



UNIVERSITI PUTRA MALAYSIA

***DETERMINATION OF RELATIVE DAMAGE OF ASPHALT PAVEMENT
FROM REDUCED TIRE CONTACT AREA***

DANIAL MOAZAMI

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**DETERMINATION OF RELATIVE DAMAGE OF ASPHALT PAVEMENT
FROM REDUCED TIRE CONTACT AREA**

By

DANIAL MOAZAMI

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

April 2015

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DEDICATION

This thesis is especially dedicated to:
*My most-beloved wife Maryam Hashemian and
My lovely little daughter Adrina Moazami*

To My Praiseworthy Parents and Parents- In-law

And my dearest brothers and sister

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

**DETERMINATION OF RELATIVE DAMAGE OF ASPHALT PAVEMENT
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By

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April 2015

Chairman: Professor Ratnasamy Muniandy, PhD

Faculty : Engineering

Considering the traditional contact area which is a full circular contact area without any tread, in the current pavement design procedure, is an extreme overestimation of contact area and hence extreme underestimation of the real contact stress. Since the relationship between the contact stress and pavement damage is not linear but exponential, even a trivial difference between tire contact areas leads to significant difference in terms of induced pavement damage.

This study was conducted to quantify the relative damage caused by realistic tire-pavement contact area with respect to the full contact area and incorporated three objectives: To design a wheel tracking and instrumentation system, to establish a method for determination and analysis of effective tire contact areas, to quantify the relative damage of asphalt pavement due to various tire-pavement contact areas.

In this study, a new equipment called Rotary Compactor and Wheel Tracker (RCWT) was designed and fabricated for capturing the effective tire contact areas, resembling the compaction effort of Stone Mastic Asphalt (SMA) site rollers, and conducting simulative wheel tracking test.

In order to capture the effective contact area, 155/70R12 tire was selected with the six most common treads in the market besides a completely worn-out tread resembling the full contact area without any tread. The footprints of these treads were captured at five tire load groups of 1.50 kN, 2.0, 2.5, 3.0, and 3.5 kN and four tire inflation pressures of 137.90 kPa, 172.37, 206.84 and 241.32 kPa.

Using the developed tire imaging procedure, the obtained footprints were very clear and free of any image noises. The footprints were then scanned and uploaded in a MATLAB-based image processing program to calculate the effective contact areas. Comparison between effective and traditional contact areas indicated that the current

pavement design procedure overestimates the actual tire-pavement contact area up to 92 percent.

Among the tested treads, Dunlop Ec201, Dunlop SP Sport J3, and Sime Astar 100 induced minimum, intermediate and maximum contact areas besides the full contact area which was caused by the worn-out tread. Therefore, these treads were selected for further wheel tracking performance study at three different load groups (three normal loading of a Kancil car) of 1.43 kN, 1.91 kN, and 2.13 kN by preparing 12 slabs.

Permanent deformation and permanent strain profiles of different contact areas in each tire load group were obtained and the relative damage analyses were done between tires with and without tread from various aspects. These aspects include operational life reduction ratio, rutting rate, linear and nonlinear relative damage concepts. Based on nonlinear relative damage analyses, real tire with tread induced about three times more rutting compared to the worn-out control tread. In addition, the induced permanent vertical strain by the real tire with tread was two times higher compared to the worn-out control tread.

Finally, the current pavement design, by using the full circular contact area, underestimates the amount of rutting significantly, and it is recommended to incorporate the realistic tire-pavement contact area in the design procedure to obtain an optimum design.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
Sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

**PENENTUAN KEROSAKAN RELATIF DARIPADA PENGURANGAN
KAWASAN SENTUHAN TAYAR PADA TURAPAN**

Oleh

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Mengambil kira kawasan sentuhan tipikal yang merupakan sentuhan keliling yang penuh tanpa sebarang alur, dalam prosedur reka bentuk turapan semasa, ianya kawasan sentuhan yang diambilkira secara ekstrem dan kurang mengambilkira kawasan tegasan yang sebenar. Oleh kerana hubungan antara kawasan tegasan dan kerosakan turapan bukan linear tetapi secara eksponen, walaupun terdapat perbezaan kecil antara kawasan sentuhan tayar membawa kepada perbezaan yang signifikan dari segi kerosakan turapan teraruh.

Kajian ini dijalankan untuk mengukur kerosakan relatif disebabkan oleh kawasan sentuh realistik tayar dengan kawasan sentuhan penuh bagi memenuhi tiga objektif: Untuk mereka bentuk sistem pengesanan roda dan peralatan, untuk mewujudkan satu kaedah untuk penentuan dan analisis hubungan tayar berkesan kawasan, untuk mengukur kerosakan relatif asfalt turapan disebabkan oleh pelbagai kawasan sentuhan tayar.

Laporan mengatakan perbezaan kecil kawasan sentuhan tayar menyumbang kepada perbezaan ketara bagi penyebab kerosakan turapan. Dalam kajian ini, alat baru yang panggil sebagai Pemadat Putar and alat Pengesan Roda (RCWT) telah direka and dipasang untuk memperoleh keberkesanan kawasan sentuhan tayar, menyamartakan kebolehan memadat Asfalt Matrik Batuan (SMA) keluli statik skala penuh dengan pengolek and melakukan ujian simulasi pengesan roda di makmal.

Bagi mendapatkan kawasan sentuh berkesan untuk tayar 155/70R12, enam corak bebanang tayar yang terdapat di pasaran tetapi sudah sepenuhnya haus telah dipilih and diuji dengan lima kumpulan beban tayar iaitu 1.50 kN, 2.0, 2.5, 3.0, and 3.5 kN and empat inflasi tekanan iaitu 137.90 kPa, 172.37, 206.84 and 241.32 kPa.

Melalui prosidur pengimejan tayar didapati kawasan sentuhan yang diperolehi adalah bebas daripada mana-mana kerosakan imej. Kawasan sentuhan tersebut telah diteliti and dianalisa menggunakan kaedah pemprosesan imej MATLAB untuk mentaksir atau mengira kawasan sentuhan berkesan. Perbandingan antara kawasan sentuh berkesan

(efektif) dengan kawasan sentuh tipikal yang mengikut teori menunjukkan bahawa prosedur rekabentuk turapan tradisional yang sedia ada beserta kawasan sentuhan bulat telah melebihi kawasan sentuh sebenar antara tayar dan turapan sehingga 92 peratus.

Antara corak bebenang tayar yang diuji, Dunlop Ec201, Dunlop SP Sport J3, Sime Astar 100 dan tayar yang sepenuhnya haus telah dikategorikan kepada corak bebenang yang minima, pertengahan, maksimum dan kawasan sentuhan sepenuhnya dipilih untuk ujian prestasi bagi roda pengesan bagi tiga kumpulan beban yang berbeza (tiga beban normal sebuah kereta Kancil) iaitu 1.43 kN, 1.91 kN, dan 2.13 kN dengan menyediakan 12 kepingan rasuk.

Profil untuk ujian aluran dan keterikan bagi tayar yang berbeza dengan beban tayar yang sama kumpulan diperolehi dan analisis kerosakan relatif diambil diantara tayar dengan/tanpa alur dari pelbagai aspek. Aspek ini termasuklah nisbah pengurangan operasi jangka hayat, kadar alunan, dan konsep kerosakan relatif linear dan tidak linear. Analisis kerosakan relatif tidak linear, kawasan sentuhan tayar biasa beralur 3 kali lebih mudah berbanding tayar yang haus. Selain itu, kadar aruhan bagi terikan tegak tetap untuk tayar biasa adalah dua kali lebih tinggi berbanding tayar haus kawalan beralur.

Akhir sekali dengan reka bentuk turapan semasa, menggunakan kawasan sentuhan penuh, dapat mengurangkan jumlah alunan dengan ketara. Adalah disyorkan untuk memasukkan kawasan sentuhan realistik dalam prosedur reka bentuk untuk mendapatkan reka bentuk yang optima.

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APPROVAL

I certify that a Thesis Examination Committee has met on 15 April 2015 to conduct the final examination of Danial Moazami on his thesis entitled "Determination of Relative Damage of Asphalt Pavement from Reduced Tire Contact Area " in accordance with the Univesrities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U. (A) 106] 15 March 1998. The committee recommends that the student be awarded the Doctor of Philosophy.

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TABLE OF CONTENTS

| | Page |
|--|---------------|
| ABSTRACT | i |
| ABSTRAK | iii |
| ACKNOWLEDGEMENTS | v |
| APPROVAL | vi |
| DECLARATION | viii |
| LIST OF TABLES | xiii |
| LIST OF FIGURES | xvi |
| LIST OF ABBREVIATIONS | xx |
| CHAPTER | |
| 1 INTRODUCTION | 1 |
| 1.1 General Background | 1 |
| 1.2 Problem Statement | 3 |
| 1.3 Objectives of Study | 5 |
| 1.4 Scope of Study | 5 |
| 1.5 Thesis Layout | 6 |
| 2 LITERATURE REVIEW | 7 |
| 2.1 Empirical Method of Pavement Design | 7 |
| 2.2 Mechanistic-Empirical Method of Pavement Design and Hot Mix Asphalt Rutting Model | 8 |
| 2.3 Conventional Method of Pavement Design | 10 |
| 2.4 Modified Layered Elastic Method of Pavement Design | 12 |
| 2.5 Axle Load Configurations | 14 |
| 2.6 Background of Various Tire Types | 15 |
| 2.7 Typical Tire Size and Tread Pattern | 17 |
| 2.8 Tire-Pavement Contact Area Studies | 17 |
| 2.8.1 Shape and Dimensions of a Tire Contact Patch | 21 |
| 2.8.2 MATLAB Image Processing in Tire Footprint Studies | 22 |
| 2.8.3 Summary | 26 |
| 2.9 Compaction Protocol of UPM Rotary Compactor | 26 |
| 2.10 Rutting Mechanism | 29 |
| 2.10.1 HMA Rutting Distress | 29 |
| 2.10.2 Subgrade rutting Distress | 31 |
| 2.11 Test Methods for Permanent Deformation Evaluation | 31 |
| 2.11.1 Empirical Tests | 33 |
| 2.11.2 Fundamental Tests | 38 |
| 2.11.3 Simulative Tests | 50 |
| 2.12 Various Curve Fittings in Vertical Deformation Studies | 61 |
| 2.13 Relative Damage Studies in Asphalt Mixtures | 63 |
| 2.14 Concluding Remarks | 69 |
| 3 RESEARCH METHODOLOGY | 70 |
| 3.1 Test Plan 1: Design a Wheel Tracking and Instrumentation System | 76 |
| 3.2 Test Plan 2: Tire Footprint Imaging in the Rotary Compactor and Wheel Tracking (RCWT) Equipment | 78 |

| | | |
|----------|---|------------|
| 3.2.1 | Tire Type, Tire Tread, Tire Load and Tire Inflation Pressure | 78 |
| 3.2.2 | Capturing Tire Imprints | 80 |
| 3.2.3 | Image Processing for Actual Contact Area Calculation | 81 |
| 3.3 | Test Plan 3: Quantifying the Relative Damage of Asphalt Pavement due to Various Contact Areas | 82 |
| 3.3.1 | Material Testing and Mix Design | 83 |
| 3.3.2 | Rotary Slab Preparation Procedure | 86 |
| 3.3.3 | Rotary Slab Compaction Process | 88 |
| 3.3.4 | Conditioning of Rotary Slabs | 92 |
| 3.3.5 | Wheel Tracking of Rotary Slabs | 93 |
| 3.3.6 | Relative Damage Analysis with and without Tire Tread | 101 |
| 4 | DESIGN A WHEEL TRACKING AND INSTRUMENTATION SYSTEM | 104 |
| 4.1 | RCWT Components and the Technical Specifications | 104 |
| 4.1.1 | Mechanical Parts of the Rotary Compactor and Wheel Tracker | 104 |
| 4.1.2 | Control System and Instrumentation Parts | 106 |
| 4.2 | Fabrication of In-house Vertical Asphalt Strain Gages (VASG) | 112 |
| 4.3 | Installation of In-house Vertical Asphalt Strain Gages | 117 |
| 4.4 | Wheel Tracking and Instrumentation Results | 120 |
| 4.4.1 | Two and Three Dimensions Drawings | 120 |
| 4.4.2 | Calibration Results for Sensors | 133 |
| 4.4.3 | Reliability of the Manufactured Vertical Asphalt Strain Gages | 137 |
| 4.5 | Summary | 138 |
| 5 | RESULTS AND DISCUSSION | 140 |
| 5.1 | Results of Wheel Tracking and Instrumentation Design | 140 |
| 5.2 | Results of Tire Footprint Imaging | 140 |
| 5.2.1 | Tire Imaging Output | 140 |
| 5.2.2 | Calculation of Tire Contact Area | 143 |
| 5.2.3 | Validation of the Image Processing Software | 146 |
| 5.2.4 | Factorial Analysis for Tire Contact Area | 147 |
| 5.2.5 | Contact Area Variations | 148 |
| 5.2.6 | Regression Models for Various Tread Patterns | 149 |
| 5.2.7 | Current Pavement Design Procedure, Contact Area Aspect | 150 |
| 5.3 | Results of Quantifying the Relative Damage of Asphalt Pavement due to Various Contact Areas | 152 |
| 5.3.1 | Material and Mix Design Results | 152 |
| 5.3.2 | Required Amount of Different Stockpiles in Each Batch | 160 |
| 5.3.3 | Improved Compaction Procedure of UPM Rotary Compactor and Compaction Temperature Profiles | 161 |
| 5.3.4 | Temperature Records during Conditioning | 163 |
| 5.3.5 | Wheel Tracking Test Results | 164 |
| 5.3.6 | Relative Damage Analysis | 203 |
| 5.3.7 | Contact Stress for the RCWT Tires and Truck Tires | 224 |
| 5.3.8 | Rutting Damage Ratio of the Effective Contact Area with Respect to the Traditional Contact Area -Theoretical Analysis | 225 |
| 5.3.9 | Pavement Design based on the Traditional and Effective Contact Areas using the Modified Layered Elastic Method | 232 |
| | CONTRIBUTIONS | 239 |

| | | |
|----------|---------------------------------------|------------|
| 6 | CONCLUSION AND RECOMMENDATIONS | 240 |
| 6.1 | Conclusions from the First Objective | 240 |
| 6.2 | Conclusions from the Second Objective | 241 |
| 6.3 | Conclusions from the Third Objective | 242 |
| 6.4 | Recommendation for Further Studies | 244 |
| | REFERENCES | 245 |
| | APPENDICES | 258 |
| | BIODATA OF STUDENT | 297 |
| | LIST OF PUBLICATIONS | 298 |



LIST OF TABLES

| Table | Page |
|--|------|
| 1.1. Traditional and Effective Contact Areas and Induced Fatigue Damage | 3 |
| 2.1. Contact Calculations in Conventional and Modified Methods | 13 |
| 2.2. Axle Load Configurations and Axle Load Limit | 15 |
| 2.3. Contact Pressure of the in situ Rollers | 27 |
| 2.4. UPM Rotary Compaction Procedure | 28 |
| 2.5. Induced Vertical Pressures in the UPM Rotary Compactor | 29 |
| 2.6. Marshall Mix Design Criteria | 33 |
| 2.7. Typical Hveem Design Criteria | 35 |
| 2.8. Superpave Gyratory Compaction Parameters | 37 |
| 2.9. Damage Ratios of HMA Rutting for Tire configuration and Loading | 64 |
| 2.10. Damage Ratios for HMA Rutting (Densification) between Two Tire Configurations | 65 |
| 2.11. Damage Ratios for HMA Rutting (Shear) between Two Tire Configurations | 65 |
| 3.1. Aggregate Physical Properties Tests | 83 |
| 3.2. Asphalt Binder Physical Properties Tests | 83 |
| 3.3. SMA Gradation Specification | 84 |
| 3.4. Sieve Analysis of Kajang Quarry Stockpile Samples | 86 |
| 3.5. Test Configurations in the Wheel Tracking Experiments | 94 |
| 4.1. Mechanical Parts of the RCWT Equipment | 106 |
| 4.2. Technical Specifications of the Load Cells | 107 |
| 4.3. Technical Specifications of the LVDTs | 108 |
| 4.4. Slip ring Wire Connections | 109 |
| 4.5. Components of the Data Acquisition System | 110 |
| 4.6. Technical Specifications of the Thermocouples | 110 |
| 4.7. Control System and the Instrumentation Parts | 112 |
| 4.8. Technical Specifications of the Strain Gages | 116 |
| 4.9. Components of the In-house Vertical Asphalt Strain Gages with the Specifications | 117 |
| 4.10. Appropriateness of the Wheel Tracking Design | 128 |
| 4.11. Percentage Difference between the CTL Group and the In-house Strain Gages | 138 |
| 5.1. Realistic Contact Areas for Dunlop Ec201 Tread (Continental) | 144 |
| 5.2. Realistic Contact Areas for Worn-out Tread | 145 |
| 5.3. Factorial Analysis of the Main Effects of TT, TL, and TIP on the Realistic Contact Area | 147 |
| 5.4. Regression Models for Various Tread Patterns | 150 |
| 5.5. Aggregate Tests Results | 152 |
| 5.6. Bitumen Tests Results | 152 |
| 5.7. Marshall Samples Test Results | 154 |
| 5.8. Summary of the Marshall Samples Results | 155 |
| 5.9. Summary of the Marshall Mix Design Analysis | 157 |
| 5.10. Mixture Specifications and Requirements Checking | 157 |
| 5.11. Required Amount of Each Aggregate Fraction in a Single Slab | 158 |
| 5.12. Final Blending against the NAPA Specifications | 160 |
| 5.13. Required Amount of different Stockpiles in each Batch | 160 |
| 5.14. Improved Compaction Procedure for the RCWT Equipment | 161 |
| 5.15. Slip Angle Measurements for Various Contact Areas | 165 |
| 5.16. Rut Depths Measurements and Tests Termination Points | 167 |

| | |
|---|-----|
| 5.17. First and Second Derivatives at different Load Cycle Intervals, Power Curve Fitting | 173 |
| 5.18. Comparison of Various Fitted Models | 174 |
| 5.19. Rate of Rutting for different Load Cycle Intervals, Two-Term Exponential Fit | 176 |
| 5.20. Established Exponential Rutting Models for each Slab | 178 |
| 5.21. Factorial Analysis of the Main Effects of N, TL, and TT on Permanent Deformation | 197 |
| 5.22. Cumulative Permanent Strains and Loading Variations | 199 |
| 5.23. Established Permanent Strain Models for each Slab | 200 |
| 5.24. Factorial Analysis of the Main Effects of N, TL, and TT on Permanent Strain | 202 |
| 5.25. Rutting Damage Ratios with Respect to the Full Contact Area-First Load Group | 204 |
| 5.26. Rutting Damage Ratios with Respect to the Full Contact Area -Second Load Group | 204 |
| 5.27. Rutting Damage Ratios with Respect to the Full Contact Area -Third Load Group | 204 |
| 5.28. Rutting Nonlinear Relative Damage Relationships with Respect to the Full Contact Area-First Load Group | 206 |
| 5.29. Rutting Nonlinear Relative Damage Relationships with Respect to the Full Contact Area-Second Load Group | 206 |
| 5.30. Rutting Nonlinear Relative Damage Relationships with Respect to the Full Contact Area-Third Load Group | 206 |
| 5.31. Rutting Nonlinear Damage Ratios at Different Load Cycle Intervals-First Load Group | 207 |
| 5.32. Rutting Nonlinear Damage Ratios at Different Load Cycle Intervals-Second Load Group | 208 |
| 5.33. Rutting Nonlinear Damage Ratios at Different Load Cycle Intervals-Third Load Group | 208 |
| 5.34. Strain Damage Ratios with Respect to the Full Contact Area- First Load Group | 212 |
| 5.35. Strain Damage Ratios with Respect to the Full Contact Area- Second Load Group | 212 |
| 5.36. Strain Linear Damage Ratios with Respect to the Full Contact Area- Third Load Group | 212 |
| 5.37. Permanent Strain Nonlinear Relative Damage Relationships with Respect to the Full Contact Area-First Load Group | 214 |
| 5.38. Permanent Strain Nonlinear Relative Damage Relationships with Respect to the Full Contact Area-Second Load Group | 214 |
| 5.39. Permanent Strain Nonlinear Relative Damage Relationships with Respect to the Full Contact Area-Third Load Group | 215 |
| 5.40. Permanent Strain Nonlinear Damage Ratios with Respect to the Full Contact Area at Different Load Cycle Intervals-First Load Group | 215 |
| 5.41. Permanent Strain Nonlinear Damage Ratios with Respect to the Full Contact Area at Different Load Cycle Intervals -Second Load Group | 215 |
| 5.42. Permanent Strain Nonlinear Damage Ratios with Respect to the Full Contact Area at Different Load Cycle Intervals -Third Load Group | 216 |
| 5.43. Rutting Rate With and Without Tread at Various Load Cycle Intervals-First Load Group | 220 |
| 5.44. Rutting Rate With and Without Tread at Various Load Cycle Intervals-Second Load Group | 220 |

| | |
|---|-----|
| 5.45. Rutting Rate With and Without Tread at Various Load Cycle Intervals- Third Load Group | 221 |
| 5.46. Overall Damage Ratios With and Without Tire Tread | 223 |
| 5.47. Contact Stresses in the RCWT Equipment and Truck Tires | 224 |
| 5.48. Theoretical Damage Ratios between TCA and ECA for Various Asphalt Thicknesses | 229 |
| 5.49. Damage Ratio of the ECA with Respect to the TCA- a Typical Structure with 70 mm Asphalt Thickness | 230 |
| 5.50. Damage Ratio of the ECA with Respect to the TCA- a Typical Structure with 120 mm Asphalt Thickness | 231 |
| 5.51. Resilient Vertical Strains and Rutting Depths for Design Example 1 | 233 |
| 5.52. Resilient Vertical Strains and Rutting Depths for Design Example 2 | 236 |
| 5.53. Resilient Vertical Strains and Rutting Depths for Design Example 3 | 238 |



LIST OF FIGURES

| Figure | Page |
|--|------|
| 1.1. Full and Effective Contact Areas, Close-up View of the Void Areas | 4 |
| 2.1. Empirical Method of Pavement Design | 8 |
| 2.2. Procedure for the Mechanistic-Empirical Method of Pavement Design | 9 |
| 2.3. Vertical, Transverse and Longitudinal Contact Stresses in the Contact Patch | 11 |
| 2.4. Conventional, Modified and Comprehensive Methods of Pavement Design | 14 |
| 2.5. Wheel Spacing for a Typical Semitrailer | 15 |
| 2.6. An Optical Pressure Mapping Apparatus for Automobile Tire | 18 |
| 2.7. Under-Inflated Tire with Large Contact Area | 19 |
| 2.8. Patch Images for different Vertical Loads for 165/65R13 Tire | 19 |
| 2.9. Imprint for Tire 11R22.5 at 1500 kg Load and 900 kPa Tire Inflation Pressure | 20 |
| 2.10. Footprint Capturing in the Heavy Vehicle Simulator | 20 |
| 2.11. Tire Imprint for 215/75R17.5 (Tire Load of 7000 lb and Inflation Pressure of 145 psi) | 21 |
| 2.12. A sample of Disk Structuring Element | 23 |
| 2.13. Pressure – Temperature Correlation for the UPM Rotary Compactor | 28 |
| 2.14. Asphalt Layer Rutting Distress | 30 |
| 2.15. HMA Rutting Caused by the Surface Shear Stresses | 30 |
| 2.16. Subgrade Rutting Distress | 31 |
| 2.17. The Hveem Stabilometer Apparatus | 34 |
| 2.18. Cohesimeter Apparatus | 36 |
| 2.19. Superpave Gyrotory Compactor Set-up | 36 |
| 2.20. Typical Static Creep Stress and Strain Relationships | 38 |
| 2.21. Relationship between Rut Depth, Rut Rate and Permanent Strain in Confined Static Creep | 39 |
| 2.22. Jig and Vertical LVDTs in Laboratory Permanent Deformation Tests | 39 |
| 2.23. The Repeated Load Triaxial Test Set-up | 40 |
| 2.24. Loading Conditions in a Repeated Load Triaxial Test | 41 |
| 2.25. Typical Plot in a Dynamic Creep Test | 41 |
| 2.26. Correlation between Hamburg Wheel Tracking and Flow Number | 42 |
| 2.27. Correlation between Asphalt Pavement Analyzer and Flow Number | 42 |
| 2.28. Rut Depth and Laboratory Strain Correlation in Confined Repeated Load Test | 43 |
| 2.29. Load and Strain Values in Dynamic Modulus Test | 44 |
| 2.30. Confined Dynamic Modulus Set-up | 45 |
| 2.31. Quality Control using Dynamic Modulus for Rutting Distress | 45 |
| 2.32. Shear Tester Set-up | 46 |
| 2.33. FSCH Test Schematic | 47 |
| 2.34. A Typical Plot for a Series of FSCH Test | 48 |
| 2.35. A Typical Plot for a RSCH Test | 49 |
| 2.36. Correlation between RSCH and Asphalt Pavement Analyzer | 49 |
| 2.37. Asphalt Pavement Analyzer (APA) Test Set-up | 50 |
| 2.38. Pressurized Hose over HMA Samples before and after Testing | 51 |
| 2.39. Beam and Cylindrical Specimens in APA Equipment | 51 |
| 2.40. APA Results vs. WesTrack Performance | 52 |
| 2.41. Hamburg Wheel Tracking Set-up | 53 |
| 2.42. A Typical Plot from HWTB Test and the Key Parameters | 54 |
| 2.43. Hamburg Wheel-Tracking Device Test Results vs. WesTrack Performance | 55 |
| 2.44. French Plate Compactor (Top) and French Rutting Tester (Bottom) | 56 |

| | |
|--|-----|
| 2.45. French Rutting Tester Results vs. WesTrack Performance | 57 |
| 2.46. Purdue University Laboratory Wheel Tracking Device | 58 |
| 2.47. PurWheel Test Results vs. WesTrack Performance | 59 |
| 2.48. The Model Mobile Load Simulator (MMLS) | 60 |
| 2.49. Operation Principle of a Mobile Load Simulator | 60 |
| 2.50. Newton-Raphson Method for Finding an Isolated Real Root | 68 |
| 3.1. Flowchart of the Study | 71 |
| 3.2. Test Plan 1: Design a Wheel Tracking and Instrumentation System | 72 |
| 3.3. Test Plan 2: Tire Footprint Imaging in the RCWT Equipment | 73 |
| 3.4. Test Plan 3: Quantifying the Relative Damage of Asphalt Pavement due to Various Contact Areas | 74 |
| 3.5. Comprehensive Experimental Design | 75 |
| 3.6. Existing UPM Rotary Compactor Equipment | 76 |
| 3.7. Rotary Compactor and Wheel Tracking (RCWT) Equipment | 77 |
| 3.8. Dimensions of the P155/70R12 Tire | 79 |
| 3.9. Tire Inflation Pressure Checking before Imprint Capturing | 80 |
| 3.10. Procedure of Capturing Tire Imprint | 81 |
| 3.11. Samples in Marshall Testing Machine | 85 |
| 3.12. Mixing Process at Temperature of 170 ± 5 °C | 88 |
| 3.13. Storing the Asphalt Materials at Temperature of 170-165 °C | 88 |
| 3.14. Positioning of the Vertical Asphalt Strain Gages and Implementation of the Protection Layer | 89 |
| 3.15. Dumping and Leveling Process at Temperature of 165-155 °C | 90 |
| 3.16. Procedure Sequence, Time line and Temperature Range for Slab Preparation | 91 |
| 3.17. Compaction Procedure at Temperature of 155-110 °C | 91 |
| 3.18. The Final Flat Surface of Testing Slabs | 95 |
| 3.19. Rotary Track Alignment Match | 96 |
| 3.20. Schematic View of Four Quadrants and LVDTs Positions before Starting the Rotational Movement | 97 |
| 3.21. Cross Sections of Rutted Slab in Q1 and Q2- Slab No.10 | 100 |
| 3.22. Dry Cutting Process by Hand Cutter | 100 |
| 4.1. Rotary Compactor and Wheel Tracker Components | 105 |
| 4.2. Installation of the LVDTs before Testing | 108 |
| 4.3. The Hot Air Blower and Temperature Control Panel | 111 |
| 4.4. Quarter-bridge Steel Sensor (Trial and Error Design) | 113 |
| 4.5. A sample of the Output Voltage in the Strain gage (Trial and Error Design) | 114 |
| 4.6. The Best Full-bridge Configuration for Axial Strain Measurement | 115 |
| 4.7. Evenness Checking and Installation of the In-house Vertical Asphalt Strain Gage | 118 |
| 4.8. Overall Dimensions of the In-house Vertical Asphalt Strain Gage | 118 |
| 4.9. Bottom Plate in the In-house Vertical Asphalt Strain Gage Set-up | 119 |
| 4.10. In-house Vertical Asphalt Strain Gage and the Connector for Easy Removal | 120 |
| 4.11. Front View of the RCWT Main Frame Assembly | 121 |
| 4.12. Isometric View of the RCWT Main Frame Assembly | 122 |
| 4.13. Front and Top Views of the RCWT Compaction Assembly | 123 |
| 4.14. Isometric View of the RCWT Compaction Assembly | 124 |
| 4.15. Front and Top Views of the RCWT Wheel Tracking Assembly | 125 |
| 4.16. Isometric View of the RCWT Wheel Tracking Assembly | 126 |
| 4.17. The 3D Drawing of the RCWT Full Set-up | 127 |
| 4.18. Load Cell Sensor Drawings | 129 |
| 4.19. LVDT Set-up Drawings | 130 |

| | |
|---|-----|
| 4.20. Front and Isometric Views of the Slip ring Set-up | 131 |
| 4.21. Top View and the Cross section of the Slip ring Set-up | 132 |
| 4.22. Calibration of the Load Cells | 133 |
| 4.23. Calibration Charts for the Load Cells | 134 |
| 4.24. Functionality Check in Vertical Asphalt Strain Gages | 135 |
| 4.25. Output Signal from a Typical Functionality Check | 136 |
| 4.26. Comparison between Permanent Strain Measurements by two different Strain Sensors | 138 |
| 5.1. Tire Imaging Output; Use of Special Duplicating Ink and Improvement in the Images Clarity | 141 |
| 5.2. Sample of Imprints; (a): Dunlop Ec201; (b): Dunlop SP Sport J3; (c): Sime Astar 100; (d): GPS2; (e): PBZ1800; (f): B250; and (g): Worn-out Tread | 141 |
| 5.3. A Typical Loading Trend in Footprint Testing; (a): TL=1.50 kN; (b): TL=2.00 kN; (c): TL=2.50 kN | 142 |
| 5.4. A Typical Loading Trend in Footprint Testing; (d): TL=3.00 kN; (e): TL=3.50 kN | 143 |
| 5.5. Image Processing Outcomes; (a): Scanned Imprint; (b): Recognized Full Contact Area; and (c): Recognized Effective Contact Area | 143 |
| 5.6. Manual Selection of the Effective Contact Area for Validation | 146 |
| 5.7. Calculated Contact Area by AutoCAD Software | 146 |
| 5.8. Contact Areas Variations for different Tire Treads, Tire Loads, and Tire Inflation Pressures | 149 |
| 5.9. Comparison between Traditional and Full Contact Areas | 151 |
| 5.10. Temperature -Viscosity Relationship | 153 |
| 5.11. Test Property Curves for Mix Design Data by the Marshall Method | 156 |
| 5.12. Final Blending of Four Stockpiles in a 0.45 Power Chart | 159 |
| 5.13. Mean Temperature during the Compaction of Slabs No.1 and 12 | 162 |
| 5.14. Simulation of Compaction Procedure using Multicool Software | 163 |
| 5.15. Temperature Increase during Conditioning to Reach the Target Temperature for Slabs No.1 and 12 | 164 |
| 5.16. Slip Angle Measurement in the RCWT Equipment | 165 |
| 5.17. Variations of Slip Angle against the Tire Contact Area | 166 |
| 5.18. Permanent Deformation Values in Four Quadrants of Slab No.1; (a):2D and (b):3D Plots | 168 |
| 5.19. Permanent Deformation Values in Four Quadrants of Slab No.2; (a):2D and (b):3D Plots | 169 |
| 5.20. Permanent Deformation Values in Four Quadrants of Slab No.3; (a):2D and (b):3D Plots | 170 |
| 5.21. Permanent Deformation Values in Four Quadrants of Slab No.4; (a):2D and (b):3D Plots | 171 |
| 5.22. A Sample of Rutting Damage Profile with Linear Curve Fitting and the Derivatives | 172 |
| 5.23. A Sample of Rutting Damage Profile with Power Curve Fitting and the Derivatives | 174 |
| 5.24. A Sample of Rutting Damage Profile and the Established Model, Two-Term Exponential | 175 |
| 5.25. A Sample of Rutting Damage Profile with the Inflection Point, Two-Term Exponential | 176 |
| 5.26. Exponential Rut Profiles for Slab No.1; (a): One-Term, and (b): Two-Term | 179 |
| 5.27. Exponential Rut Profiles for Slab No.2; (a): One-Term, and (b): Two-Term | 180 |
| 5.28. Exponential Rut Profiles for Slab No.3; (a): One-Term, and (b): Two-Term | 181 |

| | |
|---|-----|
| 5.29. Exponential Rut Profiles for Slab No.4; (a): One-Term, and (b): Two-Term | 182 |
| 5.30. Exponential Rut Profiles for Slab No.5; (a): One-Term, and (b): Two-Term | 183 |
| 5.31. Exponential Rut Profiles for Slab No.6; (a): One-Term, and (b): Two-Term | 184 |
| 5.32. Exponential Rut Profiles for Slab No.7; (a): One-Term, and (b): Two-Term | 185 |
| 5.33. Exponential Rut Profiles for Slab No.8; (a): One-Term, and (b): Two-Term | 186 |
| 5.34. Exponential Rut Profiles for Slab No.9; (a): One-Term, and (b): Two-Term | 187 |
| 5.35. Exponential Rut Profiles for Slab No.10; (a): One-Term, and (b): Two-Term | 188 |
| 5.36. Exponential Rut Profiles for Slab No.11; (a): One-Term, and (b): Two-Term | 189 |
| 5.37. Exponential Rut Profiles for Slab No.12; (a): One-Term, and (b): Two-Term | 190 |
| 5.38. Rutting Depths at the End of the Primary Stage, With and Without Tread- TL=1.43 kN | 191 |
| 5.39. Rutting Depths at the End of the Primary Stage, With and Without Tread- TL=1.91 kN | 192 |
| 5.40. Rutting Depths at the End of the Primary Stage, With and Without Tread- TL=2.13 kN | 193 |
| 5.41. Rut Depths for Various Tread Patterns at TL=1.43 kN | 194 |
| 5.42. Rut Depths for Various Tread Patterns up to Certain Load Cycles | 195 |
| 5.43. Rut Depths for Various Tread Patterns at TL=1.91 kN | 195 |
| 5.44. Rut Depths for Various Tread Patterns at TL=2.13 kN | 196 |
| 5.45. Numbers of Load Cycles to Failure for Various Tire Treads | 197 |
| 5.46. Exponential Permanent Strain Profile in Slab No.1 | 200 |
| 5.47. Dynamic Load Variations in Slab No.1 | 201 |
| 5.48. Numbers of Load Cycles to Strain Failure for Various Tire Treads | 201 |
| 5.49. Rutting Damage Ratios for Various Contact Areas with Respect to the Full Contact Area | 205 |
| 5.50. Rutting Nonlinear Damage Ratios for Various Contact Areas and Load Cycles-First Load Group | 209 |
| 5.51. Rutting Nonlinear Damage Ratios for Various Contact Areas and Load Cycles-Second Load Group | 210 |
| 5.52. Rutting Nonlinear Damage Ratios for Various Contact Areas and Load Cycles-Third Load Group | 211 |
| 5.53. Permanent Strain Damage Ratios for Various Contact Areas with Respect to the Full Contact Area | 213 |
| 5.54. Permanent Strain Nonlinear Damage Ratios for Various Contact Areas and Load Cycles-First Load Group | 217 |
| 5.55. Permanent Strain Nonlinear Damage Ratios for Various Contact Areas and Load Cycles-Second Load Group | 218 |
| 5.56. Permanent Strain Nonlinear Damage Ratios for Various Contact Areas and Load Cycles -Third Load Group | 219 |
| 5.57. Asphalt Mixture Rutting Rate With and Without Tire Tread | 222 |
| 5.58. Typical Pavement Structure and Loading with Varying Asphalt Thicknesses for Theoretical Damage Ratios Calculations | 226 |
| 5.59. Counter Plots of Rutting Depths for a half SADT Configuration (a): TCA; (b): ECA | 228 |
| 5.60. A Typical Pavement Structure with 70 mm Asphalt Thickness | 230 |
| 5.61. A Typical Pavement Structure with 120 mm Asphalt Thickness | 231 |
| 5.62. Design Example 1 | 232 |
| 5.63. Design Example 2 | 235 |
| 5.64. Design Example 3 | 237 |

LIST OF ABBREVIATIONS

| | |
|--------|--|
| AASHTO | American Association of State Highway and Transportation Officials |
| AC | Asphalt Concrete |
| ANOVA | Analysis of Variance |
| APA | Asphalt Pavement Analyzer |
| ASTM | American Society for Testing and Materials |
| BC | BISAR Conventional |
| BM | BISAR Modified |
| BS | British Standard |
| CF | Calibration Factor |
| DPI | Dots per Inch |
| ECA | Effective Contact Area |
| ESAL | Equivalent Standard Axle Load |
| FCA | Full Contact Area |
| FHWA | Federal Highway Administration |
| FN | Flow Number |
| FRT | French Rutting Tester |
| FSCH | Frequency Sweep at Constant Height |
| GSI | Gyratory Shear Index |
| GTM | Gyratory Testing Machine |
| HMA | Hot Mix Asphalt |
| HVS | Heavy Vehicle Simulator |
| HWTD | Hamburg Wheel-Tracking Device |
| JKR | Jabatan Kerja Raya |
| LVDT | Linear Variable Differential Transformer |
| M-E | Mechanistic-Empirical |

| | |
|-----------|---|
| MMLS3 | Model Mobile Load Simulator |
| NAPA | National Asphalt Pavement Association |
| NCAT | National Center for Asphalt Technology |
| NCHRP | National Cooperative Highway Research Program |
| NMAS | Nominal Maximum Aggregate Size |
| OAC | Optimum Asphalt Content |
| PC | Personal Computer |
| QD | Quarry Dust |
| RCWT | Rotary Compactor and Wheel Tracker |
| RPM | Revolutions Per Minute |
| RSCH | Repeated Shear at Constant Height |
| SADT | Single Axle Dual Tire |
| SD | Standard Deviation |
| SHRP | Strategic Highway Research Program |
| SMA | Stone Mastic Asphalt |
| SSD | Saturated Surface Dry |
| Superpave | Superior Performing Asphalt Pavement |
| SST | Superpave Shear Tester |
| TCA | Traditional Contact Area |
| TIP | Tire Inflation Pressure |
| TL | Tire Load |
| TMD | Theoretical Maximum Density |
| TT | Tire Tread |
| UPM | Universiti Putra Malaysia |
| VASG | Vertical Asphalt Strain Gage |
| VFA | Voids filled with Asphalt |

| | |
|-----|-----------------------------|
| VMA | Voids in Mineral Aggregates |
| VTM | Voids in Total Mix |



CHAPTER 1

INTRODUCTION

1.1 General Background

In the past, structural design approaches to flexible pavements were mainly empirical in nature. The American Association of State Highway and Transportation Officials (AASHTO) method of pavement design (AASHTO, 1993), is still used by some highway agencies as an empirical approach.

In the AASHTO design 1993, equations were developed to guide users to the appropriate design. These equations are based on results from previous field experiments (e.g. AASHTO road test of 1960s).

It should be noted that, empirical methods can be applied only to a given set of environmental, material, and loading conditions. If these conditions are changed, the design is no longer valid, and a new method must be developed to be conformant to the new conditions. For example in the AASHTO road tests bias-ply tires were used which are completely out-of-date nowadays. Considering serviceability instead of different failure criteria, Equivalent Standard Axle Load (ESAL) instead of load spectra (axle type and load group), and old loading combinations are some of the limitations with this release of AASHTO design procedure.

Limitations of the empirical approach are becoming increasingly obvious with developments in the transportation system and increased knowledge in the fields of pavement mechanics and material science.

Premature failures of asphalt overlays within few years of construction are so common; therefore the need for a more comprehensive mechanistic pavement design model has been recognized.

Newly proposed guideline (NCHRP, 2004) is a great step toward the mechanistic-empirical design of pavements. The asphalt institute method of pavement design in the ninth edition of MS-1 (Asphalt Institute, 1982) is also considered empirical-mechanistic although this method still uses the concept of load equivalency in the empirical methods of pavement design.

Despite efforts by researchers in the last decades to enhance the mechanistic part of the design, no fully satisfactory or comprehensive alternative to the empirical approach has been found (Croney et al., 1997) with some exception proposed in the new mechanistic-empirical design guide. This could be because of the complexity in the tire-pavement interaction analysis.

The necessity of incorporating realistic non-uniform measured contact stresses, realistic tire contact areas, as well as other non-linear and viscoelastic behavior within tire-pavement interaction have been suggested by many researchers in order to obtain more reliable pavement responses for further engineering judgments (Al-Qadi et al., 2009a; Luo et al., 2007b; Machemehl et al., 2005; Park et al., 2008).

So far various aspects of complex radial tire contact stresses have not been widely analyzed (Novak et al., 2003a) and typically simplifying assumptions (e.g. layered linear elastic theory) and/or limited number of variables (e.g. vertical contact stresses, unique and constant tread pattern, constant speed, free rolling condition without steering and braking maneuvers to name but a few) have been incorporated for predicting pavement responses. These simplifying assumptions are due to the importance of fast computation in common pavement design procedure as well.

In this study the main focus was on the realistic tire-pavement contact area and determination of relative damage induced to asphalt mixtures from reduced tire contact area with respect to the full contact area. Effective tire-pavement contact area seems to affect the relative damage of pavement and should be incorporated in both mechanistic and empirical response analyses of asphalt pavements. Traditional Contact Area (TCA), Full Contact Area (FCA) and Effective Contact Area (ECA) are the three common tire-pavement contact areas for the study with different order of magnitude. TCA is the ratio of tire load (TL) over tire inflation pressure (TIP) which is assumed a full circular contact area. FCA is the elliptical contact area of a bald or worn-out tire without any grooves (control sample). ECA which is the actual contact area equals the full contact area of a tire minus the tread areas (void areas). In this study, the realistic tire-pavement contact areas were measured for various combinations of tire tread patterns, tire loads and tire inflation pressures. In order to study the effect of tire-pavement contact area on the induced pavement damage, various contact areas were examined in wheel tracking experiment and the resulting Hot Mix Asphalt (HMA) failures were investigated.

Finally in the design procedure of any new pavement structure, incorporating the effective contact area was recommended and for any already designed pavement structures, a set of theoretical damage ratios were established for various asphalt thicknesses which account for effective tire-pavement contact area. Theoretical damage ratios are used to modify the existing ESAL and by the use of the corrected ESAL, the design should be repeated to obtain the optimum design.

1.2 Problem Statement

Although high quality materials from different quarries, typically different types of aggregates and binders, various kinds of additives in the mixtures, different types of asphalt mixtures such as dense graded, Stone Mastic Asphalt (SMA), and various methods of mix design and compaction have been used so far still a large amount of load-related distresses such as fatigue and rutting occur. Therefore, there could be some drawbacks with the current pavement design procedure.

The hypothesis is to investigate whether the various tire-pavement contact areas affect the relative damage of asphalt mixtures or not. According to the theoretical calculations on the traditional and effective contact area values provided by (Michelin, 2005) in Table 1.1., the researcher reported that in a typical pavement structure, even a trivial difference of 10% between contact areas leads to relatively significant difference (up to 50%) in terms of induced pavement damage.

Table 1.1. Traditional and Effective Contact Areas and Induced Fatigue Damage

| Tire Type with the associated fatigue life | Single Axle Load (kN) | Tire Inflation Pressure (kPa) | Calculated Contact Area (mm ²) | Measured Contact Area (mm ²) | Difference |
|--|-----------------------|-------------------------------|--|--|------------|
| GOODYEAR 425/65R22.5 | 75.6 | 790 | 47848 | 43140 | 10% |
| Number of Load Cycles to Fatigue Failure | | | 2378451 | 1420744 | 50% |

(Source: Adapted from Michelin, 2005)

Current pavement design is based on traditional contact area which is an extreme overestimation of contact area and extreme underestimation of real stress state. As it can be seen in Figure 1.1 and the following technical correlation, there might be a significant difference between the induced stress states from the full contact area and the effective contact area (including the void areas).

Considering the linear layered elastic theory, the induced stress can be calculated as in Equation 1.1 and 1.2 for the tire without and with tread, respectively:

$$\sigma = \frac{TL}{TCA \text{ or } FCA} \quad (1.1)$$

$$\sigma = \frac{TL}{ECA} \quad (1.2)$$

where;

σ : The applied stress on asphalt mixture

TL: Tire load, and

TCA, FCA and ECA are Traditional, full and effective areas of contact, respectively.

Therefore, considering TCA or FCA as the tire-pavement contact area extremely underestimate the actual induced stresses on the asphalt mixtures.



Figure 1.1. Full and Effective Contact Areas, Close-up View of the Void Areas

Tire companies reported a minimum 25% void areas for the tire based on the mold size. On the other hand, some studies mentioned about higher values of void areas (Marsili, 2000). Therefore, the realistic tire-pavement contact area should be taken into consideration in pavement design procedure. (De Beer et al., 2008) also recommended studying the effect of surface texture and tire tread patterns on contact stresses because of its importance.

Tire-pavement contact area studies showed that the traditional contact area is larger than the actual area, since a full circular contact area is considered between the tire and the asphalt pavement (Luo & Prozzi, 2007b). In addition, both circular and equivalent rectangular contact areas overestimated the net contact area (Al-Qadi & Wang, 2009a). Therefore, the necessity of incorporating the actual area has been suggested in the literature (Park, 2008).

In this study the importance of incorporating the realistic and effective tire-pavement contact area was highlighted and relative damage of asphalt mixtures from reduced tire contact area was determined with respect to the full contact area.

In this research in order to capture the realistic and effective tire-pavement contact area and study the effect of various contact areas on HMA rutting, a new equipment called Rotary Compactor and Wheel Tracker (RCWT) was designed and fabricated with three different functionalities. The RCWT captures the realistic contact areas of pneumatic tires, simulates the field compaction process, up to the desired density, and conducts simulative laboratory wheel tracking test. This test set-up was designed to prepare and test heavy-duty asphalt mixtures in slab form.

Following the design and fabrication of the RCWT, in the next stage the effective tire contact areas were captured. In addition, in order to quantify the relative damage caused by various contact areas, different induced tire-pavement contact areas were tested in the wheel tracking experiment and the associated performance criteria

including rutting depth and vertical compressive strain were captured to enable the relative damage analyses.

1.3 Objectives of Study

The main objective of this study is to determine the permanent deformation of asphalt mixtures from reduced tire contact area. To fulfill this main objective the following objectives were introduced:

1. To design a wheel tracking and instrumentation system.
2. To establish a method for determination and analysis of tire-pavement effective contact area.
3. To quantify the relative damage of asphalt pavement due to various tire contact areas.

1.4 Scope of Study

Effective tire-pavement contact area seems to affect the relative damage of pavement and should be incorporated in both mechanistic and empirical response analyses of asphalt pavements. In order to quantify the damage induced by various contact areas, a simulative compactor and wheel tracking equipment was developed in the first test plan. In the second test plan, realistic contact areas were captured and calculated. In test plan 3, slab preparation, compaction of asphalt slabs to the desired density, wheel tracking test and relative damage analysis were discussed.

The RCWT equipment with real pneumatic tires is able to apply non-uniform contact stresses, realistic tire contact area, as well as other non-linear and viscoelastic behavior within tire-pavement interaction.

In order to study the effect of tire-pavement contact area on the induced pavement damage, various contact areas were examined in wheel tracking experiment and the resulting HMA failures were investigated.

Failure parameters including permanent deformation and vertical compressive strains were captured in the data acquisition system continuously. In the next part, relative damage analyses were done on the obtained results to quantify the damage caused by various contact areas.

It was recommended to incorporate the effective tire-pavement contact area in pavement design procedure. In addition, for any already designed pavement, a set of theoretical damage ratios, for various asphalt thicknesses, were established to account for effective tire-pavement contact area. These damage ratios are used to modify the existing ESAL for the effective tire-pavement contact area and repeat the design according to the modified value of ESAL to obtain the optimum layer thicknesses.

1.5 Thesis Layout

Chapter two includes the relevant literature review. Experimental procedures and research methodologies for the overall study are described in chapter three. Chapter four describes the design, fabrication and instrumentation for the RCWT equipment, and chapter five presents the tests results and includes the analysis parts. Conclusion and recommendations are presented in chapter six.



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