y = -0.025x^2 + 0.265x + 5.846$ having $R^2 = 1.000$ are observed between hydraulic anisotropy measured under the saturated conditions (represented by parameter “y”) and the mica content (represented by parameter “x”) for coarse mica and medium mica contents, respectively.

Figure 6.5 Regression analysis between hydraulic anisotropy values measured under the saturated conditions and mica contents in the specimens

Regardless if it is coarse or medium mica, the general behavior is that the hydraulic anisotropy of the specimen increases with addition of 9% mica content and, subsequently, decreases with further addition of 20% mica content. This relationship may exist because the addition of 9% mica content induces Bridging and Ordering soil structure, as shown in Figure 2.12. Mica particles are platy and have different parameters of particle shapes compared to sand and kaolin, as presented in Section 4.2. During compaction, mica particles are expected to align themselves in a parallel direction with their greater length perpendicular to the direction of compaction load, i.e. act as “bridge” as illustrated in Figure 2.12, in order to keep themselves in a minimum state of energy as suggested by Martin (1962). This Bridging and Ordering soil structure can enhance the hydraulic anisotropy of the soil since water can flow significantly faster in the direction parallel to the “bridge” (represented in VL

specimen) as opposed to the direction perpendicular to the “bridge” (represented by HL specimen).

Nonetheless, the measured hydraulic anisotropy in the specimens with 20% coarse mica is smaller than that in the specimens with 9% coarse mica; the value is also smaller compared to the initial specimens without mica content (50S50K (C)). This observation is closely related to the fact that specimens with 20% mica content have a very low initial dry density, i.e. 1.64 Mg/m^3 and 1.54 Mg/m^3 , respectively, for specimens with coarse mica and medium mica contents. For comparison, 50S50K (C) has an initial dry density of 1.75 Mg/m^3 , as shown in Table 5.1. The addition of too much mica induces a looser soil structure compared to the initial soil structure of 50S5K (C) and, consequently, there is no significant directional-dependence for water to flow, i.e. less tortuous flow between HL and VL orientations. It is also observed in Table 5.5 that, for a given mica content, coarse mica induces higher hydraulic anisotropy values than medium mica. This may occur because coarse mica leads to more pronounced Bridging and Ordering soil structure than medium mica. As illustrated in Figure 2.12, the Bridging and Ordering soil structure is formed when the mica particles create “the bridge” between the soil particles above and below them. It is reasonable to expect that coarse mica particles can create more pronounced (greater in dimension) “bridges” in the Bridging and Ordering soil structure than medium mica particles.

6.2. Hydraulic Anisotropy Behavior in the Drying Path of Unsaturated Conditions

Discussions on the hydraulic anisotropy behavior of various specimens in the drying path of unsaturated conditions, as shown in Section 5.5 and Section 5.6, are presented in this section. As described in Section 4.1.1, the statically-compacted specimens prepared in this research were used to understand the effect of different initial compaction conditions and different mica contents on hydraulic anisotropy behavior. In the drying path of unsaturated conditions, the values of hydraulic anisotropy were measured directly using unsaturated triaxial permeameters and indirectly determined from the corresponding drying SWCC for 50S50K (B), 50S50K (C) and specimens with 9% coarse mica. These hydraulic anisotropy values are discussed and compared using the statistical coefficient of determination (R^2) and relative difference (Δ_r) criteria described in Section 4.3. In addition, the behavior of equilibrium times measured during the drying permeability and SWCC tests of 50S50K (B), 50S50K (C) and specimens with 9% coarse mica is analyzed and correlated with the measured hydraulic anisotropy values using the same criteria described in Section 4.3.

Table 6.1 shows the hydraulic anisotropy values of 50S50K (B) obtained directly through the drying permeability tests. Table 6.2 shows the hydraulic anisotropy values of 50S50K (C) obtained directly through the drying permeability tests. Table 6.3 shows the hydraulic anisotropy values of specimens with 9% coarse mica obtained directly through the drying permeability tests. In order to illustrate the hydraulic anisotropy values measured in the drying path of unsaturated conditions compared to those measured in the saturated conditions, Table 6.1 and Table 6.2 are plotted as Figure 6.6 and Figure 6.7, respectively.

Table 6.1 Measured hydraulic anisotropy values of 50S50K (B) in the drying path of unsaturated conditions

Matric suction (kPa)	$k_{w, HL}$ (m/s)	$k_{w, VL}$ (m/s)	Hydraulic anisotropy	Δ_r (%)
5	1.56E-08	4.86E-08	3.12	7.26
10	1.20E-08	3.69E-08	3.08	8.47
20	1.58E-09	6.23E-09	3.94	17.37
30	1.50E-09	5.46E-09	3.64	8.35
40	1.19E-09	4.15E-09	3.49	3.81
50	8.70E-10	2.85E-09	3.28	2.49
75	1.91E-10	5.97E-10	3.13	6.96
90	1.27E-10	4.13E-10	3.25	3.20
200	2.46E-12	8.50E-12	3.46	2.86
400	1.74E-13	5.61E-13	3.22	4.03
		Average	3.36	6.48

Table 6.2 Measured hydraulic anisotropy values of 50S50K (C) in the drying path of unsaturated conditions

Matric suction (kPa)	$k_{w, HL}$ (m/s)	$k_{w, VL}$ (m/s)	Hydraulic anisotropy	Δ_r (%)
5	1.82E-09	1.06E-08	5.82	1.52
20	1.46E-09	7.98E-09	5.47	4.73
35	1.42E-09	7.23E-09	5.09	11.25
50	4.23E-10	2.59E-09	6.12	6.73
75	8.32E-11	4.81E-10	5.78	0.77
90	2.74E-11	1.56E-10	5.69	0.76
200	9.93E-13	5.93E-12	5.97	4.09
400	1.80E-13	1.07E-12	5.94	3.62
		Average	5.74	4.18

Table 6.3 Measured hydraulic anisotropy values of specimens with 9% coarse mica in the drying path of unsaturated conditions

Matric suction (kPa)	$k_{w, HL}$ (m/s)	$k_{w, VL}$ (m/s)	Hydraulic anisotropy	Δ_r (%)
5	1.06E-08	1.08E-07	10.20	2.58
10	5.87E-09	6.22E-08	10.60	1.24
20	4.80E-10	4.94E-09	10.30	1.62
30	4.20E-10	4.20E-09	10.00	4.49
40	2.68E-10	3.00E-09	11.20	6.97
50	1.81E-10	1.90E-09	10.50	0.29
75	1.19E-10	1.20E-09	10.10	3.53
90	7.61E-11	8.22E-10	10.80	3.15
200	7.87E-12	8.11E-11	10.30	1.62
400	3.10E-13	3.32E-12	10.70	2.20
		Average	10.47	2.77

Figure 6.6 Measured hydraulic anisotropy of 50S50K (B) under the saturated conditions and following the drying path of unsaturated conditions

Figure 6.7 Measured hydraulic anisotropy of 50S50K (C) under the saturated conditions and following the drying path of unsaturated conditions

The relative differences (Δ_r) and their average (ARD) were computed for each specimen to show the variation between the measured hydraulic anisotropy at each application of matric suction and the mean of all hydraulic anisotropy values measured during the drying test. The use of Δ_r significantly aids in providing quick and reliable engineering assessment on the difference between two data. The difference is considered satisfactory if the value is less than 20%, as suggested in Goh et al. (2010) and Satyanaga et al. (2013). Physically, Δ_r indicates the difference between two data in terms of a percentage from the referenced data, instead of just a plain number (absolute value). For 50S50K (B), the relative difference (Δ_r) is observed to vary between 2.49 % and 17.37% with an average (ARD) of 6.48%. For specimen 50S50K (C), the relative difference (Δ_r) varies between 0.76% and 11.25% with an average (ARD) of 4.18%. For specimens with 9% coarse mica, the relative difference (Δ_r) varies between 0.29 % and 6.97% with an average (ARD) of 2.77%. The relative differences (Δ_r) and their average (ARD) are less than 20% for all specimens, indicating a reliably consistent hydraulic anisotropy directly measured throughout the drying permeability tests for all specimens in this research. Each specimen, i.e. 50S50K (B), 50S50K (C) and specimens with 9% coarse mica, has particular initial conditions (dry or wet of optimum), mica content (with or without mica) and shape of drying unsaturated permeability data (unimodal or bimodal), as presented in Section 5.5. Therefore, the behavior of consistent hydraulic anisotropy values throughout the drying path of unsaturated conditions is applicable for any initial conditions, mica content or shape of unsaturated permeability data.

Hydraulic anisotropy values in the drying path of unsaturated conditions of the specimen can also be indirectly determined from the corresponding drying SWCC. The drying SWCC of the specimen was first best-fitted using Equation 2.14 and

Equation 2.15 for the unimodal and bimodal drying SWCC data, respectively. As presented in Section 5.6, 50S50K (B) and specimens with 9% coarse mica have a bimodal shape whereas 50S50K (C) has a unimodal shape of the drying SWCC data, similar to the corresponding drying unsaturated permeability data presented in Section 5.5. Table 6.4 shows the bimodal fitting parameters of Equation 2.15 for the drying SWCC data of 50S50K (B) obtained using all measurement apparatuses. Figure 6.8 – Figure 6.10 illustrate best fitting for the measured drying SWCC data of 50S50K (B) based on the respective Tempe cell and pressure plate, modified triaxial SWCC and unsaturated triaxial permeameter measurements. Table 6.5 shows the unimodal fitting parameters of Equation 2.14 for the drying SWCC data of 50S50K (C) obtained using all measurement apparatuses. Figure 6.11 – Figure 6.13 illustrate best fitting for the measured drying SWCC data of 50S50K (C) based on the respective Tempe cell and pressure plate, modified triaxial SWCC and unsaturated triaxial permeameter measurements. Table 6.6 shows the bimodal fitting parameters of Equation 2.15 for the drying SWCC data of specimens with 9% coarse mica obtained using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses. Figure 6.14 and Figure 6.15 illustrate best fitting for the measured drying SWCC data of specimens with 9% coarse mica based on the respective modified triaxial SWCC and unsaturated triaxial permeameter measurements. The coefficient of determination (R^2) was computed in order to achieve the best fitting parameters for each orientation (HL and VL) of the drying SWCC obtained using each measurement apparatus. For 50S50K (B), R^2 value is observed to vary between 0.999 and 1.000. For 50S50K (C), R^2 value varies between 0.999 and 1.000. For specimens with 9% coarse mica, R^2 value varies between 0.992 and 0.999. High R^2 values (close to unity) are obtained for all specimens, indicating the specimens compacted at dry and wet of optimum

initial conditions have pronounced bimodal and unimodal shapes of the drying SWCC, respectively.

Table 6.4 Bimodal fitting parameters of the measured drying SWCC data of 50S50K
(B)

Fitting parameters	TC&PP		Triaxial		Permeameter	
	HL	VL	HL	VL	HL	VL
θ_{s1}	0.404	0.385	0.364	0.349	0.360	0.364
ψ_{a1} (kPa)	9.940	10.000	10.338	10.110	10.441	9.998
ψ_{m1} (kPa)	10.288	10.018	11.048	10.888	11.236	11.357
s_1	1.846	4.269	0.195	0.438	3.782	4.671
θ_{s2}	0.303	0.288	0.281	0.268	0.237	0.223
ψ_{a2} (kPa)	15.582	16.002	27.386	26.831	35.248	34.190
ψ_{m2} (kPa)	75.789	75.018	72.953	76.128	72.973	70.126
s_2	0.804	0.796	1.234	1.193	1.618	1.480
ψ_r (kPa)	600.005	600.007	499.958	499.990	499.990	500.003
θ_r	0.065	0.064	0.051	0.045	0.009	0.015
R^2	1.000	1.000	0.999	1.000	0.999	1.000

Figure 6.8 Best fitting for the measured drying SWCC data of 50S50K (B) based on the Tempe cell and pressure plate measurements

Figure 6.9 Best fitting for the measured drying SWCC data of 50S50K (B) based on the modified triaxial SWCC measurements

Figure 6.10 Best fitting for the measured drying SWCC data of 50S50K (B) based on the unsaturated triaxial permeameter measurements

Table 6.5 Unimodal fitting parameters of the measured drying SWCC data of 50S50K (C)

Fitting parameters	TC&PP		Triaxial		Permeameter	
	HL	VL	HL	VL	HL	VL
θ_s	0.430	0.429	0.386	0.385	0.379	0.389
a (kPa)	48.967	50.243	44.765	44.560	45.316	45.495
n	2.752	2.668	5.135	4.879	4.279	3.669
m	1.112	1.191	0.712	0.726	0.695	0.814
R^2	1.000	0.999	1.000	1.000	0.999	0.999

Figure 6.11 Best fitting for the measured drying SWCC data of 50S50K (C) based on the Tempe cell and pressure plate measurements

Figure 6.12 Best fitting for the measured drying SWCC data of 50S50K (C) based on the modified triaxial SWCC measurements

Figure 6.13 Best fitting for the measured drying SWCC data of 50S50K (C) based on the unsaturated triaxial permeameter measurements

Table 6.6 Bimodal fitting parameters of the measured drying SWCC data of specimens with 9% coarse mica

Fitting parameters	Triaxial		Permeameter	
	HL	VL	HL	VL
θ_{s1}	0.409	0.437	0.430	0.430
ψ_{a1} (kPa)	9.968	9.994	9.853	9.996
ψ_{m1} (kPa)	10.588	10.967	10.993	10.813
s_1	2.028	1.958	1.404	1.794
θ_{s2}	0.289	0.298	0.303	0.299
ψ_{a2} (kPa)	33.026	43.106	39.976	48.620
ψ_{m2} (kPa)	135.027	139.395	136.679	134.112
s_2	1.062	1.160	0.951	1.071
ψ_r (kPa)	499.984	499.986	499.922	504.996
θ_r	0.010	0.010	0.015	0.015
R²	0.998	0.992	0.999	0.999

Figure 6.14 Best fitting for the measured drying SWCC data of specimens with 9% coarse mica based on the modified triaxial SWCC measurements

Figure 6.15 Best fitting for the measured drying SWCC data of specimens with 9% coarse mica based on the unsaturated triaxial permeameter measurements

The drying unsaturated permeability of each specimen was subsequently estimated from the corresponding best-fitted drying SWCC using Equation 3.4. Table 6.7 shows the indirectly determined drying hydraulic anisotropy values of 50S50K (B) from the corresponding measured drying SWCC using the Tempe cell and pressure plate apparatuses. Table 6.8 shows the indirectly determined drying hydraulic anisotropy values of 50S50K (B) from the corresponding measured drying SWCC using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses. Table 6.9 shows the indirectly determined drying hydraulic anisotropy values of 50S50K (C) from the corresponding measured drying SWCC using the Tempe cell and pressure plate apparatuses. Table 6.10 shows the indirectly determined drying hydraulic anisotropy values of 50S50K (C) from the corresponding measured drying SWCC using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses. Table 6.11 shows the indirectly determined drying hydraulic anisotropy values of specimens with 9% coarse mica from the corresponding measured drying SWCC using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses.

Table 6.7 Estimated drying hydraulic anisotropy values of 50S50K (B) from the measured drying SWCC using the Tempe cell and pressure plate apparatuses

Matric suction (kPa)	Tempe cell and pressure plate			
	$k_{w, HL}$ (m/s)	$k_{w, VL}$ (m/s)	Hydraulic anisotropy	Δ_r (%)
5	1.68E-08	5.34E-08	3.20	2.33
10	1.27E-08	4.01E-08	3.15	0.95
20	1.10E-09	3.39E-09	3.09	1.11
30	9.56E-10	3.00E-09	3.14	0.55
40	6.93E-10	2.18E-09	3.15	0.81
50	4.75E-10	1.49E-09	3.14	0.53
75	1.38E-10	4.26E-10	3.08	1.40
90	6.28E-11	1.91E-10	3.04	2.79
200	1.58E-12	4.70E-12	2.98	4.75
400	4.18E-14	1.37E-13	3.28	4.89
		Average	3.12	2.01

Table 6.8 Estimated drying hydraulic anisotropy values of 50S50K (B) from the measured drying SWCC using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses

Matric suction (kPa)	Modified triaxial SWCC				Unsaturated triaxial permeameter			
	k_{w, HL} (m/s)	k_{w, VL} (m/s)	Hydraulic anisotropy	Δ_r (%)	k_{w, HL} (m/s)	k_{w, VL} (m/s)	Hydraulic anisotropy	Δ_r (%)
5	1.67E-08	5.34E-08	3.20	1.32	1.67E-08	5.34E-08	3.20	10.99
10	1.28E-08	4.12E-08	3.22	0.62	1.43E-08	4.28E-08	2.99	3.88
20	1.10E-09	3.28E-09	2.97	8.20	1.48E-09	4.28E-09	2.89	0.18
30	1.08E-09	3.24E-09	2.99	7.63	1.29E-09	3.67E-09	2.84	1.45
40	7.32E-10	2.27E-09	3.10	4.28	9.40E-10	2.63E-09	2.80	2.91
50	4.20E-10	1.37E-09	3.25	0.47	5.03E-10	1.43E-09	2.84	1.31
75	1.05E-10	3.61E-10	3.44	6.30	1.04E-10	3.01E-10	2.89	0.35
90	4.81E-11	1.69E-10	3.51	8.48	4.68E-11	1.34E-10	2.86	0.74
200	2.35E-12	8.18E-12	3.48	7.32	2.95E-12	8.03E-12	2.72	5.68
400	1.18E-13	3.79E-13	3.22	0.51	1.97E-13	5.50E-13	2.79	3.31
		Average	3.24	4.51		Average	2.88	3.08

Table 6.9 Estimated drying hydraulic anisotropy values of 50S50K (C) from the measured drying SWCC using the Tempe cell and pressure plate apparatuses

Matric suction (kPa)	Tempe cell and pressure plate			
	$k_{w, HL}$ (m/s)	$k_{w, VL}$ (m/s)	Hydraulic anisotropy	Δ_r (%)
5	1.91E-09	1.11E-08	5.83	1.70
20	1.64E-09	9.45E-09	5.75	0.41
35	1.09E-09	6.23E-09	5.71	0.36
50	5.92E-10	3.40E-09	5.74	0.20
75	1.63E-10	9.54E-10	5.86	2.32
90	7.00E-11	4.13E-10	5.91	3.07
200	2.42E-12	1.38E-11	5.70	0.51
400	1.58E-13	8.44E-13	5.34	6.83
		Average	5.73	1.93

Table 6.10 Estimated drying hydraulic anisotropy values of 50S50K (C) from the measured drying SWCC using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses

Matric	Modified triaxial SWCC				Unsaturated triaxial permeameter			
suction	k_{w, HL}	k_{w, VL}	Hydraulic	Δ_r	k_{w, HL}	k_{w, VL}	Hydraulic	Δ_r
(kPa)	(m/s)	(m/s)	anisotropy	(%)	(m/s)	(m/s)	anisotropy	(%)
5	1.92E-09	1.12E-08	5.83	0.50	1.92E-09	1.12E-08	5.83	6.26
20	1.89E-09	1.10E-08	5.81	0.86	1.87E-09	1.06E-08	5.68	3.44
35	1.63E-09	9.26E-09	5.68	3.07	1.52E-09	7.98E-09	5.25	4.32
50	8.92E-10	4.98E-09	5.59	4.64	8.54E-10	4.33E-09	5.06	7.75
75	1.34E-10	7.88E-10	5.89	0.40	1.73E-10	9.60E-10	5.56	1.32
90	4.39E-11	2.64E-10	6.01	2.59	6.35E-11	3.69E-10	5.82	6.03
200	1.43E-12	8.70E-12	6.07	3.50	2.31E-12	1.29E-11	5.61	2.26
400	1.29E-13	7.73E-13	6.01	2.57	2.09E-13	1.07E-12	5.09	7.25
		Average	5.86	2.27		Average	5.49	4.83

Table 6.11 Estimated drying hydraulic anisotropy values of specimens with 9% coarse mica from the measured drying SWCC using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses

Matric	Modified triaxial SWCC				Unsaturated triaxial permeameter			
suction	k_{w, HL}	k_{w, VL}	Hydraulic	Δ_r	k_{w, HL}	k_{w, VL}	Hydraulic	Δ_r
(kPa)	(m/s)	(m/s)	anisotropy	(%)	(m/s)	(m/s)	anisotropy	(%)
5	1.07E-08	1.12E-07	10.47	2.90	1.07E-08	1.12E-07	10.47	3.63
10	8.47E-09	9.43E-08	11.13	9.45	8.82E-09	9.33E-08	10.59	4.80
20	3.37E-10	3.29E-09	9.76	4.03	2.94E-10	2.97E-09	10.12	0.20
30	3.03E-10	2.78E-09	9.18	9.72	2.65E-10	2.67E-09	10.08	0.20
40	2.87E-10	2.65E-09	9.23	9.23	2.59E-10	2.60E-09	10.01	0.89
50	2.59E-10	2.55E-09	9.85	3.17	2.55E-10	2.57E-09	10.10	0.01
75	1.31E-10	1.38E-09	10.52	3.46	1.60E-10	1.62E-09	10.13	0.32
90	8.16E-11	8.45E-10	10.35	1.77	1.06E-10	1.04E-09	9.82	2.73
200	6.40E-12	6.46E-11	10.10	0.75	6.74E-12	6.19E-11	9.17	9.18
400	3.09E-13	3.43E-12	11.12	9.33	2.20E-13	2.31E-12	10.51	4.06
		Average	10.17	5.38		Average	10.10	2.60

The relative differences (Δ_r) and their average (ARD) were computed for each specimen to show the variation between the estimated drying hydraulic anisotropy value at each application of matric suction and the mean of all estimated drying hydraulic anisotropy values for each measurement apparatus. For the hydraulic anisotropy of 50S50K (B) estimated from the measured drying SWCC using the Tempe cell and pressure plate apparatuses, the relative difference (Δ_r) is observed to vary between 0.53% and 4.89% with an average (ARD) of 2.01%. For the hydraulic anisotropy of 50S50K (B) estimated from the measured drying SWCC using the modified triaxial SWCC apparatus, the relative difference (Δ_r) varies between 0.47% and 8.48% with an average (ARD) of 4.51%. For the hydraulic anisotropy of 50S50K (B) estimated from the measured drying SWCC using the unsaturated triaxial permeameter apparatus, the relative difference (Δ_r) varies between 0.18% and 10.99% with an average (ARD) of 3.08%. For the hydraulic anisotropy of 50S50K (C) estimated from the measured drying SWCC using the Tempe cell and pressure plate apparatuses, the relative difference (Δ_r) varies between 0.20% and 6.83% with an average (ARD) of 1.93%. For the hydraulic anisotropy of 50S50K (C) estimated from the measured drying SWCC using the modified triaxial SWCC apparatus, relative difference (Δ_r) varies between 0.40% and 4.64% with an average (ARD) of 2.27%. For the hydraulic anisotropy of 50S50K (C) estimated from the measured drying SWCC using the unsaturated triaxial permeameter apparatus, relative difference (Δ_r) varies between 1.32% and 7.75% with an average (ARD) of 4.83%. For the hydraulic anisotropy of specimens with 9% coarse mica estimated from the measured drying SWCC using the modified triaxial SWCC apparatus, relative difference (Δ_r) varies between 0.75% and 9.72% with an average (ARD) of 5.38. For the hydraulic anisotropy of specimens with 9% coarse mica estimated from the measured drying

SWCC using unsaturated triaxial permeameter apparatus, relative difference (Δ_r) varies between 0.01% and 9.18% with an average (ARD) of 2.60%. The relative differences (Δ_r) and their average (ARD) are less than 20% for all specimens, indicating reliably consistent estimation of hydraulic anisotropy values throughout the drying path of unsaturated conditions for all specimens. This observation supports the behavior of consistent hydraulic anisotropy values throughout the drying path of unsaturated conditions obtained using the direct measurement, as shown in Table 6.1 - Table 6.3

For further understanding, a comparison between the unsaturated coefficients of permeability and their corresponding hydraulic anisotropy values obtained using the direct permeability measurement (Table 6.1 – Table 6.3) and the indirect determination from the corresponding drying SWCC (Table 6.7– Table 6.11) was performed for each specimen. Figure 6.16 shows a graphical comparison between the drying unsaturated coefficients of permeability of 50S50K (B) obtained using the direct measurement and the indirect determination. Figure 6.17 shows a graphical comparison between the drying unsaturated coefficients of permeability of 50S50K (C) obtained using the direct measurement and the indirect determination. Figure 6.18 shows a graphical comparison between the drying unsaturated coefficients of permeability of specimens with 9% coarse mica obtained using the direct measurement and the indirect determination. For each specimen, it is observed that the drying unsaturated coefficients of permeability obtained using the direct measurement and the indirect determination from the corresponding drying SWCC are relatively close regardless the measurement apparatus. Figure 6.19 shows a summary of relative differences between the mean values of drying hydraulic

anisotropy obtained using the direct measurement and the indirect determination for each specimen.

Figure 6.16 Comparison between the measured and the estimated unsaturated coefficients of permeability of 50S50K (B) in the drying path of unsaturated conditions

Figure 6.17 Comparison between the measured and the estimated unsaturated coefficients of permeability of 50S50K (C) in the drying path of unsaturated conditions

Figure 6.18 Comparison between the measured and the estimated unsaturated coefficients of permeability of specimens with 9% coarse mica in the drying path of unsaturated conditions

Figure 6.19 Relative differences between the mean values of drying hydraulic anisotropy obtained using the direct measurement and the indirect determination from the corresponding measured drying SWCC obtained using various apparatuses for each specimen

For 50S50K (B), the relative difference (Δ_r) between the mean values of drying hydraulic anisotropy obtained using the direct measurement and the indirect determination from the corresponding drying SWCC is observed to vary between 3.57% and 14.24% with an average (ARD) of 8.26%. For 50S50K (C), the relative difference (Δ_r) between the mean values of drying hydraulic anisotropy obtained using the direct measurement and the indirect determination from the corresponding drying SWCC varies between 0.13% and 4.35% with an average (ARD) of 2.22%. For specimens with 9% coarse mica, the relative difference (Δ_r) between the mean values of drying hydraulic anisotropy obtained using the direct measurement and the indirect determination from the corresponding drying SWCC varies between 2.85% and 3.53% with an average (ARD) of 3.19%. All relative differences (Δ_r) and their average (ARD) are less than 20% for all specimens, indicating reliably close drying

hydraulic anisotropy values obtained using the direct measurement and the indirect determination from the corresponding measured drying SWCC obtained using various measurement apparatuses used in the research. This observation confirms the strong agreement between the direct measurement and the indirect determination results to the extent of similar values of the unsaturated coefficients of permeability and the corresponding hydraulic anisotropy as well as consistent behavior of hydraulic anisotropy in the drying path of unsaturated conditions, as expected in the proposed framework (Section 3.3).

Different equilibrium times during the drying unsaturated permeability and SWCC tests were observed for each HL and VL orientation of a given specimen. In the drying unsaturated permeability tests, the different equilibrium times for each HL and VL orientation of a given specimen were measured starting from the application of 90 kPa matric suction, as shown in Figure 5.14. Table 6.12 shows the ratio of equilibrium times observed for 50S50K (B) during the drying unsaturated permeability test compared to the hydraulic anisotropy measured at the corresponding matric suction. Table 6.13 shows the ratio of equilibrium times observed for 50S50K (C) during the drying unsaturated permeability test compared to the hydraulic anisotropy measured at the corresponding matric suction. Table 6.14 shows the ratio of equilibrium times observed for specimens with 9% coarse mica during the drying unsaturated permeability test compared to the hydraulic anisotropy measured at the corresponding matric suction.

Table 6.12 Ratio of equilibrium times observed during the drying permeability test compared to the measured hydraulic anisotropy for 50S50K (B)

Matric suction (kPa)	Drying permeability test			Measured hydraulic anisotropy	Δ_r (%)
	$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL} / t_{eq, VL}$)		
90	21.35	6.84	3.12	3.25	4.06
200	27.17	8.13	3.34	3.46	3.34
400	41.56	13.08	3.18	3.22	1.37
		Average	3.21	3.31	2.92

Table 6.13 Ratio of equilibrium times observed during the drying permeability test compared to the measured hydraulic anisotropy for 50S50K (C)

Matric suction (kPa)	Drying permeability test			Measured hydraulic anisotropy	Δ_r (%)
	$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL} / t_{eq, VL}$)		
90	50.72	8.63	5.88	5.69	3.28
200	62.33	11.17	5.58	5.97	6.56
400	91.98	16.15	5.70	5.94	4.11
		Average	5.72	5.87	4.65

Table 6.14 Ratio of equilibrium times observed during the drying permeability test compared to the measured hydraulic anisotropy for specimens with 9% coarse mica

Matric suction (kPa)	Drying permeability test			Measured hydraulic anisotropy	Δ_r (%)
	$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL} / t_{eq, VL}$)		
90	43.33	4.11	10.54	10.80	2.41
200	64.01	6.29	10.18	10.30	1.17
400	110.16	10.38	10.61	10.70	0.84
		Average	10.44	10.60	1.47

The relative differences (Δ_r) and their average (ARD) were computed for each specimen to show the correlation between the ratio of observed equilibrium times in different orientations (HL and VL) during the drying unsaturated permeability tests and the measured drying hydraulic anisotropy values at the corresponding matric suction. For 50S50K (B), the relative difference (Δ_r) is observed to vary between 1.37% and 4.06% with an average (ARD) of 2.92%. For 50S50K (C), the relative difference (Δ_r) varies between 3.28% and 6.56% with an average (ARD) of 4.65%. For specimens with 9% coarse mica, the relative difference (Δ_r) varies between 0.84% and 2.41% with an average (ARD) of 1.47%. All relative differences (Δ_r) and their average (ARD) are less than 20% for all specimens, indicating reliably close values of the ratio between equilibrium times measured in different orientations (HL and VL) and hydraulic anisotropy measured at the corresponding matric suction during the drying permeability tests. In other words, the hydraulic anisotropy values are reflected in the ratio of equilibrium times between HL and VL orientations of a given specimen (regardless the initial conditions, mica content or shape of the drying unsaturated

permeability) during the drying unsaturated permeability test at high matric suction condition.

In the drying SWCC tests, the different equilibrium times for HL and VL orientations of a given specimen were observed at matric suctions higher than the air-entry value (AEV) of the specimen, as shown in Figure 5.28. Figure 6.20 shows a graphical comparison between the measured hydraulic anisotropy and the corresponding measured ratio of equilibrium times during the drying SWCC tests using various measurement apparatuses for 50S50K (B). Table 6.15 shows the ratio of equilibrium times observed for 50S50K (B) during the drying SWCC test using the Tempe cell and pressure plate apparatuses compared to the hydraulic anisotropy measured at the corresponding matric suction. Table 6.16 shows the ratio of equilibrium times observed for 50S50K (B) during the drying SWCC test using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses compared to the hydraulic anisotropy measured at the corresponding matric suction. Figure 6.21 shows a graphical comparison between the measured hydraulic anisotropy and the corresponding measured ratio of equilibrium times during the drying SWCC tests using various measurement apparatuses for 50S50K (C). Table 6.17 shows the ratio of equilibrium times observed for 50S50K (C) during the drying SWCC test using the Tempe cell and pressure plate apparatuses compared to the hydraulic anisotropy measured at the corresponding matric suction. Table 6.18 shows the ratio of equilibrium times observed for 50S50K (C) during the drying SWCC test using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses compared to the hydraulic anisotropy measured at the corresponding matric suction. Figure 6.22 shows a graphical comparison between the measured hydraulic anisotropy and the corresponding measured ratio of equilibrium times during the drying SWCC tests

using various measurement apparatuses for specimens with 9% coarse mica. Table 6.19 shows the ratio of equilibrium times observed for specimens with 9% coarse mica during the drying SWCC test using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses compared to the hydraulic anisotropy measured at the corresponding matric suction.

Figure 6.20 Comparison between the measured hydraulic anisotropy and the corresponding measured ratio of equilibrium times during the drying SWCC tests for 50S50K (B)

Table 6.15 Ratio of equilibrium times observed during the drying SWCC test using the Tempe cell and pressure plate compared to the measured hydraulic anisotropy for 50S50K (B)

Matric suction (kPa)	Measured hydraulic anisotropy	Tempe cell and pressure plate			Δ_r (%)
		$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL} / t_{eq, VL}$)	
30	3.64	28.35	8.35	3.40	6.59
40	3.49	28.68	8.75	3.28	5.95
50	3.28	29.57	9.25	3.20	2.32
75	3.13	35.95	10.55	3.41	9.10
90	3.25	47.36	15.08	3.14	3.44
200	3.46	125.75	39.82	3.16	8.55
400	3.22	450.89	140.25	3.21	0.44
Average	3.35			3.26	5.20

Table 6.16 Ratio of equilibrium times observed during the drying SWCC test using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses compared to the measured hydraulic anisotropy for 50S50K (B)

Matric suction (kPa)	Measured hydraulic anisotropy	Triaxial			Δ_r (%)	Permeameter			Δ_r (%)
		$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL}/$ $t_{eq, VL}$)		$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL}/$ $t_{eq, VL}$)	
30	3.64	32.85	9.95	3.30	9.34	36.06	11.01	3.27	10.16
40	3.49	35.01	11.15	3.14	9.96	40.74	13.27	3.07	11.97
50	3.28	36.82	11.48	3.21	2.01	41.94	13.96	3.01	8.12
75	3.13	42.74	13.28	3.22	3.02	46.64	14.14	3.30	5.58
90	3.25	67.34	21.26	3.17	2.52	72.29	22.88	3.16	2.83
200	3.46	146.82	46.88	3.13	9.41	154.86	49.19	3.15	8.84
400	3.22	583.04	181.55	3.21	0.44	602.08	190.08	3.17	1.68
Average	3.35			3.20	5.24			3.16	7.02

Figure 6.21 Comparison between the measured hydraulic anisotropy and the corresponding measured ratio of equilibrium times during the drying SWCC tests for 50S50K (C)

Table 6.17 Ratio of equilibrium times observed during the drying SWCC test using the Tempe cell and pressure plate apparatuses compared to the measured hydraulic anisotropy for 50S50K (C)

Matric suction (kPa)	Measured hydraulic anisotropy	Tempe cell and pressure plate			Δ_r (%)
		$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL} / t_{eq, VL}$)	
50	6.12	55.83	10.08	5.54	9.57
75	5.78	71.17	11.83	6.01	4.03
90	5.69	120.58	22.67	5.32	6.56
200	5.97	247.78	44.17	5.61	6.06
400	5.94	893.33	160.42	5.57	6.32
Average	5.90			5.61	6.51

Table 6.18 Ratio of equilibrium times observed during the drying SWCC test using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses compared to the measured hydraulic anisotropy for 50S50K (C)

Matric suction (kPa)	Measured hydraulic anisotropy	Triaxial			Δ_r (%)	Permeameter			Δ_r (%)
		$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL}/t_{eq, VL}$)		$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL}/t_{eq, VL}$)	
50	6.12	67.68	11.15	6.07	0.87	69.52	12.49	5.57	9.09
75	5.78	80.08	13.66	5.86	1.36	86.97	14.57	5.97	3.26
90	5.69	144.15	24.14	5.97	4.86	153.01	26.07	5.87	3.10
200	5.97	288.41	50.49	5.71	4.38	301.16	54.58	5.52	7.57
400	5.94	1078.44	187.90	5.74	3.44	1132.02	194.54	5.82	2.09
Average	5.90			5.87	2.98			5.75	5.02

Figure 6.22 Comparison between the measured hydraulic anisotropy and the corresponding measured ratio of equilibrium times during the drying SWCC tests for specimens with 9% coarse mica

Table 6.19 Ratio of equilibrium times observed during the drying SWCC test using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses compared to the measured hydraulic anisotropy for specimens with 9% coarse mica

Matric suction (kPa)	Measured hydraulic anisotropy	Triaxial			Δ_r (%)	Permeameter			Δ_r (%)
		$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL}/t_{eq, VL}$)		$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL}/t_{eq, VL}$)	
30	10.00	88.1	8.49	10.38	3.80	102.2	10.19	10.03	0.30
40	11.20	93.68	8.78	10.67	4.73	118.04	11.41	10.34	7.68
50	10.50	100.84	9.24	10.91	3.90	127.06	12.01	10.58	0.76
75	10.10	112.82	10.31	10.94	8.32	142.15	13.4	10.61	5.05
90	10.80	289.19	28.03	10.32	4.44	364.38	33.83	10.77	0.27
200	10.30	368.28	34.07	10.81	4.95	464.03	44.29	10.48	1.75
400	10.70	801.7	72.41	11.07	3.46	962.04	90.51	10.63	0.65
Average	10.51			10.73	4.80			10.49	2.35

For each specimen, it is observed that the measured hydraulic anisotropy and the corresponding measured ratio of equilibrium times during the drying SWCC tests are relatively close regardless the measurement apparatus. The relative differences (Δ_r) and their average (ARD) were computed for each specimen to show the correlation between the ratio of observed equilibrium times in different orientations (HL and VL) during the drying SWCC tests using various measurement apparatuses and the measured drying hydraulic anisotropy values at the corresponding matric suction. For the ratio of equilibrium times during the drying SWCC tests of 50S50K (B) obtained using the Tempe cell and pressure plate apparatuses, the relative difference (Δ_r) is observed to vary between 0.44% and 9.10% with an average (ARD) of 5.20%. For the ratio of equilibrium times during the drying SWCC tests of 50S50K (B) obtained using the modified triaxial SWCC apparatus, the relative difference (Δ_r) varies between 0.44% and 9.96% with an average (ARD) of 5.24%. For the ratio of equilibrium times during the drying SWCC tests of 50S50K (B) obtained using the unsaturated triaxial permeameter apparatus, the relative difference (Δ_r) varies between 1.68% and 11.97% with an average (ARD) of 7.02%. For the ratio of equilibrium times during the drying SWCC tests of 50S50K (C) obtained using the Tempe cell and pressure plate apparatuses, the relative difference (Δ_r) varies between 4.03% and 9.57% with an average (ARD) of 6.51%. For the ratio of equilibrium times during the drying SWCC tests of 50S50K (C) obtained using the modified triaxial SWCC apparatus, the relative difference (Δ_r) varies between 0.87% and 4.86% with an average (ARD) of 2.98%. For the ratio of equilibrium times during the drying SWCC tests of 50S50K (C) obtained using the unsaturated triaxial permeameter apparatus, the relative difference (Δ_r) varies between 2.09% and 9.09% with an average (ARD) of 5.02%. For the ratio of equilibrium times during the drying SWCC tests of

specimens with 9% coarse mica obtained using the modified triaxial SWCC apparatus, the relative difference (Δ_r) varies between 3.46% and 8.32% with an average (ARD) of 4.80%. For the ratio of equilibrium times during the drying SWCC tests of specimens with 9% coarse mica obtained using the unsaturated triaxial permeameter apparatus, the relative difference (Δ_r) varies between 0.30% and 7.68% with an average (ARD) of 2.35%. All relative differences (Δ_r) and their average (ARD) are less than 20% for all specimens, indicating reliably close values of the ratio between equilibrium times measured in different orientations (HL and VL) during the drying SWCC tests using various apparatuses and the hydraulic anisotropy values measured at the corresponding matric suction. In other words, hydraulic anisotropy values are reflected in the ratio of equilibrium times between HL and VL orientations of a given specimen (regardless the initial conditions, mica content or shape of the drying SWCC) during the drying SWCC test (regardless the measurement apparatus) at matric suctions higher than the AEV of the specimen, as expected in the proposed framework (Section 3.3).

6.3. Hydraulic Anisotropy Behavior in the Wetting Path of Unsaturated Conditions

Discussions on the hydraulic anisotropy behavior of various specimens in the wetting path of unsaturated conditions, as shown in Section 5.5 and Section 5.6, are presented in this section. In the wetting path of unsaturated conditions, the different values of hydraulic anisotropy measured directly using unsaturated triaxial permeameter and indirectly determined from the corresponding wetting SWCC for 50S50K (B), 50S50K (C) and specimens with 9% coarse mica are discussed and compared using the statistical coefficient of determination (R^2) and relative difference (Δ_r) criteria described in Section 4.3. In addition, the behavior of equilibrium times measured

during the wetting permeability and SWCC tests of 50S50K (B), 50S50K (C) and specimens with 9% coarse mica is analyzed and correlated with the measured hydraulic anisotropy values using the same statistical criteria described in Section 4.3. Principally, statistical analyses performed in the drying path of unsaturated conditions, as discussed in Section 6.2, are repeated in this section for the corresponding wetting path of unsaturated conditions. Table 6.20 shows hydraulic anisotropy values of 50S50K (B) measured directly through the wetting permeability test. Table 6.21 shows hydraulic anisotropy values of 50S50K (C) measured directly through the wetting permeability test. Table 6.22 shows hydraulic anisotropy values of specimens with 9% coarse mica measured directly through the wetting permeability test.

Table 6.20 Measured hydraulic anisotropy values of 50S50K (B) in the wetting path of unsaturated conditions

Matric suction (kPa)	$k_{w, HL}$ (m/s)	$k_{w, VL}$ (m/s)	Hydraulic anisotropy	Δ_r (%)
200	2.59E-13	6.48E-13	2.50	2.40
90	1.76E-12	4.96E-12	2.82	15.56
75	4.27E-12	1.15E-11	2.69	10.18
50	3.47E-11	7.44E-11	2.14	12.26
35	6.81E-11	1.56E-10	2.29	6.19
20	2.28E-10	5.92E-10	2.59	6.10
10	3.01E-10	7.24E-10	2.41	1.41
5	3.45E-10	8.02E-10	2.32	4.99
1	3.65E-10	8.09E-10	2.21	9.39
		Average	2.44	7.61

Table 6.21 Measured hydraulic anisotropy values of 50S50K (C) in the wetting path of unsaturated conditions

Matric suction (kPa)	$k_{w, HL}$ (m/s)	$k_{w, VL}$ (m/s)	Hydraulic anisotropy	Δ_r (%)
200	1.08E-14	4.73E-14	4.38	5.57
90	1.65E-13	7.79E-13	4.72	1.79
75	3.83E-13	1.65E-12	4.31	7.11
50	6.78E-12	3.20E-11	4.72	1.76
35	1.96E-11	9.33E-11	4.76	2.63
20	3.15E-11	1.53E-10	4.86	4.72
5	4.09E-11	1.97E-10	4.82	3.85
1	4.91E-11	2.23E-10	4.54	2.08
		Average	4.64	3.69

Table 6.22 Measured hydraulic anisotropy values of specimens with 9% coarse mica in the wetting path of unsaturated conditions

Matric suction (kPa)	$k_{w, HL}$ (m/s)	$k_{w, VL}$ (m/s)	Hydraulic anisotropy	Δ_r (%)
200	9.80E-14	8.48E-13	8.65	0.12
90	1.84E-12	1.47E-11	8.02	7.38
75	6.10E-12	5.14E-11	8.43	2.73
50	1.42E-11	1.27E-10	8.94	3.15
35	5.35E-11	4.77E-10	8.92	2.91
20	9.57E-11	8.45E-10	8.83	1.90
10	1.46E-10	1.31E-09	8.98	3.60
5	1.62E-10	1.38E-09	8.53	1.50
1	1.63E-10	1.41E-09	8.68	0.18
		Average	8.66	2.61

The relative differences (Δ_r) and their average (ARD) were computed for each specimen to show the variation between the measured hydraulic anisotropy at each application of matric suction and the mean of all hydraulic anisotropy values measured during the wetting test. For 50S50K (B), the relative difference (Δ_r) is observed to vary between 1.41% and 15.56% with an average (ARD) of 7.61%. For 50S50K (C), the relative difference (Δ_r) varies between 1.76% and 7.11% with an average (ARD) of 3.69%. For specimens with 9% coarse mica, the relative difference (Δ_r) varies between 0.12% and 7.38% with an average (ARD) of 2.61%. All relative differences (Δ_r) and their average (ARD) are less than 20% for all specimens, indicating reliably consistent hydraulic anisotropy directly measured throughout the

wetting permeability tests for all specimens. All specimens, i.e. 50S50K (B), 50S50K (C) and specimens with 9% coarse mica, have common shape of wetting unsaturated permeability data (unimodal), as presented in Section 5.5, for each particular initial conditions (dry or wet of optimum) and mica content (with or without mica). Therefore, the behavior of consistent hydraulic anisotropy values throughout the wetting path of unsaturated conditions is applicable for any initial conditions and mica content. This behavior is similar to that discussed in Section 6.2 for the drying path of unsaturated conditions.

Hydraulic anisotropy values in the wetting path of unsaturated conditions of the specimen can also be indirectly determined from the corresponding wetting SWCC. The wetting SWCC of the specimen was firstly best-fitted using Equation 2.14 since all specimens i.e. 50S50K (B), 50S50K (C) and specimens with 9% coarse mica have unimodal shape of the wetting SWCC data as presented in Section 5.6, similar to the corresponding wetting unsaturated permeability data presented in Section 5.5. Table 6.23 shows the unimodal fitting parameters of Equation 2.14 for the wetting SWCC data of 50S50K (B) obtained using all measurement apparatuses. Figure 6.23 – Figure 6.25 illustrate best fitting for the measured wetting SWCC data of 50S50K (B) based on the respective Tempe cell and pressure plate, modified triaxial SWCC and unsaturated triaxial permeameter measurements. Table 6.24 shows the unimodal fitting parameters of Equation 2.14 for the wetting SWCC data of 50S50K (C) obtained using all measurement apparatuses. Figure 6.26– Figure 6.28 illustrate best fitting for the measured wetting SWCC data of 50S50K (C) based on the respective Tempe cell and pressure plate, modified triaxial SWCC and unsaturated triaxial permeameter measurements. Table 6.25 shows the unimodal fitting parameters of Equation 2.14 for the wetting SWCC data of specimens with 9% coarse mica obtained

using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses. Figure 6.29 and Figure 6.30 illustrate best fitting for the measured wetting SWCC data of specimens with 9% coarse mica based on the respective modified triaxial SWCC and unsaturated triaxial permeameter measurements.

Table 6.23 Unimodal fitting parameters of the measured wetting SWCC data of 50S50K (B)

Fitting parameters	TC&PP		Triaxial		Permeameter	
	HL	VL	HL	VL	HL	VL
θ_s	0.266	0.271	0.255	0.244	0.249	0.235
a (kPa)	24.992	24.701	23.142	23.673	28.772	28.122
n	2.467	2.322	2.405	2.557	2.245	2.240
m	0.794	0.791	0.786	0.799	1.031	0.985
R^2	0.998	0.997	0.999	0.999	0.997	0.999

Figure 6.23 Best fitting for the measured wetting SWCC data of 50S50K (B) based on the Tempe cell and pressure plate measurements

Figure 6.24 Best fitting for the measured wetting SWCC data of 50S50K (B) based on the modified triaxial SWCC measurements

Figure 6.25 Best fitting for the measured wetting SWCC data of 50S50K (B) based on the unsaturated triaxial permeameter measurements

Table 6.24 Unimodal fitting parameters of the measured wetting SWCC data of 50S50K (C)

Fitting parameters	TC&PP		Triaxial		Permeameter	
	HL	VL	HL	VL	HL	VL
θ_s	0.341	0.348	0.321	0.321	0.309	0.321
a (kPa)	34.960	33.824	28.659	27.581	23.641	24.255
n	3.197	3.251	4.417	4.567	5.294	4.742
m	0.901	0.879	0.680	0.626	0.512	0.570
R^2	0.998	0.997	0.997	0.997	0.999	0.999

Figure 6.26 Best fitting for the measured wetting SWCC data of 50S50K (C) based on the Tempe cell and pressure plate measurements

Figure 6.27 Best fitting for the measured wetting SWCC data of 50S50K (C) based on the modified triaxial SWCC measurements

Figure 6.28 Best fitting for the measured wetting SWCC data of 50S50K (C) based on the unsaturated triaxial permeameter measurements

Table 6.25 Unimodal fitting parameters of the measured wetting SWCC data of specimens with 9% coarse mica

Fitting parameters	Triaxial		Permeameter	
	HL	VL	HL	VL
θ_s	0.279	0.287	0.287	0.285
a (kPa)	62.177	60.459	62.337	60.194
n	1.527	1.538	1.503	1.550
m	1.760	1.736	1.915	1.860
R^2	0.997	0.997	0.993	0.992

Figure 6.29 Best fitting for the measured wetting SWCC data of specimens with 9% coarse mica based on the modified triaxial SWCC measurements

Figure 6.30 Best fitting for the measured wetting SWCC data of specimens with 9% coarse mica based on the unsaturated triaxial permeameter measurements

The coefficient of determination (R^2) was computed in order to achieve the best fitting parameters for each orientation (HL and VL) of the wetting SWCC obtained using each measurement apparatus. For 50S50K (B), R^2 value is observed to vary between 0.997 and 0.999. For 50S50K (C), R^2 value varies between 0.997 and 0.999. For specimens with 9% coarse mica, R^2 value varies between 0.992 and 0.997. High R^2 values (close to unity) are obtained for all specimens, indicating all specimens have pronounced unimodal shape of the wetting SWCC, regardless different shapes observed in the drying SWCC.

The wetting unsaturated permeability of each specimen was subsequently estimated from the corresponding best-fitted wetting SWCC using Equation 3.4. Table 6.26 shows the indirectly determined wetting hydraulic anisotropy values of 50S50K (B) from the corresponding measured wetting SWCC using the Tempe cell and pressure plate apparatuses. Table 6.27 shows the indirectly determined wetting hydraulic anisotropy values of 50S50K (B) from the corresponding measured wetting SWCC

using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses. Table 6.28 shows the indirectly determined wetting hydraulic anisotropy values of 50S50K (C) from the corresponding measured wetting SWCC using the Tempe cell and pressure plate apparatuses. Table 6.29 shows the indirectly determined wetting hydraulic anisotropy values of 50S50K (C) from the corresponding measured wetting SWCC using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses. Table 6.30 shows the indirectly determined wetting hydraulic anisotropy values of specimens with 9% coarse mica from the corresponding measured wetting SWCC using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses.

Table 6.26 Estimated wetting hydraulic anisotropy values of 50S50K (B) from the measured wetting SWCC using the Tempe cell and pressure plate apparatuses

Matric suction (kPa)	Tempe cell and pressure plate			
	$k_{w, HL}$ (m/s)	$k_{w, VL}$ (m/s)	Hydraulic anisotropy	Δ_r (%)
200	1.10E-13	2.63E-13	2.38	9.44
90	1.69E-12	3.87E-12	2.29	4.99
75	3.73E-12	8.35E-12	2.24	2.79
50	1.76E-11	3.73E-11	2.12	2.60
35	5.40E-11	1.10E-10	2.04	6.40
20	1.74E-10	3.51E-10	2.02	7.16
10	3.03E-10	6.41E-10	2.11	2.97
5	3.50E-10	7.63E-10	2.18	0.10
1	3.65E-10	8.09E-10	2.22	1.81
		Average	2.18	4.25

Table 6.27 Estimated wetting hydraulic anisotropy values of 50S50K (B) from the measured wetting SWCC using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses

Matric	Modified triaxial SWCC				Unsaturated triaxial permeameter			
suction	k_{w, HL}	k_{w, VL}	Hydraulic	Δ_r	k_{w, HL}	k_{w, VL}	Hydraulic	Δ_r
(kPa)	(m/s)	(m/s)	anisotropy	(%)	(m/s)	(m/s)	anisotropy	(%)
200	9.15E-14	1.88E-13	2.06	9.58	1.12E-13	2.36E-13	2.33	5.68
90	1.33E-12	2.88E-12	2.16	5.00	1.98E-12	4.37E-12	2.22	0.66
75	2.90E-12	6.42E-12	2.21	2.81	4.42E-12	9.90E-12	2.20	0.56
50	1.36E-11	3.18E-11	2.34	2.91	2.02E-11	4.60E-11	2.16	2.18
35	4.27E-11	1.04E-10	2.44	7.41	5.75E-11	1.31E-10	2.16	2.40
20	1.51E-10	3.71E-10	2.46	8.10	1.68E-10	3.79E-10	2.18	1.44
10	2.89E-10	6.73E-10	2.33	2.52	2.91E-10	6.50E-10	2.20	0.31
5	3.45E-10	7.79E-10	2.25	0.95	3.44E-10	7.64E-10	2.21	0.16
1	3.65E-10	8.09E-10	2.22	2.61	3.65E-10	8.09E-10	2.22	0.38
		Average	2.28	4.65		Average	2.21	1.53

Table 6.28 Estimated wetting hydraulic anisotropy values of 50S50K (C) from the measured wetting SWCC using the Tempe cell and pressure plate apparatuses

Matric suction (kPa)	Tempe cell and pressure plate			
	$k_{w, HL}$ (m/s)	$k_{w, VL}$ (m/s)	Hydraulic anisotropy	Δ_r (%)
200	2.11E-14	8.75E-14	4.15	2.96
90	4.98E-13	1.99E-12	4.00	6.37
75	1.27E-12	5.08E-12	4.00	6.49
50	7.26E-12	2.99E-11	4.12	3.55
35	2.00E-11	8.67E-11	4.33	1.24
20	4.00E-11	1.80E-10	4.51	5.54
5	4.89E-11	2.22E-10	4.54	6.30
1	4.91E-11	2.23E-10	4.54	6.29
		Average	4.27	4.84

Table 6.29 Estimated wetting hydraulic anisotropy values of 50S50K (C) from the measured wetting SWCC using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses

Matric	Modified triaxial SWCC				Unsaturated triaxial permeameter			
suction	k_{w, HL}	k_{w, VL}	Hydraulic	Δ_r	k_{w, HL}	k_{w, VL}	Hydraulic	Δ_r
(kPa)	(m/s)	(m/s)	anisotropy	(%)	(m/s)	(m/s)	anisotropy	(%)
200	1.12E-14	5.13E-14	4.60	6.06	8.33E-15	3.93E-14	4.71	2.73
90	1.98E-13	8.37E-13	4.23	2.46	1.09E-13	5.53E-13	5.07	4.73
75	4.96E-13	2.04E-12	4.12	5.07	2.46E-13	1.28E-12	5.19	7.07
50	3.65E-12	1.45E-11	3.98	8.26	1.56E-12	8.28E-12	5.32	9.87
35	1.61E-11	6.70E-11	4.16	4.00	8.50E-12	4.23E-11	4.98	2.83
20	4.25E-11	1.92E-10	4.52	4.24	4.06E-11	1.78E-10	4.40	9.23
5	4.90E-11	2.23E-10	4.54	4.74	4.90E-11	2.23E-10	4.54	6.28
1	4.91E-11	2.23E-10	4.54	4.74	4.91E-11	2.23E-10	4.54	6.26
		Average	4.34	4.95		Average	4.85	6.13

Table 6.30 Estimated wetting hydraulic anisotropy values of specimens with 9% coarse mica from the measured wetting SWCC using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses

Matric suction (kPa)	Modified triaxial SWCC				Unsaturated triaxial permeameter			
	k_{w, HL}	k_{w, VL}	Hydraulic	Δ_r	k_{w, HL}	k_{w, VL}	Hydraulic	Δ_r
	(m/s)	(m/s)	anisotropy	(%)	(m/s)	(m/s)	anisotropy	(%)
200	2.63E-13	2.14E-12	8.12	4.31	2.05E-13	1.72E-12	8.38	5.85
90	3.88E-12	3.22E-11	8.28	2.48	3.26E-12	2.87E-11	8.81	1.06
75	7.08E-12	5.91E-11	8.35	1.70	6.05E-12	5.40E-11	8.94	0.35
50	1.89E-11	1.60E-10	8.47	0.20	1.67E-11	1.53E-10	9.12	2.43
35	3.49E-11	2.98E-10	8.56	0.79	3.15E-11	2.90E-10	9.19	3.18
20	6.74E-11	5.82E-10	8.64	1.73	6.30E-11	5.77E-10	9.16	2.87
10	1.07E-10	9.25E-10	8.67	2.14	1.02E-10	9.24E-10	9.02	1.31
5	1.35E-10	1.17E-09	8.67	2.15	1.32E-10	1.17E-09	8.87	0.37
1	1.63E-10	1.41E-09	8.65	1.89	1.63E-10	1.41E-09	8.65	2.87
		Average	8.49	1.93		Average	8.91	2.26

The relative differences (Δ_r) and their average (ARD) were computed for each specimen to show the variation between the estimated wetting hydraulic anisotropy value at each application of matric suction and the mean of all estimated wetting hydraulic anisotropy values for each measurement apparatus. For the hydraulic anisotropy of 50S50K (B) estimated from the measured wetting SWCC using the Tempe cell and pressure plate apparatuses, the relative differences (Δ_r) is observed vary between 0.10% and 9.44% with an average (ARD) of 4.25%. For the hydraulic anisotropy of 50S50K (B) estimated from the measured wetting SWCC using the modified triaxial SWCC apparatus, the relative difference (Δ_r) varies between 0.95% and 9.58% with an average (ARD) of 4.65%. For the hydraulic anisotropy of 50S50K (B) estimated from the measured wetting SWCC using the unsaturated triaxial permeameter apparatus, the relative difference (Δ_r) varies between 0.16% and 5.68% with an average (ARD) of 1.53%. For the hydraulic anisotropy of 50S50K (C) estimated from the measured wetting SWCC using the Tempe cell and pressure plate apparatuses, the relative difference (Δ_r) varies between 1.24% and 6.49% with an average (ARD) of 4.84%. For the hydraulic anisotropy of 50S50K (C) estimated from the measured wetting SWCC using the modified triaxial SWCC apparatus, the relative difference (Δ_r) varies between 2.46% and 8.26% with an average (ARD) of 4.95%. For the hydraulic anisotropy of 50S50K (C) estimated from the measured wetting SWCC using the unsaturated triaxial permeameter apparatus, the relative difference (Δ_r) varies between 2.73% and 9.87% with an average (ARD) of 6.13%. For the hydraulic anisotropy of specimens with 9% coarse mica estimated from the measured wetting SWCC using the modified triaxial SWCC apparatus, the relative difference (Δ_r) varies between 0.20% and 4.31% with an average (ARD) of 1.93%. For the hydraulic anisotropy of specimens with 9% coarse mica estimated from the measured

wetting SWCC using the unsaturated triaxial permeameter apparatus, the relative difference (Δ_r) varies between 0.35% and 5.85% with an average (ARD) of 2.26%. All relative differences (Δ_r) and their average (ARD) are less than 20% for all specimens, indicating reliably consistent estimation of hydraulic anisotropy values throughout the wetting path of unsaturated conditions for all specimens. This observation supports the behavior of consistent hydraulic anisotropy values throughout the wetting path of unsaturated conditions obtained using the direct measurement, as shown in Table 6.20-Table 6.22.

For further understanding, a comparison between the unsaturated coefficients of permeability and their corresponding hydraulic anisotropy values obtained using the direct permeability measurement (Table 6.20–Table 6.22) and the indirect determination from the corresponding drying SWCC (Table 6.26 – Table 6.30) was performed for each specimen. Figure 6.31 shows a graphical comparison between the wetting unsaturated coefficients of permeability of 50S50K (B) obtained using the direct measurement and the indirect determination. Figure 6.32 shows a graphical comparison between the wetting unsaturated coefficients of permeability of 50S50K (C) obtained using the direct measurement and the indirect determination. Figure 6.33 shows a graphical comparison between the wetting unsaturated coefficients of permeability of specimens with 9% coarse mica obtained using the direct measurement and the indirect determination. For each specimen, it is observed that the wetting unsaturated coefficients of permeability obtained using the direct measurement and the indirect determination from the corresponding wetting SWCC are relatively close regardless the measurement apparatus. Figure 6.34 shows a summary of relative differences between the mean values of wetting hydraulic

anisotropy obtained using the direct measurement and the indirect determination for each specimen.

Figure 6.31 Comparison between the measured and the estimated unsaturated coefficients of permeability of 50S50K (B) in the wetting path of unsaturated conditions

Figure 6.32 Comparison between the measured and the estimated unsaturated coefficients of permeability of 50S50K (C) in the wetting path of unsaturated conditions

Figure 6.33 Comparison between the measured and the estimated unsaturated coefficients of permeability of specimens with 9% coarse mica in the wetting path of unsaturated conditions

Figure 6.34 Relative differences between the mean values of wetting hydraulic anisotropy obtained using the direct measurement and the indirect determination from the corresponding measured wetting SWCC obtained using various apparatuses for each specimen

For 50S50K (B), the relative difference (Δ_r) between the mean values of wetting hydraulic anisotropy obtained using the direct measurement and the indirect determination from the corresponding wetting SWCC is observed to vary between 6.87% and 10.91% with an average (ARD) of 8.90%. For 50S50K (C), the relative difference (Δ_r) between the mean values of wetting hydraulic anisotropy obtained using the direct measurement and the indirect determination from the corresponding wetting SWCC is observed to vary between 4.46% and 7.87% with an average (ARD) of 6.28%. For specimens with 9% coarse mica, the relative difference (Δ_r) between the mean values of wetting hydraulic anisotropy obtained using the direct measurement and the indirect determination from the corresponding wetting SWCC is observed to vary between 2.00% and 2.80% with an average (ARD) of 2.40%. All relative differences (Δ_r) and their average (ARD) are less than 20% for all specimens and for all measurement apparatuses used in the research, indicating reliably close wetting hydraulic anisotropy values obtained using the direct measurement tests and the indirect determination from the corresponding measured wetting SWCC obtained using various apparatuses used in the research. This observation confirms the strong agreement between the direct measurement and the indirect determination results to the extent of similar values of the unsaturated coefficients of permeability and the corresponding hydraulic anisotropy as well as consistent behavior of hydraulic anisotropy in the wetting path of unsaturated conditions. These phenomena are similar to those discussed in Section 6.2 for the drying path of unsaturated conditions.

Different equilibrium times during both the wetting unsaturated permeability and SWCC tests were observed for each HL and VL orientation of a given specimen. In the wetting unsaturated permeability tests, the different equilibrium times for each HL and VL orientation of a given specimen were measured until the application of 75 kPa

matric suction, as shown in Figure 5.14. Table 6.31 shows the equilibrium times observed for 50S50K (B) during the wetting unsaturated permeability test compared to the hydraulic anisotropy measured at the corresponding matric suction. Table 6.32 shows the equilibrium times observed for 50S50K (C) during the wetting unsaturated permeability test compared to the hydraulic anisotropy measured at the corresponding matric suction. Table 6.33 shows the equilibrium times observed for specimens with 9% coarse mica during the wetting unsaturated permeability test compared to the hydraulic anisotropy measured at the corresponding matric suction.

Table 6.31 Ratio of equilibrium times observed during the wetting permeability test compared to the measured hydraulic anisotropy for 50S50K (B)

Matric suction (kPa)	Wetting permeability test			Measured hydraulic anisotropy	Δ_r (%)
	$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL} / t_{eq, VL}$)		
200	53.14	21.87	2.43	2.50	2.89
90	36.95	14.05	2.63	2.82	6.87
75	24.39	10.12	2.41	2.69	10.49
		Average	2.49	2.67	6.75

Table 6.32 Ratio of equilibrium times observed during the wetting permeability test compared to the measured hydraulic anisotropy for 50S50K (C)

Matric suction (kPa)	Wetting permeability test			Measured hydraulic anisotropy	Δ_r (%)
	$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL} / t_{eq, VL}$)		
200	130.64	29.06	4.50	4.38	2.65
90	95.29	20.32	4.69	4.72	0.67
75	78.84	17.20	4.58	4.31	6.40
		Average	4.59	4.47	3.24

Table 6.33 Ratio of equilibrium times observed during the wetting permeability test compared to the measured hydraulic anisotropy for specimens with 9% coarse mica

Matric suction (kPa)	Wetting permeability test			Measured hydraulic anisotropy	Δ_r (%)
	$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL} / t_{eq, VL}$)		
200	162.95	19.04	8.56	8.65	1.08
90	89.46	10.82	8.27	8.02	3.06
75	60.12	7.31	8.22	8.43	2.46
		Average	8.35	8.37	2.20

The relative differences (Δ_r) and their average (ARD) were computed for each specimen to show the correlation between the ratio of observed equilibrium times in different orientations (HL and VL) during the wetting unsaturated permeability tests and the measured wetting hydraulic anisotropy values at the corresponding matric suction. For 50S50K (B), the relative difference (Δ_r) is observed to vary between 2.89% and 10.49% with an average (ARD) of 6.75%. For 50S50K (C), the relative

difference (Δ_r) varies between 0.67% and 6.40% with an average (ARD) of 3.24%. For specimens with 9% coarse mica, the relative difference (Δ_r) varies between 1.08% and 3.06% with an average (ARD) of 2.20%. All relative differences (Δ_r) and their average (ARD) are less than 20% for all specimens, indicating reliably close values of the ratio between equilibrium times measured in different orientations (HL and VL) and hydraulic anisotropy measured at the corresponding matric suction during the wetting permeability tests. In other words, the hydraulic anisotropy values are reflected in the ratio of equilibrium times between HL and VL orientations of a given specimen (regardless the initial conditions or mica content) during the wetting unsaturated permeability test at high matric suction conditions.

In the wetting SWCC tests, the different equilibrium times for each HL and VL orientation of a given specimen were observed at the application of matric suction up to 20 kPa, as shown in Figure 5.28. Figure 6.35 shows a graphical comparison between the measured hydraulic anisotropy and the corresponding measured ratio of equilibrium times during the wetting SWCC tests using various measurement apparatuses for 50S50K (B). Table 6.34 shows the ratio of equilibrium times observed for 50S50K (B) during the wetting SWCC test using the Tempe cell and pressure plate apparatuses compared to the hydraulic anisotropy measured at the corresponding matric suction. Table 6.35 shows the ratio of equilibrium times observed for 50S50K (B) during the wetting SWCC test using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses compared to the hydraulic anisotropy measured at the corresponding matric suction. Figure 6.36 shows a graphical comparison between the measured hydraulic anisotropy and the corresponding measured ratio of equilibrium times during the wetting SWCC tests using various measurement apparatuses for 50S50K (C). Table 6.36 shows the ratio of equilibrium times observed

for 50S50K (C) during the wetting SWCC test using the Tempe cell and pressure plate apparatuses compared to the hydraulic anisotropy measured at the corresponding matric suction. Table 6.37 shows the ratio of equilibrium times observed for 50S50K (C) during the wetting SWCC test using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses compared to the hydraulic anisotropy measured at the corresponding matric suction. Figure 6.37 shows a graphical comparison between the measured hydraulic anisotropy and the corresponding measured ratio of equilibrium times during the wetting SWCC tests using various measurement apparatuses for specimens with 9% coarse mica. Table 6.38 shows the ratio of equilibrium times observed for specimens with 9% coarse mica during the wetting SWCC test using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses compared to the hydraulic anisotropy measured at the corresponding matric suction.

Figure 6.35 Comparison between the measured hydraulic anisotropy and the corresponding measured ratio of equilibrium times during the wetting SWCC tests for 50S50K (B)

Table 6.34 Ratio of equilibrium times observed during the wetting SWCC test using the Tempe cell and pressure plate apparatuses compared to the measured hydraulic anisotropy for 50S50K (B)

Matric suction (kPa)	Measured hydraulic anisotropy	Tempe cell and pressure plate			Δ_r (%)
		$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL} / t_{eq, VL}$)	
200	2.50	521.06	204.84	2.54	1.65
90	2.82	159.10	66.92	2.38	15.81
75	2.69	53.69	21.74	2.47	8.27
50	2.14	45.75	19.11	2.39	11.66
35	2.29	35.27	15.86	2.22	2.99
20	2.59	32.01	13.84	2.31	10.80
Average	2.51			2.39	8.53

Table 6.35 Ratio of equilibrium times observed during the wetting SWCC test using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses compared to the measured hydraulic anisotropy for 50S50K (B)

Matric suction (kPa)	Measured hydraulic anisotropy	Triaxial			Δ_r (%)	Permeameter			Δ_r (%)
		$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL}/t_{eq, VL}$)		$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL}/t_{eq, VL}$)	
200	2.50	611.19	249.15	2.45	1.97	652.19	271.87	2.40	4.14
90	2.82	150.31	62.81	2.39	15.26	157.91	69.68	2.27	19.75
75	2.69	72.81	28.74	2.53	5.90	78.29	31.43	2.49	7.48
50	2.14	45.58	18.32	2.49	16.05	49.078	20.12	2.44	13.77
35	2.29	40.03	16.37	2.45	6.67	43.805	18.74	2.34	1.97
20	2.59	36.79	15.58	2.36	8.93	39.32	16.20	2.43	6.38
Average	2.51			2.45	9.13			2.39	8.91

Figure 6.36 Comparison between the measured hydraulic anisotropy and the corresponding measured ratio of equilibrium times during the wetting SWCC tests for 50S50K (C)

Table 6.36 Ratio of equilibrium times observed during the wetting SWCC test using the Tempe cell and pressure plate apparatuses compared to the measured hydraulic anisotropy for 50S50K (C)

Matric suction (kPa)	Measured hydraulic anisotropy	Tempe cell and pressure plate			Δ_r (%)
		$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL} / t_{eq, VL}$)	
200	4.38	1117.65	247.29	4.52	3.20
90	4.72	361.92	80.57	4.49	4.86
75	4.31	228.79	51.24	4.47	3.64
50	4.72	161.38	35.76	4.51	4.38
35	4.76	121.96	27.17	4.49	5.70
20	4.86	97.89	21.85	4.48	7.76
Average	4.62			4.49	4.92

Table 6.37 Ratio of equilibrium times observed during the wetting SWCC test using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses compared to the measured hydraulic anisotropy for 50S50K (C)

Matric suction (kPa)	Measured hydraulic anisotropy	Triaxial			Δ_r (%)	Permeameter			Δ_r (%)
		$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL}/$ $t_{eq, VL}$)		$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL}/$ $t_{eq, VL}$)	
200	4.38	1286.72	290.85	4.42	1.01	1339.71	301.15	4.45	1.58
90	4.72	412.49	91.94	4.49	4.97	448.64	100.38	4.47	5.33
75	4.31	255.31	57.67	4.43	2.76	282.21	62.95	4.48	4.06
50	4.72	172.36	38.43	4.49	4.97	186.69	41.36	4.51	4.36
35	4.76	132.19	29.14	4.54	4.70	147.52	32.89	4.49	5.78
20	4.86	104.43	23.48	4.45	8.43	113.91	25.46	4.47	7.89
Average	4.62			4.47	4.47			4.48	4.83

Figure 6.37 Comparison between the measured hydraulic anisotropy and the corresponding measured ratio of equilibrium times during the wetting SWCC tests for specimens with 9% coarse mica

Table 6.38 Ratio of equilibrium times observed during the wetting SWCC test using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses compared to the measured hydraulic anisotropy for specimens with 9% coarse mica

Matric suction (kPa)	Measured hydraulic anisotropy	Triaxial			Δ_r (%)	Permeameter			Δ_r (%)
		$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL}/t_{eq, VL}$)		$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL}/t_{eq, VL}$)	
200	8.65	845.64	98.80	8.56	1.09	1124.62	128.44	8.76	1.19
90	8.02	365.79	41.77	8.76	9.13	478.66	54.30	8.81	9.85
75	8.43	288.31	33.56	8.59	1.95	379.73	43.63	8.70	3.29
50	8.94	210.28	24.04	8.75	2.14	271.49	31.25	8.69	2.79
35	8.92	197.21	22.39	8.81	1.23	247.15	28.96	8.53	4.29
20	8.83	172.82	19.86	8.70	1.44	193.87	22.49	8.62	2.34
Average	8.63			8.69	2.83			8.69	3.96

For each specimen, it is observed that the measured hydraulic anisotropy and the corresponding measured ratio of equilibrium times during the wetting SWCC tests are relatively close regardless the measurement apparatus. The relative differences (Δ_r) and their average (ARD) were computed for each specimen to show the correlation between the ratio of observed equilibrium times in different orientations (HL and VL) during the wetting SWCC tests using various measurement apparatuses and the measured wetting hydraulic anisotropy values at the corresponding matric suction. For the ratio of equilibrium times during the wetting SWCC tests of 50S50K (B) obtained using the Tempe cell and pressure plate apparatuses, the relative difference (Δ_r) is observed to vary between 1.65% and 15.81% with an average (ARD) of 8.53%. For the ratio of equilibrium times during the wetting SWCC tests of 50S50K (B) obtained using the modified triaxial SWCC apparatus, the relative difference (Δ_r) varies between 1.97% and 16.05% with an average (ARD) of 9.13%. For the ratio of equilibrium times during the wetting SWCC tests of 50S50K (B) obtained using the unsaturated triaxial permeameter apparatus, the relative difference (Δ_r) varies between 1.97% and 19.75% with an average (ARD) of 8.91%. For the ratio of equilibrium times during the wetting SWCC tests of 50S50K (C) obtained using the Tempe cell and pressure plate apparatuses, the relative difference (Δ_r) varies between 3.20% and 7.76% with an average (ARD) of 4.92%. For the ratio of equilibrium times during the wetting SWCC tests of 50S50K (C) obtained using the modified triaxial SWCC apparatus, the relative difference (Δ_r) varies between 1.01% and 8.43% with an average (ARD) of 4.47%. For the ratio of equilibrium times during the wetting SWCC tests of 50S50K (C) obtained using the unsaturated triaxial permeameter apparatus, the relative difference (Δ_r) varies between 1.58% and 7.89% with an average (ARD) of 4.83%. For the ratio of equilibrium times during the wetting SWCC tests of

specimens with 9% coarse mica obtained using the modified triaxial SWCC apparatus, the relative difference (Δ_r) varies between 1.09% and 9.13% with an average (ARD) of 2.83%. For the ratio of equilibrium times during the wetting SWCC tests of specimens with 9% coarse mica obtained using the unsaturated triaxial permeameter apparatus, the relative difference (Δ_r) varies between 1.19% and 9.85% with an average (ARD) of 3.96%. All relative differences (Δ_r) and their average (ARD) are less than 20% for all specimen, indicating reliably close values of the ratio between equilibrium times measured in different orientations (HL and VL) during the wetting SWCC tests using various apparatuses and the hydraulic anisotropy values measured at the corresponding matric suction. In other words, hydraulic anisotropy values are reflected in the ratio of equilibrium times between HL and VL orientations of a given specimen (regardless the initial conditions or mica content) during the wetting SWCC test (regardless the measurement apparatus) at the application of matric suction until fairly low value (20 kPa). This behavior is similar to that discussed in Section 6.2 for the drying path of unsaturated conditions.

6.4. Comparison between Hydraulic Anisotropy Values under the Saturated Conditions and following the Drying and Wetting Paths of Unsaturated Conditions

Similar hydraulic anisotropy behavior has been observed in the research, i.e. consistent hydraulic anisotropy values and the hydraulic anisotropy values are reflected in the ratio of equilibrium times during the permeability and SWCC tests for each drying and wetting path of unsaturated conditions as discussed in Section 6.2 and Section 6.3. Even though there is a strong resemblance to hydraulic anisotropy behavior, the values of hydraulic anisotropy are different for each drying and wetting path of unsaturated conditions. In this section, comparisons of different hydraulic

anisotropy values under the saturated conditions and following the drying and wetting paths of unsaturated conditions as well as the ratio of equilibrium times following the drying and wetting paths of unsaturated conditions are discussed for each specimen, i.e. 50S50K (B), 50S50K (C) and specimens with 9% coarse mica.

Prior to examining the observed hydraulic anisotropy values, significant difference between permeability values measured under the saturated conditions and following the drying and wetting paths of unsaturated conditions is discussed. The difference between saturated and unsaturated permeability values of a given specimen can be as high as five orders of magnitude, as presented in Section 5.5. This significant difference can be associated with the corresponding SWCC of the specimen. The SWCC indicates that volumetric water content of a given specimen can fall significantly, even becoming less than 0.1, during the application of high matric suction as presented in Section 5.6. At high matric suction conditions, voids in a soil are predominantly composed of pore-air, unlike under the saturated conditions when all voids are filled with water. The amount of pore-water, as represented by volumetric water content in SWCC, dictates the permeability of a soil with respect to water phase.

In addition, there are different permeability values measured at the same matric suction following the drying and wetting paths of unsaturated conditions. At the same matric suction, the unsaturated permeability as well as the SWCC measured following the wetting path are always less than those measured following the drying path of unsaturated conditions. Hysteretic phenomenon, as described in Section 2.3, has been widely recognized as the main reason of such behavior.

Figure 6.38 shows a graphical comparison between the mean values of hydraulic anisotropy obtained using the direct measurement under the saturated conditions and

following the drying and wetting paths of unsaturated conditions (as shown in Section 6.1 – Section 6.3) for each specimen. Table 6.39 shows ratios of the mean values of hydraulic anisotropy obtained using the direct measurement under the saturated conditions and following the drying and wetting paths of unsaturated conditions for each specimen. Figure 6.39 shows a graphical comparison between the mean values of hydraulic anisotropy indirectly determined from the corresponding SWCC in drying and wetting paths of unsaturated conditions using various measurement apparatuses (as shown in Section 6.2 and Section 6.3) for each specimen. Table 6.40 shows ratios of the mean values of hydraulic anisotropy indirectly determined from the corresponding SWCC in drying and wetting paths of unsaturated conditions using various measurement apparatuses for each specimen.

Figure 6.38 Comparison of the measured hydraulic anisotropy values in all conditions for each specimen

Table 6.39 Ratio of the measured hydraulic anisotropy values in all conditions for each specimen

Specimens	Ratio of measured hydraulic anisotropy			
	Saturated /Drying (%)	Δ_r (%)	Wetting/ Drying (%)	Δ_r (%)
50S50K (B)	95.24	3.74	72.62	7.75
50S50K (C)	101.57	2.66	80.84	2.69
Specimens with 9% coarse mica	100.00	1.07	82.71	5.06
Average	98.94	2.49	78.72	5.17

Figure 6.39 Comparison between the estimated hydraulic anisotropy values from the corresponding SWCC in following the drying and wetting paths of unsaturated conditions for each specimen

Table 6.40 Ratio of the estimated hydraulic anisotropy values from the corresponding SWCC in following the drying and wetting paths of unsaturated conditions for each specimen

Specimens	Ratio of estimated hydraulic anisotropy in wetting/drying					
	TC&PP		Triaxial		Permeameter	
	Ratio (%)	Δ_r (%)	Ratio (%)	Δ_r (%)	Ratio (%)	Δ_r (%)
50S50K (B)	69.52	10.81	70.34	9.77	76.50	1.87
50S50K (C)	74.43	4.52	74.01	5.06	87.68	12.48
Specimens with 9% coarse mica			83.25	6.79	87.89	12.75
Average of all (%)	77.95					
ARD of all (%)	8.01					

The relative differences (Δ_r) and their average (ARD) were computed for each specimen to show the correlation between the ratio of mean hydraulic anisotropy values measured during different saturation conditions, i.e. saturated to drying hydraulic anisotropy values and wetting to drying hydraulic anisotropy values, as well as the correlation between the ratio of mean hydraulic anisotropy values estimated in the drying and wetting tests using various measurement apparatuses. The mean hydraulic anisotropy value measured following the drying path of unsaturated conditions is observed to be close (98.94%) to the value measured under the saturated conditions having relative differences (Δ_r) between 1.07% and 3.74% with an average (ARD) of 2.49% for all specimens. The mean hydraulic anisotropy value measured following the wetting path is smaller (78.72%) to the value measured in the drying path of unsaturated conditions having relative differences (Δ_r) between 2.69% and

7.75% with an average (ARD) of 5.17% for all specimens. In addition, the mean hydraulic anisotropy value estimated following the wetting path is smaller (77.95%) to the value estimated in the drying path of unsaturated conditions having relative differences (Δ_r) between 4.51% and 12.48% with an average (ARD) of 8.00% for all specimens using various measurement apparatuses. All relative differences (Δ_r) and their average (ARD) are less than 20% for all specimens, indicating reliably close values of hydraulic anisotropy measured in the saturated and drying path of unsaturated conditions as well as considerably smaller values of hydraulic anisotropy in the wetting path compared to those in the drying path of unsaturated conditions obtained using both the direct measurement and the indirect determination methods. A steady and relatively slow static loading rate (1 mm/min) during compaction performed in this research ensures that the specimens are homogeneous, which then leads to the similar hydraulic anisotropy values measured under the saturated conditions and drying path of unsaturated conditions, as expected in the proposed framework (Section 3.3). Therefore, these results are applicable to soils having conditions similar to that imposed by static compaction and may or may not be applicable to other soils having different conditions and fabric. In addition, it is highly plausible that hysteretic phenomena such as ink-bottle effect induce smaller values of hydraulic anisotropy in the wetting path compared to the drying path of unsaturated conditions, as expected in the proposed framework (Section 3.4).

There were also different values of ratio of equilibrium times measured during the unsaturated permeability and SWCC tests in following the drying and wetting paths of unsaturated conditions for each specimen. Table 6.41 shows a comparison of the mean values of ratio of equilibrium times during permeability tests in following the drying and wetting paths of unsaturated conditions for each specimen. Table 6.42

shows a comparison of the mean values of ratio of equilibrium times during SWCC tests in following the drying and wetting paths of unsaturated conditions for each specimen.

Table 6.41 Comparison of the mean values of ratio of equilibrium times during the drying and wetting unsaturated permeability tests for each specimen

Specimens	Ratio of equilibrium times during permeability tests			
	Drying	Wetting	Wetting/Drying (%)	Δ_r (%)
50S50K (B)	3.21	2.49	77.49	0.92
50S50K (C)	5.72	4.59	80.24	1.27
Specimens with 9% coarse mica	10.44	8.35	79.96	2.19
		Average	79.23	1.46

Table 6.42 Comparison of the mean values of ratio of equilibrium times during the drying and wetting SWCC tests for each specimen

Specimens	Ratio of equilibrium times in wetting/drying SWCCs					
	TC&PP		Triaxial		Permeameter	
	Ratio	Δ_r	Ratio	Δ_r	Ratio	Δ_r
	(%)	(%)	(%)	(%)	(%)	(%)
50S50K (B)	73.28	5.96	76.50	1.84	75.71	2.85
50S50K (C)	80.09	2.78	76.11	2.33	77.91	0.03
Specimens with 9% coarse mica			81.03	3.98	82.79	6.24
Average of all (%)	77.93					
ARD of all (%)	3.25					

The relative differences (Δ_r) and their average (ARD) were computed for each specimen to show the correlation between the ratio of equilibrium times during permeability and SWCC tests using various measurement apparatuses tests in following the drying and wetting paths of unsaturated conditions. The mean ratio of equilibrium times obtained during the wetting permeability tests is observed to be smaller (79.23%) to the value obtained during the drying permeability tests having relative differences (Δ_r) between 0.92% and 2.19% with an average (ARD) of 1.46% for all specimens. The mean ratio of equilibrium times obtained during the wetting SWCC tests is smaller (78.91%) to the value obtained during the drying SWCC tests having relative differences (Δ_r) between 0.59% and 7.13% with an average (ARD) of 3.56% for all specimens using various measurement apparatuses. All relative differences (Δ_r) and their average (ARD) are less than 20% for all specimens, indicating considerably smaller values of the ratio of equilibrium times during the wetting permeability and SWCC tests compared to the corresponding drying permeability and SWCC tests. This observation shows that smaller values of hydraulic anisotropy in the wetting path compared to the drying path of unsaturated conditions are reflected in the smaller ratio of equilibrium times in the wetting tests compared to the corresponding drying tests, as expected in the proposed framework (Section 3.4).

6.5. Characteristics of the Drying Soil-Water Characteristic Curve with regards to Hydraulic Anisotropy

Discussions on the characteristics of soil-water characteristic curve (SWCC) with regards to hydraulic anisotropy in the drying path of unsaturated conditions for various specimens, as shown in Section 5.6, are presented in this section. Various statically-compacted specimens were prepared in this research, as described in Section 4.1.1, and all of the specimens were subjected to the drying SWCC tests using various apparatuses in order to understand the characteristics of the drying SWCCs. The main characteristic to be observed was whether the drying SWCC is a scalar property of a soil considering different drying hydraulic anisotropy values, initial compaction conditions and mica contents. The statistical coefficient of determination (R^2), as described in Section 4.3, was used as the criteria for understanding the scalar property of the drying SWCC.

In addition, a comparison between the ratio of equilibrium times measured during the drying SWCC tests using various measurement apparatuses and the hydraulic anisotropy value measured under the saturated conditions was performed for each specimen, which has not been discussed in Section 6.2 (50S50K (A), 50S50K (D) with heights of 30 mm and 50 mm and specimens with 20% coarse mica). The relative difference (Δ_r) and its average (ARD), as described in Section 4.3, were used to show the correlation between the ratio of equilibrium times measured during the drying SWCC tests and the hydraulic anisotropy measured under the saturated conditions, similar to the analyses performed in Section 6.2. Lastly, a comparison between the mean ratio of equilibrium times during the drying SWCC tests using various measurement apparatuses observed in the laboratory tests and numerical modeling was performed.

The measured drying SWCC of each specimen was best-fitted using Equation 2.14 and Equation 2.15 for the unimodal and bimodal drying SWCC data, respectively. As presented in Section 5.6, 50S50K (A), 50S50K (B), specimens with 9% coarse mica and specimens with 20% coarse mica have a bimodal shape whereas 50S50K (C) and 50S50K (D) have a unimodal shape of the drying SWCC data. Table 6.43 shows the bimodal fitting parameters of Equation 2.15 for the drying SWCC data of 50S50K (A) obtained using the Tempe cell and pressure plate apparatuses. Table 6.44 shows the bimodal fitting parameters of Equation 2.15 for the drying SWCC data of 50S50K (B) obtained using all measurement apparatuses. Figure 6.8– Figure 6.10 in Section 6.2 illustrate best fitting for the measured drying SWCC data of 50S50K (B) based on the respective Tempe cell and pressure plate, modified triaxial SWCC and unsaturated triaxial permeameter measurements. Table 6.45 shows the unimodal fitting parameters of Equation 2.14 for the drying SWCC data of 50S50K (C) obtained using all measurement apparatuses. Figure 6.11 – Figure 6.13 in Section 6.2 illustrate best fitting for the measured drying SWCC data of 50S50K (C) based on the respective Tempe cell and pressure plate, modified triaxial SWCC and unsaturated triaxial permeameter measurements. Table 6.46 shows the unimodal fitting parameters of Equation 2.14 for the drying SWCC data of 50S50K (D) with heights of 30 mm and 50 mm obtained using the Tempe cell and pressure plate apparatuses. Table 6.47 shows the bimodal fitting parameters of Equation 2.15 for the drying SWCC data of specimens with 9% coarse mica obtained using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses. Figure 6.14 and Figure 6.15 in Section 6.2 illustrate best fitting for the measured drying SWCC data of specimens with 9% coarse mica based on the respective modified triaxial SWCC and unsaturated triaxial permeameter measurements. Table 6.48 shows the bimodal fitting parameters of

Equation 2.15 for the drying SWCC data of specimens with 20% coarse mica obtained using the modified triaxial SWCC apparatus. All figures illustrating best fitting for the drying SWCC data of each specimen which has not been discussed in Section 6.2 (50S50K (A), 50S50K (D) with heights of 30 mm and 50 mm and specimens with 20% coarse mica) are presented in Appendix A.

Table 6.43 Bimodal fitting parameters of the measured drying SWCC data of 50S50K (A) and the summarized R^2 analyses

Fitting parameters	TC&PP	
	HL	VL
θ_{s1}	0.435	0.421
ψ_{a1} (kPa)	9.949	9.748
ψ_{m1} (kPa)	11.491	18.310
s_1	2.614	2.367
θ_{s2}	0.300	0.240
ψ_{a2} (kPa)	34.768	44.694
ψ_{m2} (kPa)	99.803	98.994
s_2	1.646	2.003
ψ_r (kPa)	499.999	500.003
θ_r	0.015	0.015
R^2 (HL data)	0.997	0.991
R^2 (VL data)	0.992	0.997

Table 6.44 Bimodal fitting parameters of the measured drying SWCC data of 50S50K
(B) and the summarized R^2 analyses

Fitting parameters	TC&PP		Triaxial		Permeameter	
	HL	VL	HL	VL	HL	VL
θ_{s1}	0.404	0.385	0.364	0.349	0.360	0.364
ψ_{a1} (kPa)	9.940	10.000	10.338	10.110	10.441	9.998
ψ_{m1} (kPa)	10.288	10.018	11.048	10.888	11.236	11.357
s_1	1.846	4.269	0.195	0.438	3.782	4.671
θ_{s2}	0.303	0.288	0.281	0.268	0.237	0.223
ψ_{a2} (kPa)	15.582	16.002	27.386	26.831	35.248	34.190
ψ_{m2} (kPa)	75.789	75.018	72.953	76.128	72.973	70.126
s_2	0.804	0.796	1.234	1.193	1.618	1.480
ψ_r (kPa)	600.005	600.007	499.958	499.990	499.990	500.003
θ_r	0.065	0.064	0.051	0.045	0.009	0.015
R^2 (HL TC&PP)	1.000	0.989	0.945	0.890	0.890	0.902
R^2 (VL TC&PP)	0.990	1.000	0.983	0.948	0.935	0.947
R^2 (HL Triaxial)	0.946	0.978	0.999	0.991	0.974	0.983
R^2 (VL Triaxial)	0.909	0.950	0.988	1.000	0.984	0.990
R^2 (HL Permeameter)	0.882	0.922	0.968	0.981	0.999	0.998
R^2 (VL Permeameter)	0.908	0.944	0.981	0.987	0.998	1.000

Table 6.45 Unimodal fitting parameters of the measured drying SWCC data of 50S50K (C) and the summarized R^2 analyses

Fitting parameters	TC&PP		Triaxial		Permeameter	
	HL	VL	HL	VL	HL	VL
θ_s	0.430	0.429	0.386	0.385	0.379	0.389
a (kPa)	48.967	50.243	44.765	44.560	45.316	45.495
n	2.752	2.668	5.135	4.879	4.279	3.669
m	1.112	1.191	0.712	0.726	0.695	0.814
R^2 (HL TC&PP)	1.000	0.999	0.942	0.940	0.930	0.956
R^2 (VL TC&PP)	0.998	0.999	0.902	0.898	0.883	0.925
R^2 (HL Triaxial)	0.948	0.953	1.000	1.000	0.988	0.992
R^2 (VL Triaxial)	0.947	0.953	1.000	1.000	0.989	0.993
R^2 (HL Permeameter)	0.944	0.948	0.988	0.989	0.999	0.995
R^2 (VL Permeameter)	0.963	0.966	0.992	0.992	0.996	0.999

Table 6.46 Unimodal fitting parameters of the measured drying SWCC data of 50S50K (D) having different heights and the summarized R^2 analyses

Fitting parameters	30 mm height		50 mm height	
	HL	VL	HL	VL
θ_s	0.486	0.487	0.490	0.492
a (kPa)	47.836	47.165	47.578	46.612
n	2.030	2.087	1.974	2.080
m	1.256	1.213	1.238	1.215
R^2 (HL 30 mm)	0.999	0.999	0.998	0.998
R^2 (VL 30 mm)	1.000	1.000	0.999	0.999
R^2 (HL 50 mm)	0.999	0.999	1.000	0.999
R^2 (VL 50 mm)	0.999	0.999	0.999	0.999

Table 6.47 Bimodal fitting parameters of the measured drying SWCC data of specimens with 9% coarse mica and the summarized R^2 analyses

Fitting parameters	Triaxial		Permeameter	
	HL	VL	HL	VL
θ_{s1}	0.409	0.437	0.430	0.430
ψ_{a1} (kPa)	9.968	9.994	9.853	9.996
ψ_{m1} (kPa)	10.588	10.967	10.993	10.813
s_1	2.028	1.958	1.404	1.794
θ_{s2}	0.289	0.298	0.303	0.299
ψ_{a2} (kPa)	33.026	43.106	39.976	48.620
ψ_{m2} (kPa)	135.027	139.395	136.679	134.112
s_2	1.062	1.160	0.951	1.071
ψ_r (kPa)	499.984	499.986	499.922	504.996
θ_r	0.010	0.010	0.015	0.015
R^2 (HL Triaxial)	0.998	0.976	0.982	0.981
R^2 (VL Triaxial)	0.985	0.992	0.990	0.990
R^2 (HL Permeameter)	0.979	0.995	0.999	0.998
R^2 (VL Permeameter)	0.977	0.996	0.999	0.999

Table 6.48 Bimodal fitting parameters of the measured drying SWCC data of specimens with 20% coarse mica and the summarized R^2 analyses

Fitting parameters	Triaxial	
	HL	VL
θ_{s1}	0.496	0.495
ψ_{a1} (kPa)	9.967	9.999
ψ_{m1} (kPa)	11.831	10.696
s_1	3.095	4.299
θ_{s2}	0.271	0.258
ψ_{a2} (kPa)	54.938	50.351
ψ_{m2} (kPa)	199.866	207.703
s_2	1.396	1.054
ψ_r (kPa)	499.900	499.829
θ_r	0.010	0.010
R^2 (HL data)	1.000	0.995
R^2 (VL data)	0.995	0.999

The coefficient of determination (R^2) analyses were calculated to achieve the best fitting parameters for each orientation (HL and VL) of the drying SWCC obtained using each measurement apparatus. Correlations between the measured drying SWCC data in each orientation using each measurement apparatus can be observed by applying a set of the best fitting parameters to the drying SWCC data measured in different orientations or using different apparatuses. For the drying SWCC of 50S50K (A) obtained using the Tempe cell and pressure plate apparatuses, R^2 value is observed to vary between 0.991 and 0.997. For the drying SWCC of 50S50K (B)

obtained using all measurement apparatuses, R^2 value varies between 0.882 and 1.000. For the drying SWCC of 50S50K (C) obtained using all measurement apparatuses, R^2 value varies between 0.883 and 1.000. For the drying SWCC of 50S50K (D) with heights of 30 mm and 50 mm obtained using the Tempe cell and pressure plate apparatuses, R^2 value varies between 0.998 and 1.000. For the drying SWCC of specimens with 9% coarse mica obtained using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses, R^2 value varies between 0.976 and 0.999. For the drying SWCC of specimens with 20% coarse mica obtained using the modified triaxial SWCC apparatus, R^2 value varies between 0.995 and 1.000. It is observed that for each specimen, the lowest R^2 value is calculated when the best fitting parameters based on the Tempe cell and pressure plate measurements are applied to the data obtained using the modified triaxial SWCC or unsaturated triaxial permeameter apparatus, and vice versa. This observation can be related to the fact that there was 25 kPa net confining pressure in the SWCC measurement using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses, unlike zero confining pressure in the corresponding SWCC measurement using the Tempe cell and pressure plate apparatuses. Nonetheless, all R^2 values are notably still very high (close to unity) for each specimen. This observation means that the drying SWCC should be considered as a scalar property of the soil regardless the layering orientation (HL or VL), measurement apparatus (Tempe cell, pressure plate, modified triaxial SWCC or unsaturated triaxial permeameter), specimen height (30 mm or 50 mm), shape of the drying SWCC (unimodal or bimodal), initial conditions (dry or wet of optimum) or mica content (with or without mica). This observed scalar characteristic of the drying SWCC supports the observation of consistent drying hydraulic anisotropy values discussed in Section 6.2. As described in the proposed

framework (Section 3.3), there is a close relationship between the drying SWCC and drying hydraulic anisotropy. If the drying SWCC is scalar, i.e. different orientation can be best-fitted reasonably well using an identical set of parameters regardless the measurement apparatus, constant values of hydraulic anisotropy throughout the drying path of unsaturated conditions will be estimated using Equation 3.4.

There were different equilibrium times for each HL and VL orientation of a given specimen observed during the drying SWCC tests at matric suctions higher than the air-entry value (AEV) of the specimen, as shown in Figure 5.28. A comparison between the ratio of equilibrium times measured during the drying SWCC tests using various measurement apparatuses and the hydraulic anisotropy measured under the saturated conditions was performed for each specimen, which has not been discussed in Section 6.2 (50S50K (A), 50S50K (D) with heights of 30 mm and 50 mm and specimens with 20% coarse mica). The value of hydraulic anisotropy measured under the saturated conditions was used as point of reference for each specimen because no measurement of hydraulic anisotropy was performed following the drying path of unsaturated conditions due to time consideration as well as according to the discussion in Section 6.4, the hydraulic anisotropy measured under the saturated conditions was very similar to the values measured in the drying path of unsaturated conditions. Table 6.49 shows the ratio of equilibrium times observed for 50S50K (A) during the drying SWCC test using the Tempe cell and pressure plate apparatuses compared to the hydraulic anisotropy measured under the saturated conditions. Table 6.50 shows the ratio of equilibrium times observed for 50S50K (D) with a height of 30 mm during the drying SWCC test using the Tempe cell and pressure plate apparatuses compared to the hydraulic anisotropy measured under the saturated conditions. Table 6.51 shows the ratio of equilibrium times observed for 50S50K (D)

with a height of 50 mm during the drying SWCC test using the Tempe cell and pressure plate apparatuses compared to the hydraulic anisotropy measured under the saturated conditions. Table 6.52 shows the ratio of equilibrium times observed for specimens with 20% coarse mica during the drying SWCC test using the modified triaxial SWCC apparatus compared to the hydraulic anisotropy measured under the saturated conditions.

Table 6.49 Ratio of equilibrium times observed during the drying SWCC test compared to the measured hydraulic anisotropy under the saturated conditions for 50S50K (A)

Matric suction (kPa)	$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL} / t_{eq, VL}$)	Δ_r (%)
30	8.96	5.13	1.75	2.20
40	9.53	5.28	1.80	1.06
50	10.37	5.85	1.77	0.74
75	11.09	6.19	1.79	0.32
90	15.77	8.68	1.82	1.73
200	36.73	20.55	1.79	0.08
400	132.94	74.62	1.78	0.24
		Average	1.79	0.91
Measured hydraulic anisotropy			1.80	0.78

Table 6.50 Ratio of equilibrium times observed during the drying SWCC test compared to the measured hydraulic anisotropy under the saturated conditions for 50S50K (D) with a 30 mm height

Matric suction (kPa)	$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL}/t_{eq, VL}$)	Δ_r (%)
35	17.41	4.49	3.88	0.21
50	19.77	5.07	3.90	0.77
75	22.71	5.91	3.84	0.76
90	27.53	7.11	3.87	0.01
200	59.21	15.98	3.70	4.38
400	208.66	51.77	4.03	4.15
		Average	3.87	1.71
Measured hydraulic anisotropy			3.93	1.54

Table 6.51 Ratio of equilibrium times observed during the drying SWCC test compared to the measured hydraulic anisotropy under the saturated conditions for 50S50K (D) with a 50 mm height

Matric suction (kPa)	$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL}/t_{eq, VL}$)	Δ_r (%)
35	27.48	7.14	3.85	8.20
50	28.75	8.23	3.49	1.79
75	29.08	9.67	3.01	15.46
90	33.75	9.92	3.40	4.36
200	117.75	31.42	3.75	5.35
400	479.5	124.75	3.84	8.06
		Average	3.56	7.20
Measured hydraulic anisotropy			4.04	11.95

Table 6.52 Ratio of equilibrium times observed during the drying SWCC test as compared to the measured hydraulic anisotropy under the saturated conditions for specimens with 20% coarse mica

Matric suction (kPa)	$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL}/t_{eq, VL}$)	Δ_r (%)
30	14.13	8.11	1.74	2.72
40	14.45	8.19	1.76	1.60
50	16.32	8.97	1.82	1.76
75	18.48	9.92	1.86	3.99
90	35.15	20.06	1.75	2.16
200	53.32	29.52	1.81	1.20
400	116.44	65.44	1.78	0.48
		Average	1.79	1.99
Measured hydraulic anisotropy			1.81	1.18

The relative differences (Δ_r) and their average (ARD) were computed for each specimen to show the variation between the measured ratio of equilibrium times at each application of matric suction and the mean value of all ratios of equilibrium times measured during the drying SWCC test as well as the correlation between the mean value of all ratios of equilibrium times measured during the drying SWCC test and the hydraulic anisotropy measured under the saturated conditions. For 50S50K (A), the relative difference (Δ_r) of the ratio of equilibrium times at each application of matric suction compared to its mean is observed to vary between 0.08% and 2.20% with an average (ARD) of 0.91%, whereas the relative difference (Δ_r) of the mean

ratio of equilibrium times during the drying SWCC tests compared to the hydraulic anisotropy measured under the saturated conditions is 0.78%. For 50S50K (D) with a height of 30 mm, the relative difference (Δ_r) of the ratio of equilibrium times at each application of matric suction compared to its mean varies between 0.01% and 4.38% with an average (ARD) of 1.71%, whereas the relative difference (Δ_r) of the mean ratio of equilibrium times during the drying SWCC tests compared to the hydraulic anisotropy measured under the saturated conditions is 1.54%. For 50S50K (D) with a height of 50 mm, the relative difference (Δ_r) of the ratio of equilibrium times at each application of matric suction compared to its mean varies between 1.79% and 15.46% with an average (ARD) of 7.20%, whereas the relative difference (Δ_r) of the mean ratio of equilibrium times during the drying SWCC tests compared to the hydraulic anisotropy measured under the saturated conditions is 11.95%. For specimens with 20% coarse mica, the relative difference (Δ_r) of the ratio of equilibrium times at each application of matric suction compared to its mean varies between 0.48% and 3.99% with an average (ARDs) of 1.99%, whereas the relative difference (Δ_r) of the mean ratio of equilibrium times during the drying SWCC tests compared to the hydraulic anisotropy measured under the saturated conditions is 1.18%. All relative differences (Δ_r) and their average (ARD) are less than 20% for all specimens, indicating reliably consistent ratio of equilibrium times measured during the drying SWCC tests as well as reliably close values of the mean ratio of equilibrium times measured during the drying SWCC tests and the hydraulic anisotropy measured under the saturated conditions. In other words, the hydraulic anisotropy value measured under the saturated conditions is reflected in the ratio of equilibrium times during the drying SWCC tests of a given specimen (regardless the initial conditions or mica content),

similar to the behavior discussed in Section 6.2 for the drying path of unsaturated conditions.

For further understanding, a comparison between the mean ratio of equilibrium times during the drying SWCC tests using various measurement apparatuses observed in the laboratory tests and numerical modeling was performed for the relevant specimens i.e. 50S50K (C), 50S50K (D) with heights of 30 mm and 50 mm. Figure 6.40 shows a graphical comparison between the ratio of equilibrium times during the drying SWCC tests using various measurement apparatuses observed in the laboratory tests and numerical modeling for 50S50K (C). Figure 6.41 shows a graphical comparison between the ratio of equilibrium times during the drying SWCC tests using the Tempe cell and pressure plate apparatuses observed in the laboratory tests and numerical modeling for 50S50K (D) with heights of 30 mm and 50 mm. Table 6.53 shows relative differences between the mean ratio of equilibrium times during the drying SWCC test using various measurement apparatuses observed in the laboratory tests and numerical modeling for each specimen.

Figure 6.40 Comparison between the ratio of equilibrium times during the drying SWCC tests using various measurement apparatuses observed in the laboratory tests and numerical modeling for 50S50K (C)

Figure 6.41 Comparison between the ratio of equilibrium times during the drying SWCC tests using various measurement apparatuses observed in the laboratory tests and numerical modeling for 50S50K (D) with heights of 30 mm and 50 mm

Table 6.53 Relative differences between the mean ratio of equilibrium times during the drying SWCC test using various apparatuses observed in the laboratory tests and numerical modeling

Specimens	Mean ratio of equilibrium times during the drying SWCC test								
	TC&PP			Triaxial			Permeameter		
	Lab	Num	Δ_r	Lab	Num	Δ_r	Lab	Num	Δ_r
	test	model	(%)	test	model	(%)	test	model	(%)
50S50K (C)	5.61	5.49	2.14	5.87	5.74	2.21	5.75	5.74	0.17
50S50K (D) 30 mm height	3.87	3.83	1.03						
50S50K (D) 50 mm height	3.56	3.39	4.78						
ARD of all (%)			2.07						

The relative differences (Δ_r) and their average (ARD) were computed for each specimen to show the variation between the mean value of all ratios of equilibrium times during the drying SWCC tests observed in the laboratory tests and numerical modeling for all measurement apparatuses. For all specimens obtained using various measurement apparatuses, the relative difference (Δ_r) is observed to vary between 0.17% and 4.78% with an average (ARD) of 2.07%. All relative differences (Δ_r) and their average (ARD) are less than 20% for all specimens, indicating good agreement between the results from the laboratory tests and numerical modeling on the ratio of equilibrium times during the drying SWCC tests obtained using various measurement apparatuses. This observation means that the ratio of equilibrium times during the drying SWCC tests in the laboratory are strongly supported by the numerical modeling.

6.6. Characteristics of the Wetting Soil-Water Characteristic Curve with regards to Hydraulic Anisotropy

Discussions of the characteristics of soil-water characteristic curve (SWCC) with regards to hydraulic anisotropy in the wetting path of unsaturated conditions for various specimens, as shown in Section 5.6, are presented in this section. The wetting SWCC tests were carried out directly after completion of the drying SWCC tests for each specimen, as explained in Section 4.1.6, using various measurement apparatuses. The main characteristic to be observed was whether the wetting SWCC is a scalar property of a soil considering different wetting hydraulic anisotropy values, initial compaction conditions and mica contents. The statistical coefficient of determination (R^2), as described in Section 4.3, was used as the criteria for understanding the scalar property of the wetting SWCC.

In addition, a comparison between the ratio of equilibrium times measured during the wetting SWCC tests using various measurement apparatuses and the hydraulic anisotropy value measured under the saturated conditions was performed for each specimen, which has not been discussed in Section 6.3 (50S50K (A), 50S50K (D) with heights of 30 mm and 50 mm and specimens with 20% coarse mica). The relative differences (Δ_r) and their average (ARD), as described in Section 4.3, were used to show the correlation between the ratio of equilibrium times measured during the wetting SWCC tests and the hydraulic anisotropy measured under the saturated conditions, similar to the analyses performed in Section 6.3.

The measured wetting SWCC of each specimen was best-fitted using Equation 2.14 since all specimens, i.e. 50S50K (A), 50S50K (B), 50S50K (C), 50S50K (D), specimens with 9% coarse mica and specimens with 20% coarse mica, have the unimodal wetting SWCC data, as presented in Section 5.6. Table 6.54 shows the unimodal fitting parameters of Equation 2.14 for the wetting SWCC data of 50S50K

(A) obtained using the Tempe cell and pressure plate apparatuses. Table 6.55 shows the unimodal fitting parameters of Equation 2.14 for the wetting SWCC data of 50S50K (B) obtained using all measurement apparatuses. Figure 6.23 – Figure 6.25 in Section 6.3 illustrate best fitting for the measured wetting SWCC data of 50S50K (B) based on the respective Tempe cell and pressure plate, modified triaxial SWCC and unsaturated triaxial permeameter measurements. Table 6.56 shows the unimodal fitting parameters of Equation 2.14 for the wetting SWCC data of 50S50K (C) obtained using all measurement apparatuses. Figure 6.26 – Figure 6.28 in Section 6.3 illustrate best fitting for the measured wetting SWCC data of 50S50K (C) based on the respective Tempe cell and pressure plate, modified triaxial SWCC and unsaturated triaxial permeameter measurements. Table 6.57 shows the unimodal fitting parameters of Equation 2.14 for the wetting SWCC data of 50S50K (D) obtained using the Tempe cell and pressure plate apparatuses. Table 6.58 shows the unimodal fitting parameters of Equation 2.14 for the wetting SWCC data of specimens with 9% coarse mica obtained using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses. Figure 6.29 and Figure 6.30 in Section 6.3 illustrate best fitting for the measured wetting SWCC data of specimens with 9% coarse mica based on the respective modified triaxial SWCC and unsaturated triaxial permeameter measurements. Table 6.59 shows the unimodal fitting parameters of Equation 2.14 for the wetting SWCC data of specimens with 20% coarse mica obtained using the modified triaxial SWCC apparatus. All figures illustrating best fitting for the wetting SWCC data of each specimen which has not been discussed in Section 6.3 (50S50K (A), 50S50K (D) with heights of 30 mm and 50 mm and specimens with 20% coarse mica) are presented in Appendix B.

Table 6.54 Unimodal fitting parameters of the measured wetting SWCC data of 50S50K (A) and the summarized R^2 analyses

Fitting parameters	TC&PP	
	HL	VL
θ_s	0.288	0.297
a (kPa)	21.353	20.842
n	2.532	2.678
m	0.730	0.712
R^2 (HL data)	0.998	0.994
R^2 (VL data)	0.999	0.999

Table 6.55 Unimodal fitting parameters of the measured wetting SWCC data of 50S50K (B) and the summarized R^2 analyses

Fitting parameters	TC&PP		Triaxial		Permeameter	
	HL	VL	HL	VL	HL	VL
θ_s	0.266	0.271	0.255	0.244	0.249	0.235
a (kPa)	24.992	24.701	23.142	23.673	28.772	28.122
n	2.467	2.322	2.405	2.557	2.245	2.240
m	0.794	0.791	0.786	0.799	1.031	0.985
R^2 (HL Tempe)	0.998	0.993	0.982	0.943	0.959	0.905
R^2 (VL Tempe)	0.990	0.997	0.976	0.934	0.944	0.888
R^2 (HL Triaxial)	0.984	0.967	0.999	0.984	0.985	0.957
R^2 (VL Triaxial)	0.949	0.921	0.987	0.999	0.993	0.989
R^2 (HL Permeameter)	0.919	0.920	0.958	0.983	0.997	0.984
R^2 (VL Permeameter)	0.915	0.881	0.962	0.991	0.986	0.999

Table 6.56 Unimodal fitting parameters of the measured wetting SWCC data of 50S50K (C) and the summarized R^2 analyses

Fitting parameters	TC&PP		Triaxial		Permeameter	
	HL	VL	HL	VL	HL	VL
θ_s	0.341	0.348	0.321	0.321	0.309	0.321
a (kPa)	34.960	33.824	28.659	27.581	23.641	24.255
n	3.197	3.251	4.417	4.567	5.294	4.742
m	0.901	0.879	0.680	0.626	0.512	0.570
R^2 (HL Tempe)	0.998	0.997	0.947	0.945	0.847	0.904
R^2 (VL Tempe)	0.998	0.997	0.954	0.952	0.861	0.917
R^2 (HL Triaxial)	0.950	0.944	0.997	0.996	0.968	0.986
R^2 (VL Triaxial)	0.950	0.944	0.997	0.997	0.974	0.991
R^2 (HL Permeameter)	0.891	0.884	0.975	0.979	0.999	0.993
R^2 (VL Permeameter)	0.923	0.918	0.989	0.993	0.993	0.999

Table 6.57 Unimodal fitting parameters of the measured wetting SWCC data of 50S50K (D) and the summarized R^2 analyses

Fitting parameters	30 mm height		50 mm height	
	HL	VL	HL	VL
θ_s	0.432	0.425	0.429	0.412
a (kPa)	27.236	28.102	29.846	29.664
n	2.432	2.507	2.459	2.486
m	0.947	0.899	0.904	0.868
R^2 (HL 30 mm)	0.999	0.997	0.991	0.986
R^2 (VL 30 mm)	0.997	0.998	0.995	0.993
R^2 (HL 50 mm)	0.992	0.996	1.000	0.992
R^2 (VL 50 mm)	0.989	0.994	0.992	0.998

Table 6.58 Unimodal fitting parameters of the measured wetting SWCC data of specimen with 9% coarse mica and the summarized R^2 analyses

Fitting parameters	Triaxial		Permeameter	
	HL	VL	HL	VL
θ_s	0.279	0.287	0.287	0.285
a (kPa)	62.177	60.459	62.337	60.194
n	1.527	1.538	1.503	1.550
m	1.760	1.736	1.915	1.860
R^2 (HL Triaxial)	0.997	0.995	0.995	0.995
R^2 (VL Triaxial)	0.984	0.997	0.989	0.990
R^2 (HL Permeameter)	0.988	0.990	0.993	0.992
R^2 (VL Permeameter)	0.987	0.988	0.992	0.992

Table 6.59 Unimodal fitting parameters of the measured wetting SWCC data of specimen with 20% coarse mica and the summarized R^2 analyses

Fitting parameters	Triaxial	
	HL	VL
θ_s	0.297	0.290
a (kPa)	26.990	28.681
n	1.564	1.616
m	0.838	0.876
R^2 (HL data)	0.998	0.991
R^2 (VL data)	0.990	0.997

The coefficient of determination (R^2) analyses were calculated similar to those in Section 6.5 in order to achieve the best fitting parameters for each orientation (HL and VL) of the wetting SWCC obtained using each measurement apparatus. Correlations between the measured wetting SWCC data in each orientation using each measurement apparatus can be observed by applying a set of the best fitting parameters to the wetting SWCC data measured in different orientations or using different apparatuses. For 50S50K (A) obtained using the Tempe cell and pressure plate apparatuses, R^2 value is observed to vary between 0.994 and 0.999. For 50S50K (B) obtained using all measurement apparatuses, R^2 value varies between 0.881 and 0.999. For 50S50K (C) obtained using all measurement apparatuses, R^2 value varies between 0.847 and 0.999. For 50S50K (D) with heights of 30 mm and 50 mm obtained using the Tempe cell and pressure plate apparatuses, R^2 value varies between 0.986 and 1.000. For specimens with 9% coarse mica obtained using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses, R^2 value varies

between 0.984 and 0.997. For specimens with 20% coarse mica obtained using the modified triaxial SWCC apparatus, R^2 value varies between 0.990 and 0.998. It is observed that for each specimen, the lowest R^2 value is calculated when the best fitting parameters based on the Tempe cell and pressure plate measurements are applied to the data obtained using the modified triaxial SWCC or unsaturated triaxial permeameter apparatus, and vice versa. This observation can be related to the fact that there was 25 kPa net confining pressure in the SWCC measurement using the modified triaxial SWCC and unsaturated triaxial permeameter apparatuses, unlike zero confining pressure in the corresponding SWCC measurement using the Tempe cell and pressure plate apparatuses. Nonetheless, all R^2 values are notably still very high (close to unity) for each specimen. This observation means that, for each specimen, the wetting SWCC should be considered as a scalar property of the soil regardless the layering orientation (HL or VL), measurement apparatus (Tempe cell, pressure plate, modified triaxial SWCC or unsaturated triaxial permeameter), specimen height (30 mm or 50 mm), initial conditions (dry or wet of optimum) or mica content (with or without mica). This observed scalar characteristic of the wetting SWCC supports the observation of consistent wetting hydraulic anisotropy values discussed in Section 6.3 and the scalar characteristic of the drying SWCC discussed in Section 6.5. If the wetting SWCC is scalar, i.e. different orientation can be best-fitted reasonably well using an identical set of parameters regardless the measurement apparatus, constant values of hydraulic anisotropy throughout the wetting path of unsaturated conditions will be estimated using Equation 3.4.

There were different equilibrium times for each HL and VL orientation of a given specimen observed during the wetting SWCC tests at the application of matric suction up to 20 kPa, as shown in Figure 5.28. A comparison between the ratio of equilibrium

times measured during the wetting SWCC tests using various measurement apparatuses and the hydraulic anisotropy measured under the saturated conditions was performed for each specimen, which has not been discussed in Section 6.3 (50S50K (A), 50S50K (D) with heights of 30 mm and 50 mm and specimens with 20% coarse mica). The value of hydraulic anisotropy measured under the saturated conditions was used as point of reference for each specimen because no measurement of hydraulic anisotropy was performed following the drying and wetting paths of unsaturated conditions due to time consideration. According to the discussion in Section 6.4, the hydraulic anisotropy measured under the saturated conditions was very similar to the values measured in the drying path of unsaturated conditions. The values of hydraulic anisotropy measured in the wetting path is about 80% (78.72%, to be exact) of the values of hydraulic anisotropy measured in the drying path of unsaturated conditions, as shown in Table 6.39.

Table 6.60 shows the equilibrium times observed during the wetting SWCC test using the Tempe cell and pressure plate apparatuses compared to the hydraulic anisotropy measured under the saturated conditions for 50S50K (A). Table 6.61 shows the equilibrium times observed during the wetting SWCC test using the Tempe cell and pressure plate apparatuses compared to the hydraulic anisotropy measured under the saturated conditions for 50S50K (D) with a height of 30 mm. Table 6.62 shows the equilibrium times observed during the wetting SWCC test using the Tempe cell and pressure plate apparatuses compared to the hydraulic anisotropy measured under the saturated conditions for 50S50K (D) with a height of 50 mm. Table 6.63 shows the equilibrium times observed during the wetting SWCC test using the modified triaxial SWCC apparatus compared to the hydraulic anisotropy measured under the saturated conditions for specimens with 20% coarse mica.

Table 6.60 Ratio of equilibrium times observed during the wetting SWCC test compared to the measured hydraulic anisotropy under the saturated conditions for 50S50K (A)

Matric suction (kPa)	$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL}/t_{eq, VL}$)	Δ_r (%)
200	156.03	109.94	1.42	1.83
90	57.48	41.39	1.39	0.36
75	16.02	11.48	1.40	0.13
50	14.80	10.69	1.38	0.66
35	12.07	8.72	1.38	0.68
20	10.51	7.56	1.39	0.25
		Average	1.39	0.65
Measured hydraulic anisotropy			1.80	
Ratio (%)			77.43%	

Table 6.61 Ratio of equilibrium times observed during the wetting SWCC test compared to the measured hydraulic anisotropy under the saturated conditions for 50S50K (D) with a 30 mm height

Matric suction (kPa)	$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL}/t_{eq, VL}$)	Δ_r (%)
200	217.88	66.31	3.29	4.66
90	69.25	21.76	3.18	1.37
75	31.98	10.65	3.00	4.35
50	22.03	7.01	3.14	0.10
35	16.76	5.24	3.20	1.88
20	12.49	4.13	3.02	3.67
		Average	3.14	2.67
Measured hydraulic anisotropy			3.93	
Ratio (%)			79.88%	

Table 6.62 Ratio of equilibrium times observed during the wetting SWCC test compared to the measured hydraulic anisotropy under the saturated conditions for 50S50K (D) with a 50 mm height

Matric suction (kPa)	$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL}/t_{eq, VL}$)	Δ_r (%)
200	571.93	178.41	3.21	2.15
90	154.53	48.72	3.17	1.06
75	52.87	17.15	3.08	1.77
50	44.22	13.81	3.20	2.03
35	31.71	10.11	3.14	0.06
20	24.10	7.95	3.03	3.41
		Average	3.14	1.75
Measured hydraulic anisotropy			4.04	
Ratio (%)			77.68%	

Table 6.63 Ratio of equilibrium times observed during the wetting SWCC test compared to the measured hydraulic anisotropy under the saturated conditions for specimens with 20% coarse mica

Matric suction (kPa)	$t_{eq, HL}$ (h)	$t_{eq, VL}$ (h)	Ratio ($t_{eq, HL}/t_{eq, VL}$)	Δ_r (%)
200	134.86	90.33	1.49	7.06
90	47.02	37.33	1.26	9.67
75	39.61	27.33	1.45	3.94
50	30.08	20.85	1.44	3.46
35	25.43	17.94	1.42	1.64
20	20.66	15.83	1.31	6.42
		Average	1.39	5.36
Measured hydraulic anisotropy			1.81	
Ratio (%)			77.05%	

The relative differences (Δ_r) and their average (ARD) were computed for each specimen to show the variation between the measured ratio of equilibrium times at each application of matric suction and the mean value of all ratios of equilibrium times measured during the wetting SWCC test as well as the correlation between the mean value of all ratios of equilibrium times measured during the wetting SWCC test and the hydraulic anisotropy measured under the saturated conditions. For 50S50K (A), the relative difference (Δ_r) of the ratio of equilibrium times at each application of matric suction compared to its mean is observed to vary between 0.13% and 1.83% with an average (ARD) of 0.65%, whereas the mean ratio of equilibrium times during the wetting SWCC tests is observed to be smaller (77.43%) compared to the hydraulic

anisotropy measured under the saturated conditions. For 50S50K (D) with a height of 30 mm, the relative difference (Δ_r) of the ratio of equilibrium times at each application of matric suction compared to its mean varies between 0.10% and 4.66% with an average (ARD) of 2.67%, whereas the mean ratio of equilibrium times during the wetting SWCC tests is smaller (79.88%) compared to the hydraulic anisotropy measured under the saturated conditions. For 50S50K (D) with a height of 50 mm, the relative differences (Δ_r) of the ratio of equilibrium times at each application of matric suction compared to its mean varies between 0.06% and 3.41% with an average (ARD) of 1.75%, whereas the mean ratio of equilibrium times during the wetting SWCC tests is smaller (77.68%) compared to the hydraulic anisotropy measured under the saturated conditions. For specimens with 20% coarse mica, the relative difference (Δ_r) of the ratio of equilibrium times at each application of matric suction compared to its mean varies between 1.64% and 9.67% with an average (ARD) of 5.36%, whereas the mean ratio of equilibrium times during the wetting SWCC tests is smaller (77.05%) as compared to the hydraulic anisotropy measured under the saturated conditions. All relative differences (Δ_r) and their average (ARD) are less than 20% for all specimens (regardless the initial conditions or mica content), indicating reliably consistent ratio of equilibrium times measured during the wetting SWCC tests as well as reliably smaller (78.01%, on average) ratio of equilibrium times during the wetting SWCC tests compared to the hydraulic anisotropy measured under the saturated conditions. These observations support the consistent behavior of ratio of equilibrium times measured during the wetting SWCC tests discussed in Section 6.3 as well as the smaller values of ratio of equilibrium times measured during the wetting SWCC tests (almost 80%) compared to those measured during the drying SWCC tests discussed in Section 6.4.

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

In this chapter, the conclusions drawn from the research are presented. Recommendations for future studies of this research topic are subsequently presented. Lastly, publications resulting from this research are listed.

7.1. Conclusions

The main conclusions drawn from this research are as follows:

1. Based on reviews of the relevant literature performed in this research, it was concluded that there were no comprehensive laboratory measurements of hydraulic anisotropy behavior of soils, especially under the unsaturated conditions. Direct and indirect laboratory measurements on hydraulic anisotropy behavior of soils under the saturated and unsaturated conditions were performed in this research.
2. A conceptual framework on hydraulic anisotropy behavior was developed in this research. The conceptual framework demonstrates the isotropic behavior of SWCC and the anisotropic behavior of unsaturated permeability with distinct equilibrium time behavior. The framework contributes to new understanding of hydraulic anisotropy behavior following drying and wetting paths of unsaturated conditions. By understanding the framework, an engineering expectation of the hydraulic anisotropy behavior can be developed and it will be helpful in interpreting the observed hydraulic anisotropy as discussed in Chapter 6.
3. The experimental results show that the initial compaction conditions and mica content of the specimen can affect the hydraulic anisotropy measured under

the saturated conditions. It was concluded that a high hydraulic anisotropy under the saturated conditions is achieved when a specimen has a high initial dry density, is compacted at a wet of optimum water content and has a moderate amount of coarse mica.

4. In the drying path of unsaturated conditions, both the direct measurement using permeability tests and the indirect determination from the corresponding drying SWCC tests agree on the observed hydraulic anisotropy values, which are consistent for all applied matric suctions. Moreover, the ratio of equilibrium times between horizontal-layering (HL) and vertical-layering (VL) specimens measured during the drying unsaturated permeability and SWCC tests reasonably reflects the hydraulic anisotropy measured at the corresponding matric suction. These behaviors are observed in the drying path of unsaturated conditions for each specimen, regardless the initial conditions (dry or wet of optimum), mica content (with or without mica), shape of the measured data (unimodal or bimodal) or measurement apparatus (Tempe cell, pressure plate, modified triaxial SWCC or unsaturated triaxial permeameter).
5. In the wetting path of unsaturated conditions, both the direct measurement using permeability tests and the indirect determination from the corresponding wetting SWCC tests agree on the observed hydraulic anisotropy values, which are consistent for all applied matric suctions. Moreover, the ratio of equilibrium times between HL and VL specimens measured during the wetting unsaturated permeability and SWCC tests reasonably reflects the hydraulic anisotropy measured at the corresponding matric suction. These behaviors are observed in the wetting path of unsaturated conditions for each specimen, regardless the initial conditions (dry or wet of optimum), mica content (with or

without mica) or measurement apparatus (Tempe cell, pressure plate, modified triaxial SWCC or unsaturated triaxial permeameter).

6. By comparing the experimental results of hydraulic anisotropy under the saturated conditions and following the drying and wetting paths of unsaturated conditions obtained using direct measurement and indirect determination methods, it was concluded that similar hydraulic anisotropy values are observed under the saturated conditions and drying path of unsaturated conditions. Smaller (almost 80%) values of hydraulic anisotropy are observed in the wetting path compared to those observed in the drying path of unsaturated conditions. In addition, the smaller values of hydraulic anisotropy observed in the wetting path compared to the drying path are reflected in the smaller (almost 80%) ratio of equilibrium times during the wetting tests compared to the corresponding drying tests.
7. It was concluded that the drying SWCC is a scalar property (independent of the layering orientation) of the soil regardless the initial conditions (dry or wet of optimum), mica content (with or without mica), shape of the measured data (unimodal or bimodal) or measurement apparatus (Tempe cell, pressure plate, modified triaxial SWCC or unsaturated triaxial permeameter). In addition, the numerical modeling results had good agreement with the experimental results on the ratio of equilibrium times between HL and VL orientations during the drying SWCC tests, reflecting the hydraulic anisotropy of the soil.
8. It was concluded that the wetting SWCC is a scalar property (independent of the layering orientation) of the soil regardless the initial conditions (dry or wet of optimum), mica content (with or without mica) or measurement apparatus (Tempe cell, pressure plate, modified triaxial SWCC or unsaturated triaxial

permeameter). In addition, the experimental results on the ratio of equilibrium times between HL and VL orientations during the wetting SWCC tests show smaller (almost 80%) values compared to the hydraulic anisotropy measured under the saturated conditions, similar to the results of comparing hydraulic anisotropy values under the saturated conditions and following the drying and wetting paths of unsaturated conditions.

7.2. Recommendations

Based on the work performed in this research, recommendations for future studies are as follows:

1. The observed hydraulic anisotropy behavior can be further verified by large-scale laboratory testing of homogeneously compacted soils as well as natural soils. Subsequently, the observed hydraulic anisotropy behavior can be applied to improve the current slope cover systems.
2. New measurement apparatuses for the complete drying and wetting hydraulic anisotropy tests, i.e. saturated and unsaturated permeability tests as well as SWCC tests, can be developed to expedite the testing durations.
3. The numerical modeling of SEEP/W and AIR/W packages of GeoStudio software can be improved by investigating and incorporating bimodal water and air permeability functions from the corresponding SWCC, as well as by defining hysteretic phenomena (drying and wetting cycle) for further verification of the research.

7.3. Publications

The following publications resulted from this research:

1. Priono, Rahardjo, H., Chatterjea, K., Leong, E.C., Wang, J.Y. 2016a. Effect of hydraulic anisotropy on soil-water characteristic curve. *Soils and Foundations*, 56(2):228-239.
2. Priono, Rahardjo, H., Leong, E.C., Chatterjea, K. 2016b. Effects of mica content on hydraulic anisotropy of unsaturated soil. *12th International Symposium on Landslides*, Naples, Italy.
3. Priono, Rahardjo, H., Chatterjea, K., Leong, E.C. 2016c. Laboratory investigation on hydraulic anisotropy behavior of unsaturated soil. *Canadian Geotechnical Journal*, under review.
4. Priono, Rahardjo, H., Leong, E.C., Wang, J.Y., Chatterjea, K. 2013. Improved correction factor for indirect determination of permeability function. *Coupled Phenomena in Environmental Geotechnics*, Turin, Italy.
5. Janiardy, K., Rahardjo, H., Priono. 2016d. Theoretical analysis and numerical modeling of hydraulic anisotropy behavior of unsaturated soil. *Proceedings of URECA 2015-16*, Nanyang Technological University, Singapore.
6. Tikno, N., Rahardjo, H., Priono. 2016e. Investigating hydraulic anisotropy behavior of unsaturated soils through laboratory experiments. *Proceedings of URECA 2015-16*, Nanyang Technological University, Singapore.
7. Janiardy, K., Rahardjo, H., Priono. 2015. Effect of basic soil properties on hydraulic anisotropy of homogeneous soil. *Proceedings of URECA 2014-15*, Nanyang Technological University, Singapore.

REFERENCES

ASTM D2434-68. 2006. Standard test method for permeability of granular soils (constant head). *Annual books of ASTM Standard*, ASTM International, West Conshohocken, PA.

ASTM D2487-11. 2011. Standard practice for classification of soils for engineering purposes (Unified Soil Classification System). *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA.

ASTM D422-63e2. 2007. Standard test method for particle-size analysis of soils. *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA.

ASTM D4318-10e1. 2010. Standard test methods for liquid limit, plastic limit, and plasticity index of soils. *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA.

ASTM D5084-10. 2010. Standard test methods for measurement of hydraulic conductivity of saturated porous materials using a flexible wall permeameter. *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA.

ASTM D698-12e1. 2012. Standard test methods for laboratory compaction characteristics of soil using standard effort. *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA.

ASTM D7664-10. 2010. Standard test methods for measurement of hydraulic conductivity of unsaturated soils. *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA.

ASTM D854-14. 2014. Standard test methods for specific gravity of soil solids by water pycnometer. *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA.

Aitchison, G.D. 1965. Moisture equilibria and moisture changes in soils beneath covered areas. *Symposium*, 47-52.

Assoluine, S. and Or, D. 2006. Anisotropy factor of saturated and unsaturated soils. *Water Resources Research*, 42, W12403.

Aubertin, M., Cifuentes, E., Apithy, S.A., Bussiere, B., Molson, J., Chapuis, R.P. 2009. Analyses of water diversion along inclined covers with capillary barrier effects. *Canadian Geotechnical Journal*, 46:1146-1164.

- Aubertin, M., Richard, J.-F., Chapuis, R.P. 1998. A predictive model for the water retention curve: Application to tailings from hard-rock mines. *Canadian Geotechnical Journal*, 35:55-69.
- Basak, P. 1972. Soil structure and its effects on hydraulic conductivity. *Soil Science*, 114(6): 417-422.
- Baver, L.D., Gardner, W.H., Gardner, W.R. 1972. *Soil physics*. New York : Wiley.
- Ba-Te, Zhang, L., Fredlund, D.G. 2005. A general air-phase permeability function for airflow through unsaturated soils. *Geo-Frontiers*, 2961-2985.
- Bear, J. and Cheng, A.H.D. 2010. *Modeling groundwater flow and contaminant transport*. New York: Springer.
- Bear, J. and Verruijt, A. 1987. *Modeling groundwater flow and pollution*. Netherlands: Springer.
- Birle, E., Heyer, D., Vogt, N. 2008. Influence of the initial water content and dry density on the soil-water retention curve and the shrinkage behavior of a compacted clay. *Acta Geotechnica*, 3(3): 191–200.
- Bishop, A.W. and Blight, G.E. 1963. Some aspects of effective stress under the saturated and partly saturated soils. *Geotechnique*, 13:177-197.
- Bishop, A.W. and Donald, L.B. 1961. The experimental study of partly saturated soil in the triaxial apparatus. *5th International Conference of Soil Mechanics Foundation Engineering*, Paris, France.
- Blonquist, J.M., Robinson, D.A., Humphries, S.D., Jones, S.B. 2011. Improved dielectric and electrical conductivity anisotropy measurements using TDR in unsaturated mica. *Vadose Zone Journal*, 10:1097-1104.
- Bo, M.W., Arulrajah, A., Sukmak, P. and Horpibulsuk, S. 2015. Mineralogy and geotechnical properties of Singapore marine clay at Changi. *Soils and Foundations*, 55(3):600–613.
- Brooks, R.H. and Corey, A.T. 1964. Hydraulic properties of porous media. *Hydrology Paper*, No. 3, Colorado State University, Fort Collins, Colorado, USA.
- Bussiere, B. 2007. Colloquium 2004: Hydrogeotechnical properties of hard rock tailings from metal mines and emerging geoenvironmental disposal approaches. *Canadian Geotechnical Journal*, 44 (9):1019-1052.
- Chapuis, R.P and Gill, D.E. 1989. Hydraulic anisotropy of homogeneous soils and rocks: influence of the densification process. *Engineering Geology*, 39:75-86.

- Chapuis, R.P., Gill, D.E., Baass, K. 1989. Laboratory permeability tests on sand: influence of the compaction method on anisotropy. *Canadian Geotechnical Journal*, 26:614-622.
- Chatterjea, K. 1989. Observations on the fluvial and slope processes in Singapore and their impact on the urban environment. *PhD Thesis*, National University of Singapore, Singapore.
- Childs, E. C. 1969. *An introduction to the physical basis of soil water phenomena*. New York: Wiley Interscience.
- Childs, E.C. and Collis-George, G.N. 1950. The permeability of porous materials. *Proceedings of the Royal Society*, 210A:392–405.
- Cho, G.C., Dodds, J., Santamarina, J.C. 2006. Particle shape effects on packing density, stiffness and strength: natural and crushed sands. *Journal of Geotechnical and Geoenvironmental Engineering*, 132(5):591-602.
- Cui, Y.J. 1993. Etude du comportement d'un limon compacté non saturé et sa modélisation dans un cadre élasto-plastique. *PhD Thesis*, CERMES-ENPC, Paris, France.
- Darcy, H. 1856. *Les fontaines publiques de la ville de Dijon*. Paris: Dalmont.
- Edlefsen, N.E. and Anderson, A.B.C. 1943. Thermodynamics of soil moisture. *Hilgardia*, 15:31-298.
- Evangelista, A., Nicotera, M.V., Papa, R., Urciuoli, G. 2008. Field investigation on triggering mechanisms of fast landslides in unsaturated pyroclastic soils. *1st European Conference on Unsaturated Soils*, Durham, UK.
- Fredlund, D.G. 2006. Unsaturated soil mechanics in engineering practise. *Journal of Geotechnical and Geoenvironmental Engineering*, 132(3):286-321.
- Fredlund, D.G. and Morgenstern, N.R. 1977. Stress state variables for unsaturated soils. *Journal of Geotechnical Engineering*, 103(5):447-466.
- Fredlund, D.G. and Rahardjo, H. 1993. *Soil mechanics for unsaturated soils*. New York: John Wiley and Sons Inc.
- Fredlund, D.G., Rahardjo, H., Fredlund, M.D. 2012. *Unsaturated soil mechanics in engineering practice*. New York: Wiley-Interscience.
- Fredlund, M.D., Wilson, G.W., Fredlund, D.G. 2002. Use of the grain-size distribution for estimation of the soil-water characteristic curve. *Canadian Geotechnical Journal*, 39:103–1117.

- Fredlund, D.G. and Xing, A. 1994. Equations for the soil–water characteristic curve. *Canadian Geotechnical Journal*, 31:521–532.
- Fredlund, D.G., Xing, A., Huang, S. 1994. Predicting the permeability function for unsaturated soils using the soil-water characteristic curve. *Canadian Geotechnical Journal*, 31:533-546.
- Friedman, S.P. and Jones, S.B. 2001. Measurement and approximate critical path analysis of the pore-scale-induced anisotropy factor of an unsaturated porous medium. *Water Resources Research*, 37:2929–2942.
- Friedman, S.P. and Seaton, N.A. 1996. On the transport properties of anisotropic networks of capillaries. *Water Resources Research*, 32:339–347.
- Fujibe, F. 2008. Long-term changes in precipitation in Japan. *Journal of Disaster Research*, 3(1):51-52.
- Fung, Y.C. 1977. *A first course in continuum mechanics*. New Jersey: Prentice-Hall.
- Gallant, A.J.E., Hennessy, K.J., Risbey, J. 2007. Trends in rainfall indices for six Australian regions: 1910-2005. *Australian Meteorological Magazine*, 56:223-239.
- Gardner, W.R. 1956. Calculation of capillary conductivity from pressure plate outflow data. *Soil Science Society of America Journal*, 20(3): 317-320.
- Gardner, W.R. 1958. Mathematics of isothermal water conduction in unsaturated soil. *37th Annual Meeting of the Highway Research Board*, Washington D.C., USA.
- Goh, S.G., Rahardjo, H., Leong, E.C. 2010. Shear strength equations for unsaturated soil under drying and wetting. *Journal of Geotechnical and Geoenvironmental Engineering*, 136(4):594-606.
- Goh, S.G., Rahardjo, H., Leong, E.C. 2015. Modification of triaxial apparatus for permeability measurement of unsaturated soils. *Soils and Foundations*, 55(1):63-73.
- Graham, J. and Houlsby, G.T. 1983. Anisotropic elasticity of a natural clay. *Geotechnique*, 33(2):165–180.
- Harnas, F.R., Rahardjo, H., Leong, E.C., Wang, J.Y. 2014. Experimental study on dual capillary barrier using recycled asphalt pavement materials. *Canadian Geotechnical Journal*, 51(10): 1165-1177.

- Harris, W.G., Parker, J.C., Zelazny, L.W. 1984. Effects of mica content on the engineering properties of sand. *Soil Science Society of America Journal*, 48(3):501-505.
- Head, K.H. 1998. Manual of soil laboratory testing: Effective stress tests. New York: Wiley.
- Hight, D.W. 1998. Anisotropy in soils - its measurement and practical implications. 2nd GRC Lecture, Nanyang Technological University, Singapore.
- Hilf, J.W. 1956. An investigation of pore-water pressure in compacted cohesive soils. *PhD Thesis*, United States Department of the Interior Bureau of Reclamation, Denver, USA.
- Hillel, D. 1982. *Introduction to soil physics*. New York: Academic Press.
- Hillel, D. 1998. *Environmental soil physics*. San Diego: Academic Press.
- Ho, D.Y.F. 1988. The relationship between the volumetric deformation moduli of unsaturated soils. *PhD Thesis*, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.
- Hu, M., O'Sullivan, C., Jardine, R. R. and Jiang, M. 2010: Stress-induced anisotropy in sand under cyclic loading. *Granular Matter*, 12:469–476.
- Huang, S., Fredlund, D.G., Barbour, S.L. 1998. Measurement of the coefficient of permeability for a deformable unsaturated soil using a triaxial permeameter. *Canadian Geotechnical Journal*, 35: 426-432.
- Hwang, S. and Powers, S.E. 2003. Using particle-size distribution models to estimate soil hydraulic properties. *Soil Science Society America Journal*, 67:1103–1112.
- Janssen, D.J. and Dempsey, B.J. 1980. Soil water properties of subgrade soils. *Final Report*, 1 July 1977 – 31 December 1979, Department of Civil Engineering, University of Illinois, Urbana-Champaign, USA.
- Klute, A. 1965. Laboratory measurement of hydraulic conductivity of unsaturated soils. *Methods of Soil Analysis Monograph*, Part 1 (9), American Society of Agronomy, Madison, USA.
- Knackstedt, M.A. and Zhang, X. 1994. Direct evaluation of length scales and structural parameters associated with flow in porous media. *Physical Review E*, 50(3):2134–2138

- Krisdani, H., Rahardjo, H., Leong, E.C. 2006. Experimental study of 1-D capillary barrier model using geosynthetic material as the coarse-grained layer. 4th *International Conference on Unsaturated Soils, ASCE*, Phoenix, USA.
- Krisdani, H., Rahardjo, H., Leong, E.C. 2009. Use of instantaneous profile and statistical methods to determine permeability functions of unsaturated soils. *Canadian Geotechnical Journal*, 46(7): 869-874.
- Krumbein, W.C. and Sloss, L.L. 1963. *Stratigraphy and sedimentation*. San Francisco: Freeman and Company.
- Kunkel, K.E. 2003. North American trends in extreme precipitation. *Natural Hazards*, 29: 291–305.
- Kunze, R.J., Uehara, G., Graham, K. 1968. Factors important in the calculation of hydraulic conductivity. *Soil Science Society of America Proceedings*, 32:760–765.
- Lambe, T.W. and Whitman, R.V. 1979. *Soil mechanics*. New York: John Wiley and Sons Inc.
- Lee, J.S., Guimaraes, M., Santamarina, J.C. 2007. Micaceous sands: microscale mechanisms and macroscale response. *Journal of Geotechnical and Geoenvironmental Engineering*, 133(9):1136-1143.
- Leong, E.C. and Rahardjo, H. 1997a. Permeability functions for unsaturated soils. *Journal of Geotechnical and Geoenvironmental Engineering*, 123(12):1118–1126.
- Leong, E.C. and Rahardjo, H. 1997b. Review of soil–water characteristic curve equations. *Journal of Geotechnical and Geoenvironmental Engineering*, 123 (12):1106–1117.
- Leroueil, S. and Hight, D. W. 2002. Behaviour and properties of natural soils and soft rocks. *Characterisation and Engineering Properties of Natural Soils*, pp. 29-254.
- Lings, M.L., Pennington, D.S., Nash, D.F.T. 2000. Anisotropic stiffness parameters and their measurement in a stiff natural clay. *Géotechnique*, 50 (2):109–125.
- Li, X. and Zhang, L.M. 2009. Characterization of dual-structure pore-size distribution of soil. *Canadian Geotechnical Journal*, 46(2):129-141.
- Lu, N. and Likos, W.J. 2004. *Unsaturated soil mechanics*. New Jersey: John Wiley and Sons Inc.

- Marshall, T.J. and Holmes, J.W. 1988. *Soil physics*. New York: Cambridge University Press.
- Martin, R.T. 1962. Research on the physical properties of marine soils. *Soil Division Publication*, No. 127, Department of Civil Engineering, M.I.T.
- Meerdink, J., Benson, C., Khire, M.V. 1996. Unsaturated hydraulic conductivity of two compacted barrier soils. *Journal of Geotechnical Engineering*, 122(7): 565-576.
- Mendes, J. 2011. Assessment of the impact of climate change on an instrumented embankment: an unsaturated soil mechanics approach. *PhD Thesis*, Durham University.
- Meng, G-H. and Chu, J. 2011. The strength anisotropy of a residual soil in Singapore. *Geotechnical Engineering Journal of the SEAGS & AGSSEA*, 42(4):10-18.
- Mitchell, J.K. and Soga, K. 2005. *Fundamentals of soil behavior*. New York: John Wiley and Sons Inc.
- Mualem, Y. 1984. Anisotropy of unsaturated soils. *Soil Science Society of America Journal*, 48:505-509.
- National Environment Agency. 2010. Singapore.
- Ng, C.W.W., Springman, S.M., Alonso, E.E. 2008. Monitoring the performance of unsaturated soil slopes. *Geotechnical and Geological Engineering*, 26(6):799-816.
- Nishimura, S. 2014. Assessment of anisotropic elastic parameters of saturated clay measured in triaxial apparatus: Appraisal of techniques and derivation procedures. *Soils and Foundations*, 54(3):364–376.
- Oda, M., Nemat-Nasser, S., Konishi, J. 1985. Stress-induced anisotropy in granular masses. *Soils and Foundations*, 25(3): 85–97.
- Ong, B.H. 1999. Shear strength and volume change of unsaturated soil. *Master of Engineering Thesis*, Nanyang Technological University, Singapore.
- Papa, R., Evangelista, A., Nicotera, M.V., Urciuoli, G. 2008. Mechanical properties of unsaturated pyroclastic soils affected by fast landslide phenomena. *1st European Conference on Unsaturated Soils*, Durham, UK.
- Parker, J.C., Lenhard, R.J., Koppusamy, T. 1987. A parametric model for constitutive properties governing multiphase flow in porous media. *Water Resources Research*, 23(4):618-624.

- Pickering, D.J. 1970. Anisotropic elastic parameters for soils. *Géotechnique*, 20(3):271–276.
- Priono, Rahardjo, H., Chatterjea, K., Leong, E.C., Wang, J.Y. 2016a. Effect of hydraulic anisotropy on soil-water characteristic curve. *Soils and Foundations*, 56(2):228-239.
- Priono, Rahardjo, H., Leong, E.C., Chatterjea, K. 2016b. Effects of mica content on hydraulic anisotropy of unsaturated soil. *12th International Symposium on Landslides*, Naples, Italy.
- Priono, Rahardjo, H., Leong, E.C., Wang, J.Y., Chatterjea, K. 2013. Improved correction factor for indirect determination of permeability function. *Coupled Phenomena in Environmental Geotechnics*, Turin, Italy.
- Rahardjo, H., Li, X.W., Toll, D.G., Leong, E.C. 2001. The effect of antecedent rainfall on slope stability. *Journal of Geotechnical and Geological Engineering*, 19:371 - 399.
- Rahardjo, H., Satyanaga, A. Leong, E.C. 2007. Unsaturated soil mechanics for slope stability. *National Conference of Korean Geotechnical Society (KGS)*, Busan, South Korea.
- Rahardjo, H., Satyanaga, A. Leong, E.C. 2012a. Unsaturated soil mechanics for slope stabilization. *Southeast Asian Geotechnical Journal*, 43(1): 48-58.
- Rahardjo, H., Santoso, V.A., Leong, E.C., Ng, Y.S., Hua, C.J. 2012b. Performance of an instrumented slope covered by a capillary barrier system. *Journal of Geotechnical and Geoenvironmental Engineering*, 138 (4):481-490.
- Rahardjo, H., Satyanaga, A., D'Amore, G.A.R., Leong, E.C. 2012c. Soil-water characteristic curves of gap-graded soils. *Engineering Geology*, 125:102–107.
- Rahardjo, H., Satyanaga, A., Leong, E.C. 2013. Effects of flux boundary conditions on pore-water pressure distribution in slope. *Engineering Geology*, 165:133-142.
- Rahimi, A. and Rahardjo, H. 2016. New approach to improve soil-water characteristic curve to reduce variation in estimation of unsaturated permeability function. *Canadian Geotechnical Journal*, 53(4):717-725.
- Richards, L.A. 1931. Capillary conduction of liquids through porous mediums. *Physics*, 1(5):318-333.

- Richards, S.J. and Weeks, L.V. 1953. Capillary conductivity values from moisture yield and tension measurements on soil columns. *Soil Science Society of America Journal*, 17(3):206-209.
- Roth, K. and Hammel, K. 1996. Transport of conservative chemical through an unsaturated two-dimensional Miller-similar medium with steady state flow. *Water Resources Research*, 32(6):1653-1663.
- Samingan, A.S., Leong, E.C., Rahardjo, H. 2003. A flexible wall permeameter for measurements of water and air coefficients of permeability of residual soils. *Canadian Geotechnical Journal*, 40(3):559-574.
- Samingan, A.S., Leong, E.C., Rahardjo, H. 2005. Estimating permeability functions of Singapore residual soils. *Engineering Geology*, 78(1-2):119-133.
- Satyanaga, A., Rahardjo, H., Leong, E.C., Wang, J.Y. 2013. Water characteristic curve of soil with bimodal grain-size distribution. *Computer and Geotechnics*, 48:51-61.
- Scholes, O.N., Clayton, S.A., Hoadley, A.F.A. 2007. Permeability anisotropy due to consolidation of compressible porous media. *Transport Porous Media*, 68:365–387.
- Simunek, J., Angulo-Jaramillo, R., Schaap, M.G., Vandervaere, J.P., van Genuchten, M.Th. 1998. Using an inverse method to estimate the hydraulic properties of crusted soils from tension-disk infiltrometer data. *Geoderma*, 86(1): 61-81.
- Springman, S.M., Jommi, C., Teysserie, P. 2003. Instabilities on moraine slopes induced by loss of suction: a case history. *Geotechnique*, 53(1):3–10.
- Tami, D., Rahardjo, H., Leong, E.C., Fredlund, D.G. 2004. Design and laboratory verification of a physical model of sloping capillary barrier. *Canadian Geotechnical Journal*, 41(5):814–830.
- Tarantino, A. 2010. Unsaturated soils: compacted versus reconstituted states. *5th International Conference on Unsaturated Soil*, Barcelona, Spain.
- Tarantino, A. and Tombolato, S. 2005. Coupling of hydraulic and mechanical behaviour in unsaturated compacted clay. *Geotechnique*, 55(4):307-317.
- Terzaghi, K. 1943. *Theoretical soil mechanics*. New York: John Wiley.
- Toll, D.G. 1999. A data acquisition and control system for geotechnical testing. *Computing Developments in Civil and Structural Engineering*, 237-242.
- Towsend, R.M. and Rice, S.A. 1991. Molecular dynamic studies of the liquid-vapour interface of water. *Journal of Physical Chemistry*, 94(3):2207-2218.

- To-Viet, N., Min, T.-K., Shin, H. 2013. Using inverse analysis to estimate hydraulic properties of unsaturated sand from one-dimensional outflow experiments. *Engineering Geology*, 164:163-171.
- Ursino, N., Roth, K., Gimmi, T., Fluhner, H. 2000. Upscaling of anisotropy in unsaturated Miller-similar porous media. *Water Resources Research*, 36(2):421-430.
- Vanapalli, S.K., Fredlund, D.G., Pufahl, D.E. 1999. The influence of soil structure and stress history on the soil-water characteristics of a compacted till. *Geotechnique*, 49(2):143-159.
- van Genuchten, M.Th. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*, 44:892-898.
- Wheeler, S.J. and Sivakumar, V. 2000. Influence of compaction procedure on the mechanical behaviour of an unsaturated compacted clay. Part 2: Shearing and constitutive modelling. *Géotechnique*, 50(4): 369–376.
- Wyllie, M.R.J. and Gregory, A.R. 1955. Fluid flow through unconsolidated porous aggregates. *Industrial & Engineering Chemistry*, 47(7):1379–1388.
- Wyllie, M.R.J. and Rose, W.D. 1950. Application of the Kozeny equation to consolidated porous media. *Nature*, 165:972.
- Yang, H., Rahardjo, H., Leong, E.C., Fredlund, D.G. 2004. Factors affecting drying and wetting soil-water characteristic curves of sandy soils. *Canadian Geotechnical Journal*, 41(5):908-920.
- Zhai, P., Zhang, X., Wan, H., Pan, X. 2005. Trends in total precipitation and frequency of daily precipitation extremes over China. *Journal of Climate*, 18:1096-1108.

APPENDIX A

Appendix A contains figures illustrating best fitting for the measured drying SWCC data of each specimen which has not been presented in Section 6.2, i.e. 50S50K (A), 50S50K (D) with heights of 30 mm and 50 mm and specimens with 20% coarse mica.

Figure A.1 Best fitting for the measured drying SWCC data of 50S50K (A) based on the Tempe cell and pressure plate measurements

Figure A.2 Best fitting for the measured drying SWCC data of 50S50K (D) based on the Tempe cell and pressure plate measurements on 50S50K (D) with a 30 mm height

Figure A.3 Best fitting for the measured drying SWCC data of 50S50K (D) based on the Tempe cell and pressure plate measurements on 50S50K (D) with a 50 mm height

Figure A.4 Best fitting for the measured drying SWCC data of specimens with 20% coarse mica based on the modified triaxial SWCC measurements

APPENDIX B

Appendix B contains figures illustrating best fitting for the measured wetting SWCC data of each specimen which has not been presented in Section 6.3, i.e. 50S50K (A), 50S50K (D) with heights of 30 mm and 50 mm and specimens with 20% coarse mica.

Figure B.1 Best fitting for the measured wetting SWCC data of 50S50K (A) based on the Tempe cell and pressure plate measurements

Figure B.2 Best fitting for the measured wetting SWCC data of 50S50K (D) based on the Tempe cell and pressure plate measurements on 50S50K (D) with a 30 mm height

Figure B.3 Best fitting for the measured wetting SWCC data of 50S50K (D) based on the Tempe cell and pressure plate measurements on 50S50K (D) with a 50 mm height

Figure B.4 Best fitting for the measured wetting SWCC data of specimens with 20% coarse mica based on the modified triaxial SWCC measurements