UNIVERSITI PUTRA MALAYSIA

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

DANIAL MOAZAMI

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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

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 FROM REDUCED TIRE CONTACT AREA

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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 ljazah Doktor Falsafah

PENENTUAN KEROSAKAN RELATIF DARIPADA PENGURANGAN KAWASAN SENTUHAN TAYAR PADA TURAPAN

Oleh

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Mengambilkira 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, menyamatarakan kebolehan memadat Asfat Matrik Batuan (SMA) keluli statik skala penuh dengan pengolek dan melakukan ujian simulasi pengesan roda di makmal.

Bagi mendapatkan kawasan sentuh berkesan untuk tayar 155/70R12, enam corak bebenang tayar yang terdapat di pasaran tetapi sudah sepenuhnya haus telah dipilih dan diuji dengan lima kumpulan beban tayar iaitu 1.50 kN, 2.0, 2.5, 3.0, dan 3.5 kN dan empat inflasi tekanan iaitu 137.90 kPa, 172.37, 206.84 dan 241.32 kPa.
Melalui prosidur pengimejan tayar didapati kawasan sentuhan yang diperolehi adalah bebas daripada mana-mana kerosakan imej. Kawasan sentuhan tersebut telah diteliti dan 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 entitiled "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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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 (mm²)	Measured Contact Area (mm²)	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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