



**UNIVERSITI PUTRA MALAYSIA**

**DENSITY MEASUREMENT OF COMPACTED ASPHALT MIXTURES  
USING NON-DESTRUCTIVE GROUND PENETRATING RADAR**

**MARDENI BIN ROSLEE**

**FK 2009 10**



**DENSITY MEASUREMENT OF COMPACTED ASPHALT MIXTURES USING  
NON-DESTRUCTIVE GROUND PENETRATING RADAR**

**By**

**MARDENI BIN ROSLEE**

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia,  
in Fulfilment of the Requirements for the Degree of Doctor of Philosophy**

**April 2009**



**Specially dedicated to my beloved:**

**Father, Mother,**

**Brother, Sisters,**

**Wife and Family,**

**and Friends.**



Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

**DENSITY MEASUREMENT OF COMPACTED ASPHALT MIXTURES USING  
NON-DESTRUCTIVE GROUND PENETRATING RADAR**

By

**MARDENI BIN ROSLEE**

**April 2009**

**Chairman : Raja Syamsul Azmir bin Raja Abdullah, PhD**

**Faculty : Engineering**

This thesis describes the development of Ground Penetrating Radar (GPR) system based on the electromagnetic wave reflection to determine the density of road pavement. The proposed method is simple, fast, non-destructive and within an acceptable accuracy of road pavement density. The theoretical analysis based on the three existing GPR Mixture Model (GMM) methods has been improved to produce the most optimized function to be incorporated within the proposed GPR system. The study involves three main procedures which are theoretical analysis, laboratory scale experimentation and reliability analysis. From these studies, the Lichtenecker Mixture Model is found to be the most accurate function compared to the other models like Nelson and Landau due to the smallest mean error between the prediction and the experimental result. During the laboratory experimentation, an engineering GPR prototype has been developed and used to measure the road pavement density of the road pavement slab sample. The GPR



system consists of the transmitter which is signal generator as a microwave source, horn antenna for transmitting and receiving the signal, directional coupler with an adapter and spectrum analyzer to analyze the received signal. Nine road pavement slabs of middle boundary and ten slabs of upper and lower boundary of Hot Mix Asphalt (HMA) gradation were developed and tested at four different frequencies within the range of 1.7-2.6 GHz. The predicted signal attenuation from the theoretical analysis is compared to the signal attenuation measured from the laboratory experimentation. The comparison produces the relative error between these two results and it is used in the optimization process. The finding from the optimization process suggested that three additional constant parameters which are Volume factor, Permittivity factor and Attenuation factor need to be included to improve the existing GMM model. A field test had been conducted as an outdoor reliability analysis to validate the optimized GMM model. From the field test, it shows that the proposed GPR system works well with an error range from 3.37 % to 4.72 % for nine locations. Finally, a complete GPR system has been developed based on the optimized GMM attenuation curve to predict the density of a real road pavement.



Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**PENGUKURAN KETUMPATAN CAMPURAN PADAT ASPAL  
MENGUNAKAN PENEMBUSAN RADAR KE BUMI TANPA MUSNAH**

Oleh

**MARDENI BIN ROSLEE**

**April 2009**

**Pengerusi : Raja Syamsul Azmir Bin Raja Abdullah, PhD**

**Fakulti : Kejuruteraan**

Tesis ini memperihalkan tentang pembinaan sistem penembusan radar ke bumi (GPR) berasaskan pantulan gelombang elektromagnetik untuk menentukan ketumpatan turapan jalan raya. Teknik yang dicadangkan ini adalah ringkas, cepat, tanpa musnah dan mempunyai ketepatan yang boleh diterima pakai untuk menentukan ketumpatan turapan jalan raya. Analisis teori yang berasaskan pada kaedah tiga model campuran GPR (GMM) yang sedia ada telah dipertingkatkan untuk menghasilkan fungsi pengoptimuman yang terbaik untuk digabungkan di dalam sistem GPR yang dicadangkan tersebut. Kajian ini melibatkan tiga prosedur utama iaitu analisis teori, eksperimen berkala makmal dan analysis keyakinan. Berasaskan pada kajian ini, Model campuran Lichtenecker didapati sebagai fungsi ketepatan yang terbaik dibandingkan dengan model-model yang lain seperti Nelson dan Landau disebabkan oleh min ralat



yang terkecil di antara keputusan eksperimen dan peramalan yang telah dibuat. Pada bahagian eksperimen makmal, prototaip GPR kejuruteraan telah dibina yang dapat digunakan untuk mengukur ketumpatan turapan jalan raya pada sampel kepingan turapan jalan raya. Sistem GPR terdiri daripada bahagian pemancar iaitu penjana isyarat sebagai punca gelombang mikro, antena hon sebagai pemancar dan penerima isyarat, pengawal gelombang dua arah dengan alat pengubahsuai dan penganalisis spektrum sebagai alat untuk menganalisis isyarat yang diterima. Sebanyak sembilan sampel kepingan turapan jalan raya jenis gradasi sempadan pertengahan dan sepuluh kepingan jenis atasan dan bawahan jenis HMA telah dibina dan percubaan pada empat frekuensi berlainan di dalam julat 1.7-2.6 GHz telah dilakukan. Nilai ramalan pengecilan kuasa gelombang yang berasaskan pada analisis teori telah dibandingkan dengan nilai pengukuran pengecilan daripada eksperimen di makmal. Perbandingan tersebut telah menghasilkan ralat relatif di antara dua keputusan ini dan ianya digunakan di dalam proses pengoptimuman. Penemuan berasaskan pada proses pengoptimuman mencadangkan bahawa tiga parameter tambahan iaitu faktor isipadu, faktor ketelusan dan faktor pengecilan perlu ditambah untuk memperbaiki model GMM tersebut. Analisis keyakinan pada kerja lapangan telah dilakukan dengan tujuan untuk menguji model GPR yang telah diperbaiki tersebut. Berdasarkan pada kerja lapangan, ianya menunjukkan bahawa sistem GPR yang telah dicadangkan tersebut dipercayai dapat digunakan sebaiknya dan memberikan nilai ralat daripada 3.37 % hingga 4.72 % terhadap sembilan lokasi kajian. Pada akhirnya, sistem GPR yang lengkap telah dibina dan dapat digunakan untuk menganggarkan nilai ketumpatan turapan jalan raya sebenar.



## ACKNOWLEDGEMENTS

I would like to wish a very thank so much to my beloved parents, Hj. Roslee and Hjh Normah, my siblings, Rodeano, Mazaleena, Hermaleeza, my beloved wife and daughter, Naraliayana and Deryna Norleeibsyah, my father and mother-in law with family members, Ibrahim and Esah, Asma, Amin, Ipie, Asu and Kimi for your love, support and encouragement.

I would like to extend my deepest gratitude to the chairman of the supervisory committee, Dr. Raja Syamsul Azmir Bin Raja Abdullah, for his counsel and constant encouragement during my PhD program. Thank you so much for the guidance and constructive ideas that helped speed up the progress of my PhD work. A special thanks also to the members of the supervisory committee, Dr. Helmi Zulhaidi bin Mohd Shafri and Assoc. Prof. Dr. Sabira Khatun for their guidance and advice. Many thanks to Assc. Prof. Dr. Ratnasamy Muniandy too for his helping in civil and pavement site.

Lastly, thanks extended to my friends in Microwave Millimeter Wave and Radar System Laboratory, Wireless and Network Laboratories, Department of Computer and Communication System and Traffic and Highway Laboratory, Department of Civil Engineering, Faculty of Engineering, UPM. Thanks for their help and support.





I certify that an Examination Committee has met on 7 April 2009 to conduct the final examination of Mardeni bin Roslee on his thesis entitled “Density Measurement of Compacted Asphalt Mixtures using Non-Destructive Ground Penetrating Radar” in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommended that the student be awarded the Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

**Ratnasamy Muniandy, PhD**

Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Chairman)

**Aliyani Ismail, PhD**

Lecturer  
Faculty of Engineering  
Universiti Putra Malaysia  
(Internal Examiner)

**Hussain b. Hamid, PhD**

Lecturer  
Faculty of Engineering  
Universiti Putra Malaysia  
(Internal Examiner)

**Syed Idris bin Syed Hassan, PhD**

Professor  
School of Electrical and Electronic Engineering  
Universiti Sains Malaysia  
(External Examiner)

---

**BUJANG KIM HUAT, PhD.**

Professor and Deputy Dean  
School of Graduate Studies,  
Universiti Putra Malaysia.

Date : 29 May 2009



This thesis submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee are as follows:

**Raja Syamsul Azmir bin Raja Abdullah, PhD**

Lecturer  
Faculty of Engineering  
Universiti Putra Malaysia  
(Chairman)

**Helmi Zulhaidi bin Mohd Shafri, PhD**

Lecturer  
Faculty of Engineering  
Universiti Putra Malaysia  
(Member)

**Sabira Khatun, PhD**

Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia.  
(Member)

---

**HASANAH MOHD. GHAZALI, PhD.**

Professor and Dean  
School of Graduate Studies  
Universiti Putra Malaysia

Date: 08 June 2009



## **DECLARATION**

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

---

**MARDENI BIN ROSLEE**

Date: 28 April 2009

## TABLE OF CONTENTS

	<b>Page</b>
<b>DEDICATION</b>	ii
<b>ABSTRACT</b>	iii
<b>ABSTRAK</b>	v
<b>ACKNOWLEDGEMENTS</b>	vii
<b>APPROVAL</b>	ix
<b>DECLARATION</b>	x
<b>LIST OF TABLES</b>	xv
<b>LIST OF FIGURES</b>	xviii
<b>LIST OF ABBREVIATIONS</b>	xxiii
<b>CHAPTER</b>	
<b>1. INTRODUCTION</b>	
1.1 Background	1.1
1.2 Problem Statement	1.4
1.3 Objectives	1.7
1.4 Scope and Relevance Study	1.8
1.5 Thesis Outline	1.9
<b>2. LITERATURE REVIEW</b>	
2.1 An Overview of Ground Penetrating Radar	2.1
2.2 Road Pavement Density Measurement	2.5
2.2.1 Conventional Coring Sample Method	2.5
2.2.2 Microwave Density Measurement	2.7
2.2.3 Attenuation Measurement	2.9
2.2.4 Microwave Non-Destructive Technique	2.10
2.2.5 Reducing Error Caused by Multiple Reflection	2.16
2.2.6 Electromagnetic Theory	2.17
2.3 An Overview of Road Pavement	2.24
2.3.1 Road Structure Evaluation	2.28
2.3.2 Pavement Thickness	2.29
2.3.3 Road Pavement Deterioration	2.30
2.3.4 Pavement Structural Damages Diagnosis Using GPR Reflection Technique	2.33
2.3.5 Asphalt and Aggregates	2.35
2.3.6 Hot Mix Asphalt (ACW 14)	2.38



2.3.7	Factor influencing Road Pavement Density	2.40
2.3.8	Road Pavement Study	2.41
2.3.9	Laboratory Equipment	2.42
2.4	GPR Mixture Model	2.48
2.4.1	Statistical Analysis of GPR Data	2.53
2.5	Summary	2.55

### **3. METHODOLOGY**

3.1	Introduction	3.1
3.2	Rice Method and Superpave Method	3.4
3.3	Material and Sample Preparation	
3.3.1	Middle Boundary of HMA Gradation	3.10
3.3.2	Upper and Lower Boundary of HMA Gradation	3.12
3.4	Mixing Process	3.14
3.5	GPR Measurement Setup	3.17
3.6	GPR Measurements Procedure	
3.6.1	Antennae Part	3.19
3.6.2	GPR Data Collection	3.20
3.6.3	Receiving Part and Data Analysis	3.20
3.7	Summary	3.22

### **4. GROUND PENETRATING RADAR THEORETICAL ANALYSIS**

4.1	Introduction	4.1
4.2	Relationship between Attenuation and Frequency for Various Densities of Road Pavement Samples	4.2
4.2.1	Sensitivity of Attenuation Due to Frequency for Various Densities	4.5
4.3	Relationship between Attenuation and Density for Various Thickness of Road Pavement Sample	4.8
4.3.1	Sensitivity of Attenuation Due to Density for Various Road Pavements	4.9
4.4	Relationship between Attenuation and Thickness for Various Frequencies	4.11
4.4.1	Sensitivity of Attenuation Due to Thickness for Various Frequencies	4.13
4.5	Effect of Complex Permittivity to Attenuation	4.14
4.6	Summary	4.19

## 5. GROUND PENETRATING RADAR MEASUREMENT RESULT

5.1	Middle Boundary of HMA Gradation	5.1
5.1.1	Received Signal Strength for Nine Pavement Slabs at Four Frequencies	5.1
5.1.2	Probability Density Function for Nine Pavement Slabs at Four Frequencies	5.8
5.1.3	Attenuation for Nine Pavement Slabs at Four Frequencies	5.11
5.1.4	Selection of GPR Mixture Model	5.15
5.1.5	Relative Error of Attenuation Between Measurement and Three GPR Mixture Models	5.20
5.1.6	The Accuracy of Data Between Measurement and Selected GPR Mixture Model (Lichtenecker)	5.29
5.1.7	Relative Error of Data Between Measurement and Selected GPR Mixture Model (Lichtenecker)	5.34
5.1.8	Relationship Between Attenuation and Frequency for Selected GPR Mixture Model	5.36
5.2	Upper and Lower Boundary of HMA Gradation	
5.2.1	Rice Method and Superpave Method	5.37
5.2.2	Ten New Samples with Different Density	5.50
5.2.3	Received Signal Strength for Ten New Slab Samples	5.55
5.2.4	Comparison of Attenuation between Selected GPR Mixture Model and Ten New Slab Samples	5.63
5.2.5	Relative Error of Attenuation between Selected GPR Mixture Model and Measurement for Ten New Slab Samples	5.70
5.3	Optimization Technique for Upper, Middle and Lower Boundary of HMA Gradation	5.72
5.3.1	Comparison of Attenuation between Optimized Mixture Model and Middle, Upper and Lower Boundaries	5.75
5.3.2	Relative Error of Attenuation between Optimized Mixture Model and Middle, Upper and Lower Boundaries	5.78
5.3.3	Relative Errors and Percentages of Improvement After Optimization	5.82
5.4	Summary	5.85



## **6. RELIABILITY ANALYSIS**

6.1	Introduction	6.1
6.2	Nine Measured Points of Real Road Pavement with Actual Density	6.3
6.3	Predicted Technique Using Optimized GPR Mixture Model	6.8
6.3.1	Outdoor GPR Measurement Setup	6.9
6.3.2	Received Signal Strength for Nine Points with Predicted Density	6.10
6.3.3	Attenuation for Nine Points with Predicted Density	6.16
6.4	Measured Technique (Coring Sample Density Calculation)	6.19
6.5	Comparison Between Actual Density (Measured) and Predicted Density (Optimized Model)	6.21
6.5.1	Relative Error Between Actual Density (Measured) and Predicted Density(Optimized Model)	6.23
6.6	Summary	6.28

## **7. DEVELOPMENT GPR SOFTWARE**

7.1	Introduction	7.1
7.2	Aggregate Calculation with Predicted Density of UPM GPR Road Pavement Program	7.2
7.3	Attenuation with Predicted Density of UPM GPR Road Pavement Program	7.4
7.4	Received Signal Power with Predicted Density of UPM GPR Road Pavement Program	7.6
7.5	Summary	7.8

## **8. CONCLUSION**

8.1	Conclusions	8.1
8.2	Original Contributions	8.1
8.3	Future Recommendation	8.3
8.3.1	Thickness of Road Pavement	8.3
8.3.2	Different Outdoor Environment	8.3
8.3.3	Portable Instrument	8.3

<b>REFERENCES</b>	R.1
<b>APPENDICES</b>	A.1
<b>BIODATA OF STUDENT</b>	B.1
<b>LIST OF PUBLICATION</b>	P.1



## LIST OF TABLES

<b>Table</b>		<b>Page</b>
2.1	Flexible and rigid pavements types	2.24
2.2	Typical Aggregate Gradation for Hot Mix Asphalt Middle Boundary (JKR spec)	2.36
3.1	Typical aggregate of upper boundary gradation for Hot Mix Asphalt (JKR spec)	3.7
3.2	Calculation of specimen and cake sample preparation for Rice method and Super pave method for Upper Boundary gradation	3.7
3.3	Weight of each asphalt content for upper boundary HMA gradation	3.8
3.4	Typical aggregate of lower boundary gradation for Hot Mix Asphalt (JKR spec)	3.8
3.5	Calculation of specimen and cake sample preparation for Rice method and Super pave method for lower Boundary gradation	3.9
3.6	Weight of each asphalt content for upper boundary HMA gradation	3.9
3.7	Aggregate Calculation for Nine Road Pavements (Middle Boundary)	3.12
3.8	Aggregate Calculation for Five Road Pavements (Upper Boundary) with 2420 kg/m <sup>3</sup> of TMD and 6.0 % of OAC	3.13
3.9	Aggregate Calculation for Five Road Pavements (Lower Boundary) with 2460 kg/m <sup>3</sup> of TMD and 6.0 % of OAC	3.14
5.1(a)	Mean values and standard deviation of received signal strength at frequency 1.7 GHz	5.5
5.1(b)	Mean values and standard deviation of received signal strength at frequency 2.0 GHz	5.6
5.1(c)	Mean values and standard deviation of received signal strength at frequency 2.3 GHz	5.6





5.1(d)	Mean values and standard deviation of received signal strength at frequency 2.6 GHz	5.7
5.2(a)	Mean relative error of attenuation between measurement and three models for nine road pavement slabs at frequency 1.7 GHz	5.25
5.2(b)	Mean relative error of attenuation between measurement and three models for nine road pavement slabs at frequency 2.0 GHz	5.26
5.2(c)	Mean relative error of attenuation between measurement and three models for nine road pavement slabs at frequency 2.3 GHz	5.27
5.2(d)	Mean relative error of attenuation between measurement and three models for nine road pavement slabs at frequency 2.6 GHz	5.28
5.3	Relative error of attenuation between measurement and selected GPR mixture model (Lichtenecker) for nine pavement slabs at four different frequencies	5.35
5.4(a)	Results of five rice specimens with different asphalt content of Rice Method for upper boundary gradation.	5.39
5.4(b)	Results of five rice specimens with different asphalt content of Rice Method for lower boundary gradation.	5.39
5.5(a)	Result of Rice method and Superpave method for upper boundary of gradation	5.41
5.5(b)	Result of Rice method and Superpave method for lower boundary of gradation	5.41
5.6	Aggregate Calculation for Slab 1 (2 %) for Upper Boundary HMA Gradation	5.50
5.7	Aggregate Calculation for Slab 1 (2 %) for lower Boundary HMA Gradation	5.51
5.8(a)	Mean values of received signal strength for upper boundary gradation at four frequencies	5.58
5.8(b)	Mean values of received signal strength for lower boundary gradation at four frequencies	5.61
5.9(a)	Relative error between Lichtenecker Model and measurement for upper boundary gradation	5.71
5.9(b)	Relative error between Lichtenecker Model and measurement for lower boundary gradation	5.71

5.10(a)	Mean Relative Error between, measurement, Lichenecker and optimization for upper boundary HMA gradation	5.37
5.10(b)	Mean Relative Error between, measurement, Lichenecker and optimization for lower boundary HMA gradation	5.37
5.10(c)	Mean Relative Error between ,measurement, Lichenecker and optimization For middle boundary HMA gradation	5.38
5.11(a)	Percentages of improvement after optimization for upper boundary HMA gradation	5.39
5.11(b)	Percentages of improvement after optimization for middle boundary HMA gradation	5.39
5.11(c)	Percentages of improvement after optimization for lower boundary HMA gradation	5.40
6.1	Mean of Received Signal Strength for nine measured points with unknown density at four frequencies	6.15
6.2	Attenuation for nine measured points with unknown density at four frequencies	6.17
6.3	Measured density of nine measured points from core sample density calculation	6.20
6.4	Results of measured and predicted density at four frequencies	6.21
6.5	Relative error between measured and predicted density at four frequencies	6.23

## LIST OF FIGURES

<b>Figure</b>		<b>Page</b>
1.1	Flow chart of methodology	1.11
2.1	Core sample	2.2
2.2	Schematic diagram of planar sample	2.13
2.3	Reflection for a dielectric road pavement slab at homogeneous unbounded medium	2.13
2.4	Road pavement deterioration	2.32
2.5	Asphalt	2.35
2.6	Particles of Aggregate	2.37
2.7	Main layer of road pavement in a road under construction	2.38
2.8	Vacuum	2.44
2.9	MATTA machine	2.44
2.10	Marshall stability	2.45
2.11	Mechanical Sieve Shaker	2.45
2.12	Oven	2.46
2.13	Heavy Duty Mixer	2.46
2.14	Turamachine	2.47
2.15	Typical GPR reflections from a pavement slab in GPR mixture model	2.52
3.1	Flowchart of methodology	3.2
3.2(a)	Five specimens in Rice Method	3.5
3.2(b)	Specimen to be vacuumed	3.5



3.3	Fifteen cake samples in Super pave method	3.6
3.4(a)	Slab sample of road pavement	3.11
3.4(b)	Core sample of road pavement	3.11
3.5	Aggregate preparation	3.16
3.6	Sieving Process	3.16
3.7	Process of heating asphalt in oven	3.16
3.8	Process of drying the aggregate in oven	3.16
3.9	Mixing of asphalt and aggregate in heavy duty mixer	3.16
3.10	Paving and compaction in Turamachine	3.16
3.11	Road pavement slab	3.17
3.12 (a)	GPR measurement setup	3.19
3.12 (b)	Environmental setup block diagram	3.19
4.1	Relationship between attenuation and frequency for various densities for road pavement samples	4.5
4.2	Relationship between sensitivity $\partial A/\partial F$ and density for various densities for road pavement samples	4.6
4.3	Relationship between attenuation and density for various thickness of road pavement sample	4.9
4.4	Relationship between sensitivity due to density and various thicknesses road pavement samples	4.10
4.5(a)	Relationship between attenuation and thickness for various frequencies	4.12
4.5(b)	Core road pavement sample with thickness sign	4.12
4.6	Relationship between sensitivity due to thickness and various densities of road pavement samples	4.14

4.7	Relationship between attenuation, thickness and complex permittivity	4.16
4.8	Dielectric constant and loss factor for road pavement sample with 50 mm thickness as function of density	4.18
5.1	Received signal strength (dBm) versus number of data of GPR reading for nine road pavement slabs at 4 different frequencies.	5.3
5.2	Mean received signal strength (dBm) versus four different frequencies of GPR reading for nine road pavement slabs	5.7
5.3	Probability density function of received signal strength for nine road pavement slabs at 4 different frequencies.	5.10
5.4	Attenuation (dB) versus number of data of GPR reading for nine road pavement slabs at 4 different frequencies.	5.14
5.5	Flow chart of comparison between measured and predicted attenuation	5.15
5.6	Comparison of attenuation between measurement and three GPR mixture models for nine road pavement slabs at four different frequencies.	5.18
5.7	Relative error of attenuation between measurement and three GPR mixture models (Lichtenecker, Landau and Nelson) for nine slabs at four frequencies.	5.22
5.8	Relationship of attenuation between measurement and selected GPR mixture model (Lichtenecker) for nine pavement slabs at four different frequencies.	5.31
5.9	Error analysis of attenuation between measurement and selected GPR mixture model (Lichtenecker) for nine pavement slabs at four different frequencies.	5.35
5.10	Relationship between frequency and attenuation for four pavement slabs with different density	5.36
5.11	Flowchart of Development of Ten New for Upper and Lower Boundary	5.38
5.12	Relationship between bulk density and asphalt content for upper and lower boundary	5.43



5.13	Relationship between air void and asphalt content for upper and lower boundary	5.45
5.14	Relationship between resilient modulus and asphalt content for upper and lower boundary	5.47
5.15	Relationship between Marshall stability and asphalt content for upper and lower boundary	5.49
5.16	Relationship between air void content with density for ten road pavement slabs for upper boundary HMA gradation	5.52
5.17	Flowchart of GPR data measurement in Microwave and Radar Laboratory	5.54
5.18	GPR reading for ten road pavement slabs of upper boundary gradation at four different frequencies.	5.56
5.19	GPR reading for ten road pavement slabs of lower boundary gradation at 4 different frequencies.	5.59
5.20	Attenuation of GPR reading for five road pavement slabs for upper boundary gradation at four different frequencies	5.64
5.21	Attenuation of GPR reading for five road pavement slabs for lower boundary gradation at lower different frequencies.	5.66
5.22	Attenuation comparison between Lichtecneker model and measurement for upper and lower boundary	5.69
5.23	Comparison results between Optimization, Licthenecker and measurements for upper, lower and middle boundaries.	5.76
6.1	Flow chart of GPR data measurement	6.2
6.2	Nine measured points at Faculty of Engineering, UPM	6.3
6.3	Nine measured points of real road pavement with unknown density	6.7
6.4	Core samples taken out from the nine measured point	6.8
6.5	Outdoor GPR measurement system	6.9



6.6	Received signal strength for fifty data for nine measured points at four frequencies	6.13
6.7	Mean received signal strength for fifty data for nine measured points at four frequencies (outdoor)	6.15
6.8	Mean attenuation for fifty data for nine measured points at four frequencies (outdoor)	6.17
6.9	Coring process	6.19
6.10	Core sample of real road pavement	6.19
6.11	Direct comparison between predicted and measured density at four frequencies.	6.26
7.1	Flow chart of UPM GPR Road Pavement Programs	7.2
7.2	Aggregate Calculation with predicted density in UPM GPR Road Pavement Program	7.3
7.3	Attenuation with predicted density in UPM GPR Road Pavement Program	7.6
7.4	Received signal power with predicted density in UPM GPR Road Pavement Program	7.8



## LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ACW	Asphalt Concrete Wearing
CW	Continuous Wave
EM	Electromagnetic
FRA	Federal Railroad Administration
FWD	Falling Weight Deflectometer
GPR	Ground Penetrating Radar
HMA	Hot Mix Asphalt
HMAC	Hot Mix Asphalt Concrete
JKR	Jabatan Kerja Raya
MATLAB	Matrix Laboratory
MNDT	Microwave Non-Destructive Technique
NCHRP	National Cooperative Highway Research Program
NDE	Non-Destructive Evaluation
OAC	Optimum Asphalt Content
PDF	Probability Density Function
PMS	Pavement Management System
PWD	Public Works Department
RAIRS	Railway Accident Incident Reporting Systems
SFR	Swiss Federal Railways
TE	Transverse Electric





TEM	Transverse Electromagnetic Modes
TDP	Timbalan Dekan Penyelidikan
TDR	Time Domain Reflectometry
TM	Transverse Magnetic
TMD	Theoretical Maximum Density
UPM	Universiti Putra Malaysia
VEE	Visual Engineering Environment
$A$	Attenuation
$\partial$	Sensitivity
$d$	Density of road pavement
$m$	Mass of road pavement
$v$	Volume of road pavement
$t$	Road pavement slab thickness
$D$	Diameter of core sample
$P_i$	Received power
$P_o$	Transmit power
$\alpha$	Attenuation constant
$\epsilon^*$	Complex permittivity
$\epsilon'$	Dielectric constant (or real part of permittivity)
$\epsilon''$	Loss factor (or imaginary part of permittivity)
$\pi$	pi
$E$	Electric field intensity
$H$	Magnetic field intensity
$\epsilon$	Permittivity